

Springer Series in Optical Sciences 87

P. Török

F.-J. Kao

Editors

Optical Imaging and Microscopy

Techniques and Advanced Systems

Second Edition

This text on contemporary optical systems is intended for optical researchers and engineers, graduate students and optical microscopists in the biological and biomedical sciences. This second edition contains two completely new chapters. In addition most of the chapters from the first edition have been revised and updated. The book consists of three parts: The first discusses high-aperture optical systems, which form the backbone of optical microscopes. An example is a chapter new in the second edition on the emerging field of high numerical aperture diffractive lenses which seems to have particular promise in improving the correction of lenses. In this part particular attention is paid to optical data storage. The second part is on the use of non-linear optical techniques, including nonlinear optical excitation (total internal reflection fluorescence, second and third harmonic generation and two photon microscopy) and non-linear spectroscopy (CARS). The final part of the book presents miscellaneous techniques that are either novel or well known but finding new applications. An example of the latter is photonic force microscopy that is now rapidly becoming an exciting and indispensable tool in shedding light on the inner working of certain cells or measuring nano-mechanical properties of single molecules.

ISBN 978-3-540-69563-9



 springer.com



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 Labarthe, 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
<i>11.2 SHG Microscopy</i>	292
<i>11.3 Bio-Photonic Crystal Effect in Biological SHG Microscopy</i>	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
Index	491