

Contents

1	Introduction	1
1.1	Thesis Aims	1
1.1.1	Overview	1
1.1.2	Thesis Structure	2
1.2	Quantum Measurements	3
1.2.1	Overview	3
1.2.2	Concepts of Quantum Metrology	4
1.2.3	Biological Measurements with Entangled Photons	10
1.2.4	Entangled Two-Photon Microscopy	12
1.2.5	Quantum Super-Resolution in Fluorescence Microscopy	13
1.2.6	Phase Contrast Microscopy	15
1.2.7	Atomic Magnetometers	16
1.2.8	Conclusion	19
1.3	Introductory Theory of Optical Tweezers	19
1.3.1	Relevance of Optical Tweezers	20
1.3.2	Optical Forces	22
1.3.3	Trapped Brownian Motion Spectra	25
1.3.4	Application to Sensing	27
1.3.5	Applications for Quantum Enhanced Sensitivity	28
	References	30

Part I The Quantum Limit to Particle Tracking Sensitivity

2	The Total Information Carried by the Light	41
2.1	Introduction	41
2.2	How Much Information Can a Photon Carry?	42
2.3	Optimal Tracking of a Rayleigh Particle	43
2.4	Sensitivity in the Mie Scattering Regime	44

2.5	Relevance of This Limit	46
2.5.1	Resolving Zero-Point Motion	46
2.5.2	Experimental Sensitivity	48
2.6	Lessons to Learn	48
	References.	49
3	The Quantum Noise Limit for a Specific Measurement.	51
3.1	Quantum Treatment of Fields	51
3.2	The Quantum Limit for Position Sensing	53
3.3	Particle Tracking with Squeezed States of Light	55
3.4	Relation to the Quantum Limit for Phase Estimation	57
3.5	Conclusion.	58
	References.	58
4	Characterizing Quadrant Detection	59
4.1	The Relevance of Computational Tools	59
4.2	Principle	60
4.3	Calculation of the Signal	61
4.4	Measurement Sensitivity	62
4.5	Particle Tracking Beyond Homogeneous Spheres	64
4.6	Measurement Mode in Quadrant Detection.	66
4.7	Conclusion.	67
	References.	67
 Part II Classically Optimizing Sensitivity		
5	Interferometer Enhanced Particle Tracking	71
5.1	Basic Concept	71
5.2	Sensitivity of Particle Tracking.	72
5.3	Theory of Sagnac Enhancement	76
5.4	Experimental Verification.	83
5.5	Alternative Interferometric Configurations	84
5.5.1	Sagnac-Michelson Interferometry	84
5.5.2	Mach-Zehnder Interferometry	85
5.6	Conclusion.	85
	References.	86
6	Homodyne Based Particle Tracking.	87
6.1	Homodyne Measurements	87
6.2	Self-homodyne Tracking Setup.	90
	References.	93

7	Lock-In Particle Tracking	95
7.1	Introduction	95
7.2	Basic Concept	96
7.3	Self-homodyne Demonstration	98
7.4	Experimental Verification in a Conventional Setup	101
7.5	Conclusion.	103
	References.	103
8	Selective Measurement by Optimized Dark-Field Illumination	
	Angle	105
8.1	Dark-Field Microscopy	105
8.2	Calculations	106
8.3	Application to Biological Measurement	109
8.4	Conclusion.	112
	References.	112
9	Technical Constraints on Sensitivity	115
9.1	Aberrations	115
9.1.1	Spherical Aberrations	115
9.1.2	Other Aberrations	116
9.1.3	Aberrations in the Sample Chamber	117
9.1.4	Aberration Compensation.	118
9.2	Long-Term Stability	118
9.3	Measurement Noise.	119
	References.	120

Part III Quantum Enhanced Optical Tweezers

10	Surpassing the Quantum Limit	125
10.1	Using Squeezed Light to Enhance Particle Tracking	125
10.2	Particle Tracking Method.	127
10.2.1	Production of the Probe Field.	128
10.2.2	Engineering the Local Oscillator.	129
10.3	Classically Characterizing the Experiment	131
10.4	Incorporating Squeezed States of Light	132
10.4.1	Generating Squeezed Light	132
10.4.2	Optical Losses	133
10.4.3	Amount of Quantum Enhancement	134
10.5	Experimental Characterization	135
10.6	Comparison with Theory	136
10.6.1	Relationship to the Standard Quantum Limit	139
10.7	Conclusion.	139
	References.	140

11	Biological Measurement Beyond the Quantum Limit	143
11.1	Microrheology	143
11.2	Quantum Enhanced Microrheology	145
11.2.1	The Effect of the Trapping Laser	147
11.3	Conclusion.	150
	References.	150
12	Subdiffraction-Limited Quantum Imaging of a Living Cell	153
12.1	Quantum Imaging with PFM	153
12.2	Experimental Method	155
12.3	Spatially Resolved Measurements	157
12.4	Correlation Analysis of Images.	158
12.5	Background Scattering.	160
12.6	Quantum Enhancement in Resolution	161
12.7	Theoretically Predicted Quantum Enhancement.	163
12.8	Outlook for the Future.	165
	References.	166
13	Further Extensions	169
13.1	Status of Experiments	169
13.2	Key Challenges for Quantum Enhanced Particle Tracking	171
13.3	Possible Designs.	173
13.3.1	Incorporating Classical 3D Tracking	173
13.3.2	Incorporating Sagnac Interferometry	174
13.4	Applications.	175
	References.	176
14	Summary and Conclusion	179
14.1	Part I: Characterization of the Quantum Limit	179
14.2	Part II: Strategies to Improve Sensitivity	180
14.3	Part III: Quantum Enhanced Measurements	181
14.4	Outlook for the Future.	182
	Appendix A: Source Code for Quadrant Detection	183
	Appendix B: Comment on Experimental Study on the Imaging of the Squeezed State Light at 1064 nm	189
	Curriculum Vitae: Michael Taylor	193

Quantum Microscopy of Biological Systems

Taylor, M.

2015, XIX, 195 p. 66 illus., 27 illus. in color., Hardcover

ISBN: 978-3-319-18937-6