

Contents

	Preface	<i>XI</i>
	List of Contributors	<i>XV</i>
	Color Plates	<i>XIX</i>
1	The Orbital Angular Momentum of Light: An Introduction	1
	<i>Les Allen and Miles Padgett</i>	
1.1	Introduction	1
1.2	The Phenomenology of Orbital Angular Momentum	4
	References	9
2	Vortex Flow of Light: “Spin” and “Orbital” Flows in a Circularly Polarized Paraxial Beam	13
	<i>Aleksandr Bekshaev and Mikhail Vasnetsov</i>	
2.1	Introduction	13
2.2	Spin and Orbital Flows: General Concepts	14
2.3	Transverse Energy Flows in Circularly Polarized Paraxial Beams	15
2.4	Orbital Rotation without Orbital Angular Momentum	21
2.5	Conclusion	22
	References	23
3	Helically Phased Beams, and Analogies with Polarization	25
	<i>Miles Padgett</i>	
3.1	Introduction	25
3.2	Representation of Helically Phased Beams	26
3.3	Exploiting the Analogous Representations of Spin and Orbital Angular Momentum	27
3.3.1	Rotational Doppler Shifts and Geometrical Phase	27
3.3.2	Mode Sorting using Geometric Phase	29
3.3.3	Entanglement of Spatial Modes	30
3.3.4	Photon Drag and the Mechanical Faraday Effect	32
3.4	Conclusions	33
	References	34

4	Trapping and Rotation of Particles in Light Fields with Embedded Optical Vortices	37
	<i>Michael Mazilu and Kishan Dholakia</i>	
4.1	Introduction	37
4.2	Laguerre–Gaussian Light Beams	38
4.3	Origin of Optical Torques and Forces	41
4.3.1	Intuitive Picture of Optical Forces	41
4.3.2	Angular Momentum within Geometric Optics	43
4.3.3	Paraxial Beams	44
4.3.4	Maxwell’s Stress Tensor	45
4.3.5	Linear Momentum Transfer	49
4.3.6	Angular Momentum Transfer	50
4.3.7	Polarization Spin Momentum	50
4.4	Optical Vortex Fields for the Rotation of Trapped Particles	51
4.4.1	Studies of Rotation of Trapped Objects using Optical Vortex Fields	51
4.5	Optical Vortex Fields for Advanced Optical Manipulation	57
4.6	Conclusions	61
	Acknowledgments	62
	References	62
5	Optical Torques in Liquid Crystals	67
	<i>Enrico Santamato and Bruno Piccirillo</i>	
5.1	The Optical Reorientation and the Photon Angular Momentum Flux	70
5.1.1	Dynamical Equations of Liquid Crystals	71
5.1.2	Angular Momentum Fluxes	73
5.2	Dynamical Effects Induced in Liquid Crystals by Photon SAM and OAM Transfer	78
5.2.1	Experiments on OAM Transfer in Liquid Crystals	81
5.2.1.1	Orbital Photon Angular Momentum Transfer with Unpolarized Light	83
5.2.1.2	Investigation of the Combined Effect of the Spin and Orbital Photon Angular Momentum Transfer with Linearly Polarized Light	83
5.2.1.3	Investigation of the Combined Effect of the Spin and Orbital Photon Angular Momentum Transfer with Circularly Polarized Light	85
5.3	Conclusions	89
	References	90
6	Driving Optical Micromachines with Orbital Angular Momentum	93
	<i>Vincent L.Y. Loke, Theodor Asavei, Simon Parkin, Norman R. Heckenberg, Halina Rubinsztein-Dunlop, and Timo A. Nieminen</i>	
6.1	Introduction	93
6.2	Symmetry, Scattering, and Optically Driven Micromachines	93
6.3	Experimental Demonstration	96

6.3.1	A Preliminary Design	96
6.3.2	Fabrication	97
6.3.3	Optical Trapping and Rotation	97
6.3.4	Optical Measurement of Torque	98
6.3.5	Discussion	100
6.4	Computational Optimization of Design	102
6.4.1	Computational Modeling of Microrotors	102
6.4.2	Performance of a Four-Armed Rotor	105
6.4.3	Discussion	111
6.5	Conclusion	113
	References	113
7	Rotational Optical Micromanipulation with Specific Shapes Built by Photopolymerization	117
	<i>Péter Galajda, Lóránd Kelemen, László Oroszi, and Pál Ormos</i>	
7.1	Introduction	117
7.2	Microfabrication by Photopolymerization	118
7.2.1	Fabrication by Scanning a Single Focused Laser Beam	118
7.2.2	Parallel Photopolymerization using Diffractive Optics	120
7.3	Light-Driven Rotors, Micromachines	121
7.3.1	Propeller	121
7.3.2	Propeller with Reversed Direction of Rotation	124
7.3.3	Complex Micromachines	126
7.4	Integrated Optical Motor	128
7.5	Angular Trapping of Flat Objects in Optical Tweezers Formed by Linearly Polarized Light	131
7.6	Torsional Manipulation of DNA	134
7.6.1	Direct Measurement of Torque	135
7.7	Conclusion	138
	Acknowledgment	139
	References	139
8	Spiral Phase Contrast Microscopy	143
	<i>Christian Maurer, Stefan Bernet, and Monika Ritsch-Marte</i>	
8.1	Phase Contrast Methods in Light Microscopy	143
8.2	Fourier Filtering in Optical Imaging	144
8.3	Spiral Phase Fourier Filtering	146
8.3.1	Isotropic Edge Enhancement	148
8.3.2	Pseudorelief Images	149
8.3.3	Spiral Fringe Metrology with SPC	150
8.4	Implementation and Performance	151
8.5	Conclusions	152
	References	152

9	Applications of Electromagnetic OAM in Astrophysics and Space Physics Studies	155
	<i>Bo Thidé, Nicholas M. Elias II, Fabrizio Tamburini, Siavoush M. Mohammadi, and José T. Mendonça</i>	
9.1	Introduction	155
9.2	Ubiquitous Astronomical POAM	156
9.3	Applications of POAM in Astronomy	158
9.3.1	Sub-Rayleigh Resolution	159
9.3.2	Optical Vortices with Starlight	162
9.4	Applications of POAM in Space Physics	165
9.A.	Appendix: Theoretical Foundations	169
9.A.1	Classical Field Picture	169
9.A.2	Photon Picture	170
	References	175
 10	 Optical Vortex Cat States and their Utility for Creating Macroscopic Superpositions of Persistent Flows	 179
	<i>Ewan M. Wright</i>	
10.1	Introduction	179
10.2	Optical Vortex Cat States	181
10.2.1	Linear Fiber Propagation	181
10.2.2	Quantum Fiber Propagation	182
10.2.3	Optical Vortex Cat State via Self-Phase Modulation	184
10.2.4	Photonic-Crystal Fibers	186
10.2.5	Other Schemes	188
10.3	Macroscopic Superposition of Persistent Flows	189
10.3.1	Optical Light-Shift Potential	189
10.3.2	Ring Trap and Quantum Stirring	190
10.3.3	Matter Waves on a Ring	191
10.3.4	Macroscopic Superposition of Persistent Flows	192
10.3.5	Discussion	194
10.4	Summary and Conclusions	195
	References	195
 11	 Experimental Control of the Orbital Angular Momentum of Single and Entangled Photons	 199
	<i>Gabriel Molina-Terriza and Anton Zeilinger</i>	
11.1	Introduction to the Photon OAM	199
11.2	Control of the OAM State of a Single Photon	201
11.3	Control of the OAM State of Multiple Photons	203
11.4	Applications in Quantum Information	207
11.5	Discussion	209
11.6	Conclusion	211
	References	211

12	Rotating Atoms with Light	213
	<i>Kristian Helmerson and William D. Phillips</i>	
12.1	Introduction	213
12.2	Orbital Angular Momentum of Light	213
12.3	The Mechanical Effects of Light	214
12.4	Rotating Bose–Einstein Condensates	215
12.4.1	Experiment to Transfer Orbital Angular Momentum to a BEC ($\Delta = 0$)	216
12.4.2	Efficiency of the OAM Transfer Process	218
12.5	Measuring the Rotational Motion of the Atoms	220
12.5.1	Interference of the Rotating State with a Nonrotating State	220
12.5.2	Interference of the Rotating State with a Counterrotating State	222
12.5.3	Observation of Fork-Like Interference Structure	223
12.5.4	Measurement of the Doppler Shift of the Rotating Atoms	223
12.6	Generating Other Rotational States of Atoms	224
12.6.1	Vortices of Higher Charge	224
12.6.2	Rotational States of Multilevel Atomic Condensates	227
12.6.3	Matter wave Amplification of a Vortex State	228
12.7	Supercurrents	230
12.7.1	Generation of a Supercurrent in a BEC	230
12.8	Conclusion	231
	Acknowledgments	232
	References	232
	Index	237

