

# Contents

---

## Part I High Aperture Optical Systems and Super-Resolution

---

### 1 Exploring Living Cells and Molecular Dynamics with Polarized Light Microscopy

<i>S. Inoué</i> . . . . .	3
1.1 Introduction . . . . .	3
1.2 Equipment Requirement . . . . .	4
1.3 Biological Examples . . . . .	8
1.4 Video-Enhanced Microscopy . . . . .	12
1.5 The LC Pol-Scope . . . . .	13
1.6 The Centrifuge Polarizing Microscope . . . . .	14
1.7 Polarized Fluorescence of Green Fluorescent Protein . . . . .	17
1.8 Concluding Remarks . . . . .	18
References . . . . .	19

### 2 Characterizing High Numerical Aperture Microscope Objective Lenses

<i>R. Juškaitis</i> . . . . .	21
2.1 Introduction . . . . .	21
2.1.1 Disclaimer . . . . .	21
2.1.2 Objective Lens Basics . . . . .	22
2.2 Point Spread Function . . . . .	23
2.2.1 Fibre-Optic Interferometer . . . . .	24
2.2.2 PSF Measurements . . . . .	26
2.3 Chromatic Aberrations . . . . .	28
2.3.1 Apparatus . . . . .	28
2.3.2 Axial Shift . . . . .	30
2.4 Pupil Function . . . . .	31
2.4.1 Phase-Shifting Interferometry . . . . .	32
2.4.2 Zernike Polynomial Fit . . . . .	33
2.4.3 Restoration of a 3-D Point Spread Function . . . . .	36
2.4.4 Empty Aperture . . . . .	37
2.5 <i>Esoterica</i> . . . . .	39
2.5.1 Temperature Variations . . . . .	39
2.5.2 Apodization . . . . .	40

2.5.3 Polarization Effects .....	42
2.6 Conclusion .....	42
References .....	43

### **3 Diffractive Optical Lenses in Imaging Systems – High-Resolution Microscopy and Diffractive Solid Immersion Systems**

<i>R. Brunner, H.J. Dobschal</i> .....	45
3.1 Introduction .....	45
3.2 Basics .....	46
3.2.1 Fundamentals .....	46
3.2.2 Dispersion – Achromatization – Apochromatization .....	47
3.2.3 Diffraction Efficiency .....	49
3.3 Applications .....	52
3.3.1 Hybrid Lens System for High Resolution DUV Mask Inspection .....	53
3.4 Design and Realization .....	53
3.5 Application Examples .....	56
3.6 Resolution Enhancement with Solid Immersion Lens (SIL) .....	60
3.6.1 DUV Microscopy with NIR Autofocus: Wavelength Selective DOE Combination .....	61
3.6.2 Diffraction Based Solid Immersion Lens .....	63
3.7 dSIL: Concept and Phase Effects .....	65
3.8 dSIL: Experimental .....	66
3.9 Final Remarks .....	68
References .....	68

### **4 Diffractive Read-Out of Optical Discs**

<i>J. Braat, P. Dirksen, A. Janssen</i> .....	71
4.1 Introduction .....	71
4.2 Historic Overview of Video and Audio Recording on Optical Media .....	71
4.2.1 The Early Optical Video System .....	73
4.2.2 The Origin of the CD-System .....	74
4.2.3 The Road Towards the DVD-System .....	75
4.3 Overview of the Optical Principles of the CD- and the DVD-System . . .	76
4.3.1 Optical Read-Out of the High-Frequency Information Signal . . .	76
4.3.2 Optical Error Signals for Focusing and Radial Tracking of the Information .....	81
4.3.3 Examples of Light Paths .....	84
4.4 Radial Tracking for DVD .....	86
4.4.1 A Diffraction Model for the DPD and DTD Tracking Signal . . .	86
4.4.2 The Influence of Detector Misalignment on the Tracking Signal .	88
4.4.3 The DTD Tracking Signal for the DVD-System .....	90
4.4.4 The DTD2 and the DTD4 Signal in the Presence of Defocus . . .	92
4.5 Compatibility Issues for the DVD-and the CD-System .....	93

4.5.1	The Substrate-Induced Spherical Aberration .....	95
4.5.2	The Effective Optical Transfer Function .....	99
4.5.3	The Two-Wavelength Light Path .....	100
4.6	Efficient Calculation Scheme for the Detector Signal .....	100
4.6.1	Optical Configuration and the FFT-Approach .....	101
4.6.2	The Analytic Approach .....	102
4.6.3	The Harmonic Components of the Detector Signal .....	105
4.6.4	The Representation of the Function $F_{m,n}(x, y)$ .....	107
4.6.5	Orthogonality in Pupil and Image Plane .....	109
4.7	Conclusion .....	110
	References .....	110

## 5 Superresolution in Scanning Optical Systems

	<i>E. Pike, D. Chana, P. Neocleous, S.-H. Jiang</i> .....	113
5.1	Introduction .....	113
5.2	Direct Methods .....	114
5.2.1	Pendry Lens .....	114
5.2.2	Kino's Solid Immersion Lens .....	117
5.2.3	Toraldo di Francia's Apodising Masks .....	117
5.3	Inverse Methods and Image-Plane Masks .....	120
5.4	Optical Systems for Scanning Imaging .....	122
5.4.1	Analytical Results .....	124
5.4.2	Numerical Results .....	127
5.5	The Comparison of Non-linear Optical Scanning Systems .....	130
5.6	High-Aperture Image-Plane Masks .....	133
	References .....	135

## 6 Depth of Field Control in Incoherent Hybrid Imaging Systems

	<i>S. Sherif, T. Cathey</i> .....	137
6.1	Introduction .....	137
6.2	Hybrid Imaging Systems .....	137
6.2.1	Digital Post-Processing .....	138
6.2.2	New Metric for Defocused Image Blurring .....	138
6.3	Extended Depth of Field .....	139
6.3.1	Design of a Rectangular EDF Phase Plate .....	140
6.3.2	Performance of a Logarithmic Phase Plate .....	143
6.3.3	Performance Comparison of Different EDF Phase Plates .....	151
6.4	Reduced Depth of Field .....	154
6.4.1	Design of a Rectangular RDF Phase Plate .....	154
6.4.2	Performance of a Rectangular RDF Phase Grating .....	156
6.5	Effect of Optical Detector on Depth of Field Control .....	159
6.5.1	Effect of Additive White Noise at the Optical Detector .....	159
6.5.2	Charge-Coupled Device-Limited PSF .....	161
6.5.3	CCD Effect on Depth of Field Extension .....	163
6.5.4	CCD Effect on Depth of Field Reduction .....	164

6.6	Conclusions .....	165
	References .....	167

## 7 Wavefront Coding Fluorescence Microscopy

### Using High Aperture Lenses

	<i>M.R. Arnison, C.J. Cogswell, C.J.R. Sheppard, P. Török</i> .....	169
7.1	Extended Depth of Field Microscopy .....	169
7.1.1	Methods for Extending the Depth of Field .....	170
7.2	High Aperture Fluorescence Microscopy Imaging .....	172
7.2.1	Experimental Method .....	173
7.2.2	PSF and OTF Results .....	175
7.2.3	Biological Imaging Results .....	177
7.3	Wavefront Coding Theory .....	178
7.3.1	Derivation of the Cubic Phase Function .....	179
7.3.2	Paraxial Model .....	179
7.3.3	High Aperture PSF Model .....	180
7.3.4	High Aperture OTF Model .....	182
7.3.5	Defocused OTF and PSF .....	183
7.3.6	Simulation Results .....	184
7.3.7	Discussion .....	188
7.4	Conclusion .....	190
	References .....	191

---

## Part II Nonlinear Techniques in Optical Imaging

---

### 8 Total Internal Reflection Fluorescence Microscopy

	<i>D. Axelrod</i> .....	195
8.1	Features and Applications .....	195
8.2	Theoretical Principles .....	198
8.2.1	Infinite Plane Waves .....	198
8.2.2	Finite Width Incident Beams .....	203
8.2.3	Intermediate Layers .....	203
8.2.4	Combination of TIR with Other Fluorescence Techniques .....	205
8.2.5	Surface Near Field Emission Imaging .....	207
8.2.6	Measurement of Distances from a Surface .....	209
8.2.7	Variable Incidence Angle TIR: Concentration Profiles .....	211
8.2.8	Image Deconvolution .....	212
8.3	Optical Configurations .....	212
8.3.1	High Aperture Objective-Based TIR .....	212
8.3.2	TIRF with a Prism .....	217
8.3.3	TIR from Multiple Directions .....	223
8.3.4	Rapid Chopping between TIR and EPI .....	224
8.3.5	Surface Near-Field Imaging .....	225
8.4	General Experimental Considerations .....	226

8.5	TIRF vs. other Optical Section Microscopies .....	231
	References .....	233

## 9 Nonlinear Optical Microscopy

	<i>F. Lagugné Labarhet, Y.R. Shen</i> .....	237
9.1	Introduction .....	237
9.2	Second Harmonic Nonlinear Microscopy .....	239
9.2.1	Basic Principle of SHG .....	239
9.2.2	Coherence Effects in SH Microscopy .....	242
9.2.3	Scanning Near-Field Nonlinear Second Harmonic Generation .....	243
9.3	Sum Frequency Generation Microscopy .....	246
9.3.1	Basic Principle of Sum Frequency Generation .....	246
9.3.2	Far-Field SFG Microscopy .....	247
9.3.3	Near-Field SFG Imaging .....	250
9.4	Third Harmonic Generation Microscopy .....	251
9.5	Coherent Anti-Stokes Raman Scattering Microscopy .....	252
9.6	Multiphoton Excited Fluorescence Microscopy .....	256
9.6.1	Two-Photon Excited Fluorescence (TPEF) Microscopy .....	257
9.6.2	TPEF Far-Field Microscopy Using Multipoint Excitation .....	260
9.6.3	4- $\Pi$ Confocal TPEF Microscopy .....	261
9.6.4	Simultaneous SHG/TPEF Microscopy .....	262
9.6.5	Three-Photon-Excited Fluorescence Microscopy .....	263
9.6.6	Stimulated-Emission-Depletion (STED) Fluorescence Microscopy .....	263
9.7	Conclusion .....	264
	References .....	265

## 10 Parametric Nonlinear Optical Techniques in Microscopy

	<i>M. Müller, G.J. Brakenhoff</i> .....	269
10.1	Introduction .....	269
10.2	Nonlinear Optics – Parametric Processes .....	270
10.2.1	Introduction .....	270
10.2.2	Optical Sectioning Capability .....	272
10.2.3	Second Harmonic Generation (SHG) .....	272
10.2.4	Third Harmonic Generation (THG) .....	273
10.2.5	Coherent Anti-Stokes Raman Scattering (CARS) .....	274
10.3	Third Harmonic Generation (THG) Microscopy .....	275
10.3.1	General Characteristics .....	275
10.3.2	Selected Applications .....	277
10.3.3	Summary .....	280
10.4	Coherent Anti-Stokes Raman Scattering (CARS) Microscopy .....	281
10.4.1	General Characteristics .....	281
10.4.2	Multiplex CARS .....	283
10.4.3	Summary .....	286

10.5 Conclusion .....	286
References .....	288

## **11 Second Harmonic Generation Microscopy Versus Third Harmonic Generation Microscopy in Biological Tissues**

<i>C.-K. Sun</i> .....	291
11.1 Introduction .....	291
11.2 SHG Microscopy .....	292
11.3 Bio-Photonic Crystal Effect in Biological SHG Microscopy .....	293
11.4 THG Microscopy .....	300
11.5 Conclusion .....	302
References .....	303

---

## **Part III Miscellaneous Methods in Optical Imaging**

---

### **12 Adaptive Optics**

<i>C. Dainty</i> .....	307
12.1 Introduction .....	307
12.2 Historical Background .....	308
12.3 Strehl Ratio and Wavefront Variance .....	311
12.4 Wavefront Sensing .....	312
12.5 Deformable Mirrors and Other Corrective Devices .....	315
12.6 The Control System .....	317
12.7 Low Cost AO Systems .....	320
12.8 Current Research Issues in Astronomical Adaptive Optics .....	322
12.9 Adaptive Optics and the Eye .....	324
References .....	326

### **13 Low-Coherence Interference Microscopy**

<i>C.J.R. Sheppard, M. Roy</i> .....	329
13.1 Introduction .....	329
13.2 Geometry of the Interference Microscope .....	332
13.3 Principle of Low-Coherence Interferometry .....	333
13.4 Analysis of White-Light Interference Fringes .....	335
13.4.1 Digital Filtering Algorithms .....	336
13.4.2 Phase Shift Algorithms .....	336
13.5 Spatial Coherence Effects .....	338
13.6 Experimental Setup .....	339
13.6.1 The Illumination System .....	339
13.6.2 The Interferometer .....	339
13.7 Experimental Results .....	341
13.8 Discussion and Conclusion .....	342
References .....	344

**14 Surface Plasmon and Surface Wave Microscopy**

<i>M.G. Somekh</i> .....	347
14.1 Introduction .....	347
14.2 Overview of SP and Surface Wave Properties .....	348
14.3 Surface Wave Generation and Contrast Mechanisms in Surface Wave Microscopy .....	354
14.4 Surface Plasmon Microscopy – Kretschmann Prism Based Methods ...	361
14.5 Objective Lenses for Surface Plasmon Microscopy .....	363
14.6 Objective Lens Based Surface Plasmon Microscopy:	
Non Interferometric Methods .....	368
14.6.1 Scanning Methods .....	368
14.6.2 Wide Field SP and Surface Wave Microscopy .....	369
14.6.3 Scanning Fluorescence Surface Wave Microscopy .....	374
14.7 Objective Lens Interferometric Techniques .....	383
14.7.1 Scanning Interferometry .....	383
14.7.2 Widefield Interferometric Techniques .....	389
14.8 Discussion and Conclusions .....	392
14.8.1 Relationship of SP Methods with TIR(F)M Methods .....	393
14.8.2 Localized SPs .....	394
14.8.3 ‘Exotic’ Techniques .....	394
References .....	396

**15 Optical Coherence Tomography**

<i>A.M. Zysk, S.A. Boppart</i> .....	401
15.1 Introduction .....	401
15.2 Principles of Operation .....	402
15.3 Technological Developments .....	406
15.3.1 Optical Sources for High-Resolution Imaging .....	406
15.3.2 Spectroscopic OCT .....	408
15.3.3 Real-Time Volumetric OCT Imaging .....	410
15.3.4 Optical Coherence Microscopy .....	411
15.3.5 Beam Delivery Systems .....	414
15.3.6 Contrast Agents and Molecular Imaging .....	415
15.4 Applications .....	418
15.4.1 Developmental Biology .....	418
15.4.2 Cellular Imaging .....	420
15.4.3 Medical and Surgical Microscopy – Identifying Tumors and Tumor Margins .....	423
15.4.4 Image-Guided Surgery .....	426
15.4.5 Materials Investigations .....	428
15.5 Conclusions .....	430
References .....	432

**16 Near-Field Optical Microscopy and Application to Nanophotonics**

<i>M. Ohtsu</i> .....	437
16.1 Introduction .....	437
16.2 Nano-Scale Fabrication .....	438
16.2.1 Depositing Zinc and Aluminum .....	438
16.2.2 Depositing Zinc Oxide .....	443
16.3 Nanophotonic Devices and Integration .....	444
16.3.1 Switching by Nonlinear Absorption in a Single Quantum Dot ...	445
16.3.2 Switching by Optical Near-Field Interaction Between Quantum Dots .....	446
16.4 Optical Storage and Readout by Optical Near-Field .....	449
16.5 Conclusion .....	452
References .....	453

**17 Optical Trapping of Small Particles**

<i>A. Rohrbach, E.H.K. Stelzer</i> .....	455
17.1 Introduction .....	455
17.2 Optical Trapping .....	456
17.2.1 Principles .....	456
17.2.2 Optical Tweezers .....	458
17.2.3 Photonic Force Microscopy .....	460
17.2.4 3D Tracking with Coherent Light .....	463
17.2.5 Atom Traps .....	463
17.3 Theory .....	464
17.3.1 Arbitrary Focused Fields .....	464
17.3.2 Scattering by Focused Fields .....	466
17.3.3 Interferometric Position Detection .....	466
17.3.4 Trapping forces .....	469
17.3.5 Thermal Noise .....	471
17.4 Experimental Setup and Techniques .....	472
17.4.1 Mechanics and optics .....	472
17.4.2 Lasers and Probes .....	473
17.4.3 Electronics .....	474
17.4.4 Calibration of Trap and Position Detector .....	474
17.4.5 Time-Multiplexed and Holographic Optical Traps .....	478
17.5 Applications in Brownian Systems .....	479
17.5.1 Particle Binding and Uptake by a Living Cell .....	480
17.5.2 Imaging Nano-Mechanical Properties of Single Molecules .....	481
17.6 Summary and Outlook .....	483
References .....	483

<b>Index</b> .....	491
--------------------	-----



Optical Imaging and Microscopy  
Techniques and Advanced Systems

Török, P.; Kao, F.-J. (Eds.)

2007, XIX, 497 p., Hardcover

ISBN: 978-3-540-69563-9