

Quantum Optomechanics

Warwick P. Bowen
Gerard J. Milburn



CRC Press

Taylor & Francis Group

Boca Raton London New York

CRC Press is an imprint of the
Taylor & Francis Group, an Informa business

Contents

Preface	xi
Author biographies	xv
Acknowledgements	xvii
CHAPTER 1 ■ Quantum harmonic oscillators	1
1.1 QUANTISING THE HARMONIC OSCILLATOR	2
1.2 FLUCTUATIONS AND DISSIPATION IN A QUANTUM HARMONIC OSCILLATOR	8
1.3 MODELLING OPEN SYSTEM DYNAMICS VIA QUANTUM LANGEVIN EQUATIONS	18
1.4 QUANTUM LANGEVIN EQUATION WITHIN THE ROTATING WAVE APPROXIMATION	28
CHAPTER 2 ■ Radiation pressure interaction	37
2.1 BASIC RADIATION PRESSURE INTERACTION	37
2.2 EFFECTIVE QUANTISATION	39
2.3 DISPERSIVE OPTOMECHANICS	40
2.4 ELECTRO- AND OPTO-MECHANICAL SYSTEMS	43
2.5 MECHANICAL AND OPTICAL DECOHERENCE RATES	45
2.6 DYNAMICS OF DISPERSIVE OPTOMECHANICAL SYSTEMS	47
2.7 LINEARISATION OF THE OPTOMECHANICAL HAMILTONIAN	51
2.8 DISSIPATIVE OPTOMECHANICS	55
CHAPTER 3 ■ Linear quantum measurement of mechanical motion	57
3.1 FREE-MASS STANDARD QUANTUM LIMIT	58

3.2	RADIATION PRESSURE SHOT NOISE	60
3.3	MEASUREMENT OF MECHANICAL MOTION	64
3.4	STANDARD QUANTUM LIMIT ON MECHANICAL POSITION MEASUREMENT	76
3.5	STANDARD QUANTUM LIMIT FOR GRAVITATIONAL WAVE INTERFEROMETRY	86
3.6	STANDARD QUANTUM LIMIT FOR FORCE MEASUREMENT	88
CHAPTER 4 ■ Coherent interaction between light and mechanics		93
4.1	STRONG COUPLING	94
4.2	OPTICAL COOLING OF MECHANICAL MOTION	96
4.3	OPTOMECHANICALLY INDUCED TRANSPARENCY	114
4.4	OPTOMECHANICAL ENTANGLEMENT	122
4.5	MECHANICAL SQUEEZING OF LIGHT	140
CHAPTER 5 ■ Linear quantum control of mechanical motion		151
5.1	STOCHASTIC MASTER EQUATION INCLUDING DISSIPATION	152
5.2	FEEDBACK COOLING	156
5.3	BACK-ACTION EVADING MEASUREMENT	166
5.4	SURPASSING THE STANDARD QUANTUM LIMIT USING SQUEEZED LIGHT	179
CHAPTER 6 ■ Single-photon optomechanics		193
6.1	OPTOMECHANICAL PHOTON BLOCKADE	194
6.2	SINGLE-PHOTON STATES	196
6.3	SINGLE-PHOTON PULSE INCIDENT ON A SINGLE-SIDED OPTOMECHANICAL CAVITY	202
6.4	DOUBLE-CAVITY OPTOMECHANICAL SYSTEM	206
6.5	MACROSCOPIC SUPERPOSITION STATES USING SINGLE-PHOTON OPTOMECHANICS	219
6.6	SINGLE-SIDEBAND-PHOTON OPTOMECHANICS	230
CHAPTER 7 ■ Nonlinear optomechanics		231
7.1	DUFFING NONLINEARITY	231
7.2	QUANTUM DUFFING OSCILLATOR	233

7.3	NONLINEAR DAMPING	240
7.4	SELF-PULSING AND LIMIT CYCLES	241
7.5	NONLINEAR MEASUREMENT OF A MECHANICAL RESONATOR	249
CHAPTER 8 ■ Hybrid optomechanical systems		255
8.1	ELECTROMECHANICAL SYSTEMS	256
8.2	COUPLING A MECHANICAL RESONATOR AND A TWO-LEVEL SYSTEM	261
8.3	MICROWAVE TO OPTICAL INTERFACE.	270
CHAPTER 9 ■ Arrays of optomechanical systems		277
9.1	SYNCHRONISATION IN OPTOMECHANICAL ARRAYS	277
9.2	IRREVERSIBLY COUPLED ARRAYS OF OPTOMECHANICAL SYSTEMS	293
CHAPTER 10 ■ Gravitational quantum physics and optomechanics		299
10.1	WHAT IS GRAVITATIONAL DECOHERENCE?	300
10.2	OPTOMECHANICAL TESTS OF GRAVITATIONAL DECOHERENCE	308
10.3	TESTS OF NONSTANDARD GRAVITATIONAL EFFECTS USING GEOMETRIC PHASE	315
APPENDIX A ■ Linear detection of optical fields		319
A.1	EFFECT OF INEFFICIENCIES	319
A.2	LINEAR DETECTION OF OPTICAL FIELDS	322
A.3	POWER SPECTRAL DENSITY OBTAINED BY HETERODYNE DETECTION	323
A.4	CHARACTERISING THE OPTOMECHANICAL COOPERATIVITY	324
A.5	CHARACTERISING THE TEMPERATURE OF A MECHANICAL OSCILLATOR	326
References		329
Index		355