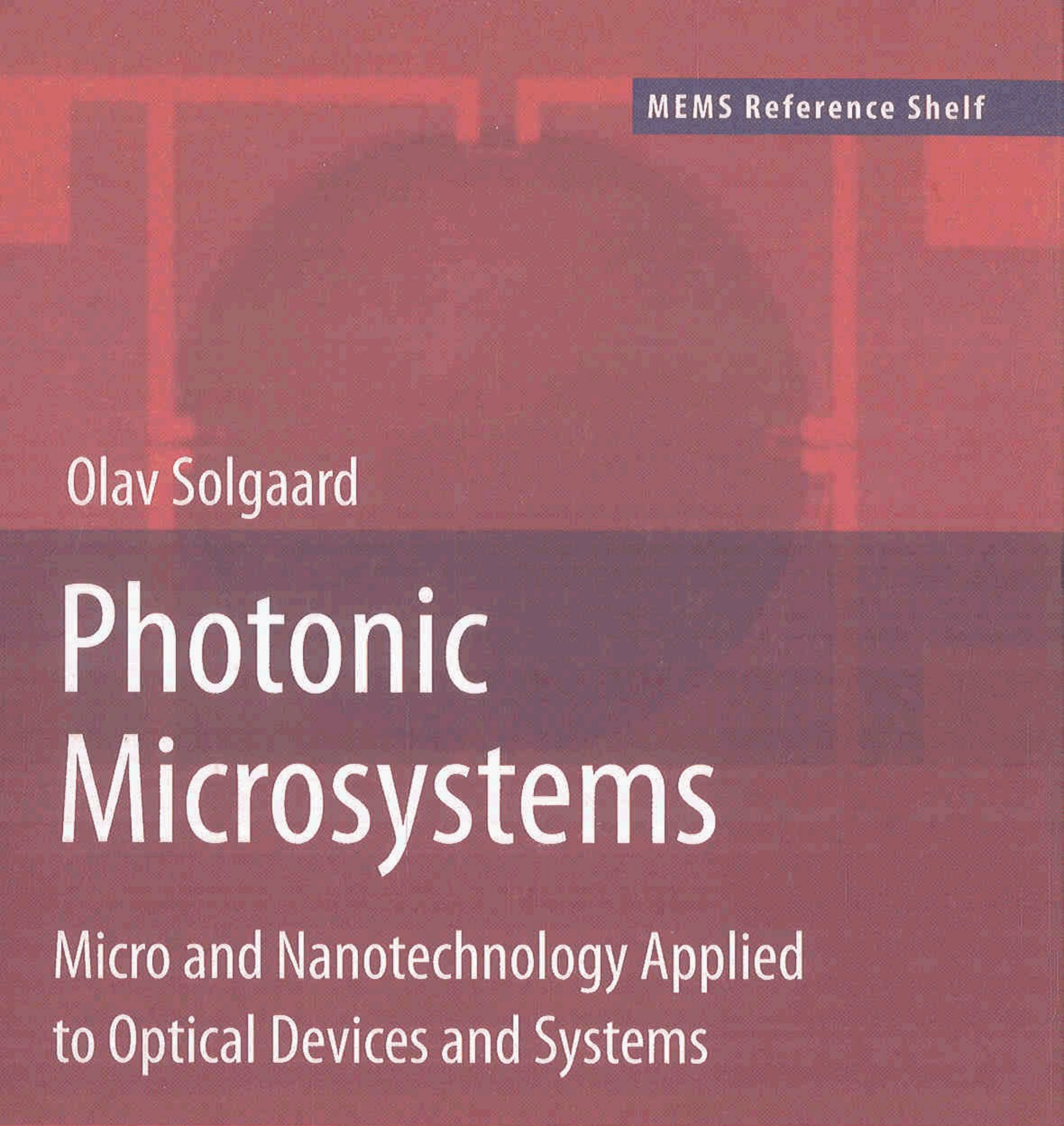

MEMS Reference Shelf

Olav Solgaard

# Photonic Microsystems

## Micro and Nanotechnology Applied to Optical Devices and Systems

Springer

# Contents

**1 Introduction to Optical Microsystems ........ 1**
1.1 Scaling of Optics ........ 1
1.2 Design of miniaturized optics ........ 3
1.3 Roadmap ........ 4
References ........ 8

**2 Electromagnetic Fields ands Energy ........ 10**
2.1 Introduction to Fields and Energy ........ 10
2.2 From Maxwell's Equations to the Wave Equation ........ 11
2.3 Plane Waves ........ 14
2.4 Phasor Notation ........ 18
2.4.1 Michelson Interferometer – Phasor notation ........ 20
2.5 The Poynting Theorem ........ 23
2.6 Combination of Optical Fields from Separate Sources ........ 26
2.7 Analysis Based on Energy Conservation - Examples ........ 28
2.7.1 "Collimated optical beam" ........ 28
2.7.2 Combination of optical beams – Fan-in ........ 29
2.7.3 Optical devices with two inputs and two outputs – General Case ........ 30
2.7.4 Dielectric interface ........ 31
2.7.5 Y-coupler ........ 32
2.7.6 Fan-in loss ........ 33
2.7.7 Practical beam combiner ........ 34
2.7.8 Wavelength Division Multiplexing ........ 34
2.8 Summary of Fields and Waves ........ 36
Further Reading ........ 38
Exercises ........ 38

**3 Plane Waves at Interfaces ........ 42**
3.1 Introduction to Plane Waves ........ 42
3.2 Plane Waves at a Dielectric Interface - Fresnel Reflections ........ 43
3.2.1 Laws of Reflection and Refraction (Geometrical Optics) ........ 43
3.2.2 Fresnel Equations ........ 45
3.2.3 Numerical Evaluation of the Fresnel Equations ........ 48

3.2.3 Reflectance and Transmittance ....50
3.2.4 Brewster Angle ....51
3.3 Wave description of Total Internal Reflection (TIR) ....52
3.3.1 Evanescent Fields ....53
3.3.2 Goos-Hänchen Shift ....55
3.3.3 Optical Devices Based on TIR ....55
3.4 Multilayer Stacks ....57
3.5 Applications of Layered Structures ....60
3.5.1 Anti-Reflection Coatings ....61
3.5.2 Bragg reflectors ....62
3.5.3 Photon Tunneling ....63
3.5.4 Surface Plasmons ....65
3.6 Summary of Plane Waves ....67
Exercises ....69
References ....75

**4 Diffraction and Gaussian Beams ....76**
4.1 Introduction to Diffraction and Gaussian Beams ....76
4.2 Paraxial Wave Equation ....77
4.2.1 The Fundamental Gaussian Profile ....78
4.2.2 Beam Waist ....79
4.2.3 Higher Order Gaussian Modes ....81
4.3 Gaussian Beam Transformation in Lenses ....84
4.4 Resolution of a Lens ....89
4.4.1 Focusing into high-index media ....91
4.5 Projecting Gaussian Beams ....95
4.6 Gaussian Beam “Imaging” ....96
4.6.1 Graphical Description of Gaussian Beam “Imaging” ....98
4.7 Truncation of Gaussian Beams ....99
4.7.1 Energy loss due to Truncation of Gaussian Beams ....100
4.7.2 Far-field of Truncated Gaussian Beams – Frauenhofer Diffraction ....103
4.8 Summary of Gaussian Beams ....107
Further Reading ....110
Exercises ....111
References ....114

**5 Optical Fibers and Waveguides ....116**
5.1 Introduction to Fibers and Waveguides ....116
5.2 Geometrical optics description of waveguides ....116
5.3 Three-layered Slab Waveguide ....118
5.3.1 Numerical Solutions to Eigenvalue Equations ....121
5.3.2 TM Solutions ....122
5.3.3 Nature of the Solutions ....122

5.3.4 Number of Modes ........ 123
5.3.5 Energy carried by a mode ........ 125
5.3.6 Properties of Modes ........ 126
5.3.7 Normalized propagation parameters ........ 127
5.4 Optical Fibers ........ 129
5.4.1 Modes in Step-Index Optical Fibers ........ 130
5.4.2 Linearly Polarized Modes ........ 131
5.4.3 The Fundamental Mode of a Cylindrical Waveguide ........ 135
5.4.4 Power Confinement ........ 136
5.5 Dispersion ........ 137
5.5.1 Material Dispersion ........ 138
5.5.1.1 Frequency Dependent Dielectric Constant ........ 140
5.5.1.2 Group Delay Caused by Material Dispersion ........ 142
5.5.2 Waveguide Dispersion ........ 143
5.5.3 Modal Dispersion ........ 144
5.5.4 Total dispersion – Simultaneous Material, Modal and Waveguide Dispersion ........ 146
5.6 Pulse Spreading on Fibers ........ 148
5.6.1 Pulse Broadening ........ 150
5.6.2 Frequency Chirp ........ 152
5.6.3 Dispersion Compensation ........ 153
5.6.4 Dispersion Expressed in Normalized Propagation Parameters ........ 154
5.6.5 Single-Mode Dispersion Expressed in Normalized Parameters ........ 157
5.6.6 Single Mode Fiber Design ........ 158
5.7 Fiber Calculation Example ........ 159
5.8 Summary of Fibers and Waveguides ........ 160
Further Reading ........ 165
Exercises ........ 166
References ........ 172

**6 Fiber and Waveguide Devices ........ 174**
6.1 Introduction to Fiber and Waveguide Devices ........ 174
6.2 Coupling to Fibers and Waveguides ........ 175
6.2.1 Loss in Single Mode Fiber Splices ........ 177
6.2.2 Coupling Coefficients ........ 179
6.2.3 Laser to Single-Mode-Fiber Coupling ........ 181
6.2.4 Laser-Mode Size Measurements Using the Knife-Edge Method ........ 182
6.2.5 Coupling from Spatially Incoherent Sources to Multi Mode Fibers ........ 184
6.2.6 Coupling between Spatially Coherent Sources and Multimode Fibers ........ 185

- 6.2.7 Coupling from Spatially Incoherent Sources to Single Mode Fibers ... 185
- 6.2.8 Prism Coupling ... 185
- 6.2.9 Grating Coupling ... 187
6.3. Coupled Optical Modes ... 189
6.4 Directional Couplers ... 193
- 6.4.1 Coupled Mode Description of Directional Couplers ... 195
- 6.4.2 Eigenmodes of the Coupled System ... 200
- 6.4.3 Conceptual Description of Directional Couplers based on Eigen Modes ... 203
6.5 Optical Devices Based on Directional Couplers ... 204
- 6.5.1 Modulators and Switches based on Directional Couplers ... 205
- 6.5.2. Power Combiners and Filters based on Directional Couplers ... 207
6.6 Periodic Waveguides – Bragg Filters ... 208
- 6.6.1 Energy Conservation in Counter Propagating Waves ... 210
- 6.6.2 Modes of the Bragg Grating ... 211
- 6.6.3 One-Dimensional Photonic Bandgaps ... 212
- 6.6.4 Bragg Filters ... 213
6.7 Waveguide Modulators ... 215
- 6.7.1 Mach-Zender modulators ... 215
- 6.7.2 Figures of Merit for Optical Modulators ... 217
- 6.7.3 Phase Modulation ... 218
- 6.7.4 Acoustooptic Modulators ... 221
- 6.7.5 Modified Mach-Zender Modulators ... 221
- 6.7.6 Directional Coupler Switches ... 222
- 6.7.7 Fabry-Perot Modulator ... 223
- 6.7.8 Resonant Waveguide Coupling ... 224
6.8 Summary of Fiber and Waveguide Devices ... 231
Exercises ... 232
References: ... 245

**7 Optical MEMS Scanners ... 246**
7.1 Introduction to MEMS Scanners ... 246
7.2 Scanner Resolution ... 248
- 7.2.1 Resolution of an Ideal Scanner ... 249
- 7.2.2 Optimum Resolution of a Scanned Gaussian Beam ... 251
- 7.2.3 Scanner Aperture ... 253
- 7.2.4 Surface Roughness, Curvature, and Bending of Micro Mirrors ... 255
7.3 Reflectivity of Metal Coated Micromirrors ... 265
7.4 Lens Scanners ... 268
7.5 Mechanical Scanner Design – One Dimensional Scanners ... 270
- 7.5.1 Transformation from Linear Motion to Rotation ... 270
- 7.5.2 Torsional Spring Design ... 272

7.5.3 *Mechanical Resonances* ..... 275
7.5.4 Higher-Order Mechanical Resonances ..... 278
7.6 *Two Dimensional Scanners* ..... 281
7.7 High Resolution 2-D Scanners – Design Examples ..... 284
7.7.1 Gimbaled Scanner ..... 284
7.7.2 Universal Joint Microscanner with "Terraced-Plate" Actuators ..... 287
7.7.3 Universal Joint Microscanner with Combdrive Actuators ..... 288
7.8 Summary of MEMS scanners ..... 289
Exercises ..... 291
References ..... 293

**8 Optical MEMS Fiber Switches ..... 296**
8.1 Introduction to MEMS Fiber Switches ..... 296
8.2 Fiber Optical Switches and Cross Connects ..... 297
8.3 MEMS Switch Architectures ..... 299
8.4 2 by 2 Matrix Switch ..... 304
8.4.1 Fiber Separation in 2 by 2 MEMS Switches ..... 304
8.4.2 Mirror Thickness in 2 by 2 Matrix Switches ..... 306
8.4.3 Low-loss 2 by 2 Matrix Switches ..... 308
8.4.4 *MEMS Implementation of 2 by 2 Fiber Switch* ..... 309
8.5 N by N Matrix Switches ..... 311
8.5.1 *Scaling of N by N Matrix Switch* ..... 313
8.5.2 MEMS Implementations of N by N Matrix Switch ..... 316
8.6 N by N Beam Steering Switches ..... 317
8.6.1 Scaling of the Beam Steering Switch ..... 318
8.6.2 MEMS Implementations of the N by N Beam Steering Switch ..... 325
8.7 Summary of MEMS Fiber Switches ..... 327
Exercises ..... 329
References ..... 331

**9 Micromirror Arrays – Amplitude and Phase Modulation ..... 332**
9.1 Introduction to Micromirror Arrays ..... 332
9.2 Amplitude Modulating Mirror Arrays ..... 333
9.2.1 Projection Display ..... 334
9.3 Projection of Micromirror Arrays ..... 338
9.3.1 The Point Spread Function ..... 339
9.3.2 Image formation with finite Point Spread Functions ..... 344
9.3.3 Projection of a Gaussian Source ..... 345
9.3.4 Projection of a Gaussian Micromirror ..... 347
9.3.5 Projection of a 1-D Gaussian Source ..... 349
9.4 *Micromirrors with Phase Modulation* ..... 349
9.4.1 Projection of a Phase Step ..... 350

9.4.2 Projection of a Phase Modulated Line ....353
9.4.3 Sub-Pixel Shifts in Phase-Modulated Micromirror arrays .356
9.5 Projection of Micromirrors through Hard Apertures ....356
9.6 Adaptive Optics ....358
9.6.1 Micromirror Arrays for Adaptive Optics....360
9.7 Phase vs. Amplitude Modulation ....362
9.7.1 Diffractive Optical MEMS ....364
9.8 Summary of Micromirror Arrays ....368
Exercises ....369
References ....371

**10 Grating Light Modulators ....374**
10.1 Introduction to Grating Light Modulators....374
10.2 Phenomenological Description of MEMS Grating Modulators ....374
10.2.1 Mechanical design and actuation of Grating Light Modulators ....374
10.2.2 Optical Design and Operation of Grating Light Modulators ....377
10.2.3 Schlieren Projection System....379
10.3 Phasor Representation of Grating Modulator Operation....380
10.4 High Contrast Grating Light Modulator....386
10.5 Diffraction gratings ....389
10.6 Projection Displays Based on Grating Modulators ....403
10.6.1 Actuator Design....403
10.6.2 Ribbon Mechanics....407
10.6.3 Linear Display Architecture ....411
10.6.4 1-D Modulator Array Fabrication ....414
10.6.5 Light Sources for swept-line projection displays ....418
10.7 Summary of Grating Light Modulators....422
Exercises ....423
References ....425

**11 Grating Light Modulators for Fiber Optics ....428**
11.1 Fiber Optic Modulators....428
11.2 Low Dispersion Grating Light Modulators....430
11.2.1 Three-level Grating Light Modulator ....430
11.2.2 Optimum Design of Three-Level Grating Modulator ....433
11.2.3 Contrast in the Three-level Grating Modulator ....435
11.2.4 Wavelength Dependence of Attenuation....437
11.2.5 Alternative Modulator Architectures....439
11.3 Polarization Independent Grating Light Modulators....440
11.4 Summary of GLMS for Fiber Optics ....444
Further Reading....444
Exercises ....445

References .......... 446

**12 Optical Displacement Sensors .......... 448**
- 12.1 Introduction to Optical Displacement Sensors .......... 448
- 12.2 Interferometers as Displacement Sensors .......... 451
  - 12.2.1 The Michelson Interferometer .......... 451
  - 12.2.2 Displacement Sensitivity .......... 454
  - 12.2.3 Implementations of Interferometric Displacement Sensors .......... 455
  - 12.2.4 Improved Sensitivity of High-Finesse Interferometers .......... 460
  - 12.2.5 Effect of Apertures in Interferometers .......... 466
- 12.3 Optical Lever .......... 469
  - 12.3.1 Displacement and Angle Sensitivity of the Optical Lever .......... 471
  - 12.3.2 Grating Optical Lever .......... 472
- 12.4 Sources of Noise in Displacement Measurements .......... 473
  - 12.4.1 Thermal Noise .......... 474
  - 12.4.2 Shot Noise .......... 475
  - 12.4.3 Relative Intensity Noise .......... 475
- 12.5 Signal-to-Noise Ratio .......... 476
  - 12.5.1 Noise Equivalent Power .......... 478
- 12.6 Detection Limits in displacement measurements .......... 479
  - 12.6.1 Resolution of Optical Interferometers .......... 479
  - 12.6.2 Resolution of Optical Levers .......... 481
  - 12.6.3 Resolution of Capacitive Sensors .......... 481
  - 12.6.4 Resolution of Piezoresistive Sensors .......... 483
  - 12.6.5 Comparison of Displacement Sensors .......... 485
- 12.7 Summary of Optical Displacement Sensors .......... 486
- Exercises .......... 487
- References: .......... 489

**13 Micro-Optical Filters .......... 490**
- 13.1 Introduction to Micro-Optical Filters .......... 490
- 13.2 Amplitude Filters .......... 491
  - 13.2.1 Fabry-Perot Filters .......... 491
  - 13.2.2 Bragg Filters .......... 495
  - 13.2.3 Microresonator Filters .......... 495
- 13.3 Dispersion compensators .......... 498
- 13.4 MEMS Spectrometers .......... 500
  - 13.4.1 Swept Pass Band Spectrometers .......... 501
  - 13.4.2 Generalized Transform Spectrometers .......... 502
  - 13.4.3 Fourier Transfor Spectrometers .......... 503
  - 13.4.4 MEMS Implementations of Transform Spectrometers .......... 507
- 13.5 Diffractive Spectrometers .......... 511
  - 13.5.1 Spectral Synthesis .......... 511

    13.5.2 Diffractive MEMS Spectrometers ....514
  13.6 Tunable lasers ....517
    13.6.1 MEMS Vertical Cavity Surface Emitting Lasers ....518
    13.6.2 MEMS External Cavity Semiconductor Diode Lasers ....519
    13.6.3 Tunable External Cavity Semiconductor Diode Lasers with Diffractive Filters ....522
  13.7 Summary of Microoptical Filters ....523
  Exercises ....524
  References ....527

**14 Photonic Crystal Fundamentals ....532**
  14.1 Introduction to Photonic Crystals ....532
  14.2 Photonic Crystal Basics ....533
    14.2.1 1-D Photonic Crystals ....535
    14.2.2 Bloch States ....538
    14.2.3 Band Structure of 2-D and 3-D Photonic Crystals ....539
  14.3 Guided Resonances ....543
    14.3.1 Reflection and Transmission through 2-D Photonic Crystals ....544
    14.3.2 Reflection and Transmission for a Mirror-Symmetric 2-port with one Guided Resonance ....546
    14.3.3 Reflection and Transmission for a Mirror-Symmetric 2-port with two Guided Resonances ....549
    14.3.4 Coupling to Guided Resonances – Symmetry ....551
  14.4 Comparison of Photonic and Electronic Crystals ....553
  14.5 Summary of PC fundamentals ....555
  Exercises ....556
  References ....557

**15 Photonic Crystal Devices and Systems ....560**
  15.1 Introduction to PC devices and systems ....560
  15.2 IC Compatible Photonic Crystals ....561
    15.2.1 Silicon Compatible 2-D Photonic Crystals ....561
    15.2.2 3-D Structuring of Photonic Crystals ....566
  15.3 Photonic Crystal Optical Components ....567
    15.3.1 Mirrors and Filters ....568
    15.3.2 Photonic Crystal Fabry-Perot Resonators ....569
    15.3.3 PC Tunneling Sensors ....570
    15.3.4 PC Polarization Optics ....571
    15.3.5 PC Index Sensors ....571
  15.4 Tunable Photonic Crystals ....573
    15.4.1 Photonic Crystal MEMS Scanners ....574
    15.4.2 Photonic Crystal Displacement Sensors ....577
  15.5 Photonic Crystal Fiber Sensors ....579

15.6 Summary of PC devices and systems ........................................581
Exercises ........................................582
References ........................................583

**Appendix A Geometrical Optics ........................................588**
A.1 Introduction to Geometrical Optics ........................................588
A.2 Geometrical Optics Treatment of Lenses ........................................588
A.2.1 Lens -- Ray Picture ........................................588
A.2.2 Lenses – Wave Picture ........................................589
A.2.3 Ray Tracing ........................................590
A.3 ABCD matrices ........................................591
A.3.1 Free space ........................................592
A.3.2 Slab of Index n ........................................592
A.3.3 Thin Lens ........................................593
A.3.4 Curved Mirror ........................................594
A.3.5 Combinations of Elements ........................................594
A.3.6 Reverse transmission: ........................................595

**Appendix B Electrostatic Actuation ........................................596**
B.1 The parallel Plate Capacitor ........................................596
B.1.1 Energy Storage in Parallel-Plate Capacitors ........................................597
B.2 The Parallel Plate Electrostatic Actuator ........................................599
B.2.1 Charge Control ........................................600
B.2.2 Voltage Control ........................................602
B.3 Energy Conservation in the Parallel Plate Electrostatic Actuator ........................................606
B.4 Electrostatic Spring ........................................610
B.4.1 Sensors Based on the Electrostatic Spring ........................................613
B.5 Electrostatic Combdrives ........................................614
B.6 Summary of Electrostatic Actuation ........................................620
References ........................................624

**Index ........................................626**