

Contents

1	Introduction	1
1.1	Motivation	1
1.2	Brief Overview of Past Work	2
1.3	Outline of Thesis	3
1.3.1	Logical Connections Between Chapters	3
	References	4
 Part I Atomic Physics Theory and Cooling Methods		
2	Atom-Field Interactions	9
2.1	Atomic Structure	9
2.2	The Density Matrix	11
2.3	The Optical Bloch Equations	14
2.3.1	Interaction with the Quantised Field	15
2.3.2	Interaction with the Incident Field	15
2.4	Polarisability of a Two-Level Atom	17
2.5	Energy Balance: Work Done on a Two-Level Atom	21
2.6	Forces on a Two-Level Atom	22
2.7	The Fluctuation-Dissipation Theorem	24
2.8	Beyond Two-Level Atoms	26
	References	31
3	Trapping and Cooling Atoms	33
3.1	Dipole Traps	33
3.2	Optical Molasses	34
3.3	Magneto-Optical Traps	36
3.4	Memory-Based Approach to Cooling in Laser Light: The Dipole Force Retarded	38

3.5	Cavity Fields and Atomic Motion: A Brief Review of Current Work	40
3.5.1	Cavity-Mediated Cooling	40
3.5.2	Ring Cavity Cooling	41
3.5.3	Self-Organisation of Atoms Inside Cavities	41
3.6	Mirror-Mediated Cooling	42
3.6.1	Mathematical Model	44
3.6.2	A Perturbative Approach to Exploring the Model	45
3.6.3	Numerical Analysis of Mirror-Mediated Cooling	53
3.6.4	Beyond Adiabatic Theory	57
3.6.5	Concluding Remarks	59
3.6.6	Appendix: A Note on Units	60
3.7	Exploiting an Optical Memory in Other Geometries	60
3.7.1	Lengthening the Time Delay: External Cavity Cooling	61
3.7.2	Lifting the Sub-Wavelength Dependence: Ring Cavity Cooling	62
3.7.3	Exploiting Three-Dimensional Electromagnetism	63
	References	64

Part II Scattering Models and Their Applications

4	The Transfer Matrix Model	71
4.1	An Extended Scattering Theory	72
4.1.1	Basic Building Blocks of the Model	72
4.1.2	General System of a Fixed and a Mobile Scatterer	79
4.1.3	Atom in Front of a Perfect Mirror	84
4.1.4	Optical Resonator with Mobile Mirror	86
4.1.5	Appendix: The Doppler Shift Operator	87
4.1.6	Appendix: Quantum Correlation Function of the Force Operator	89
4.1.7	Appendix: Mirror Cooling via the Radiation Pressure Coupling Hamiltonian	91
4.2	General Solution to the Transfer Matrix Approach	93
4.2.1	Force Acting on Moving Scatterer	94
4.2.2	Momentum Diffusion Experienced by Scatterer	95
4.3	Optomechanics of a Micromirror Inside a Cavity	99
4.4	Optical Pumping and Multi-Level Atoms	103
4.4.1	A Transfer Matrix Relating Jones Vectors	105
4.4.2	Atoms in a Gradient of Polarisation	107
4.4.3	Atoms in a Gradient of Ellipticity	109
	Appendix: Cavity Properties from the Transfer Matrix Model	110
	References	112

5 Applications of Transfer Matrices	115
5.1 External Cavity Cooling	115
5.2 Cavity Cooling of Atoms: Within and Without a Cavity	119
5.2.1 Comparison of Cavity Cooling Schemes	119
5.2.2 Scaling Properties of Cavity Cooling Forces	123
5.3 Amplified Optomechanics in a Ring Cavity	126
5.3.1 General Expressions and Equilibrium Behaviour	127
5.3.2 Numerical Results and Discussion	131
References	134
6 Three-Dimensional Scattering with an Optical Memory	137
6.1 Optical Self-Binding of Rayleigh Particles	138
6.2 Mirror-Mediated Cooling in One Dimension	139
6.3 Self-Binding: Mirror-Mediated Cooling in Three Dimensions	140
References	141

Part III Experimental Work

7 Experimental Setup	145
7.1 Vacuum and Laser System	145
7.1.1 Atom Cloud Close to Surface	146
7.1.2 Structured Surface	146
7.1.3 Rapid Changing of Surface	146
7.1.4 Good Optical Access	147
7.1.5 Laser System	148
7.2 The λ MOT and Multiphoton Imaging	149
7.2.1 Introduction and Motivation	150
7.2.2 The λ MOT	150
7.2.3 Multi-level Imaging System	153
7.2.4 Surface Loading by Magneto-Optic Launching	156
References	156
8 A Guide for Future Experiments	159
8.1 Overview of Several Different Possibilities	159
8.1.1 Trapped Ions	160
8.1.2 Neutral Atoms	160
8.1.3 Optomechanics: Cantilevers and Micromirrors	160
8.1.4 Dielectric Particles	161
8.1.5 Dipole Trap Arrays	162
8.1.6 Plane Mirror Cooling	163
8.1.7 External Cavity Cooling	163
8.1.8 Ring Cavity Cooling	164
8.1.9 Concave Mirror Cooling	164

8.2	Cooling Forces Experienced in Different Geometries	165
8.2.1	Longitudinal Mirror-Mediated Cooling	166
8.2.2	Transverse Mirror-Mediated Cooling	168
8.2.3	Ring Cavity Cooling	168
8.2.4	Summary: Orders of Magnitude	169
8.3	Cooling Times and Base Temperatures	169
8.3.1	One-Dimensional Mirror-Mediated Cooling: Trapped Ion	169
8.3.2	External Cavity Cooling: Transmissive Membrane	170
8.3.3	Amplified Optomechanics: Neutral Atom.	170
8.4	Appendix: Electric Fields Inside Dielectrics	171
8.5	Appendix: Calculating the Electric Field Inside Hemispherical Mirrors	173
8.6	Appendix: Force Acting on an Atom Inside an Arbitrary Monochromatic Field.	175
	References	176
9	Conclusions and Outlook	179
	References	181
	Author Biography	183
	Index	185