Contents

Preface XI

1 Introduction 1
1.1 Historical perspective . . . 1
1.2 Motivation: Practical effects of quantum noise . . . 3
1.3 How to use this guide . . . 8
Bibliography . . . 10

2 Classical models of light 12
2.1 Classical waves . . . 13
2.1.1 Mathematical description of waves . . . 13
2.1.2 The Gaussian beam . . . 14
2.1.3 Quadrature amplitudes . . . 16
2.1.4 Field energy, intensity, power . . . 18
2.1.5 A classical mode of light . . . 19
2.1.6 Classical modulations . . . 20
2.2 Statistical properties of classical light . . . 23
2.2.1 The origin of fluctuations . . . 23
2.2.2 Coherence . . . 23
2.2.3 Correlation functions . . . 27
2.2.4 Noise spectra . . . 29
2.2.5 An idealized classical case: Light from a chaotic source. . . . 31
Bibliography . . . 36

3 Photons – the motivation to go beyond classical optics 37
3.1 Detecting light . . . 37
3.2 The concept of photons . . . 40
3.3 Light from a thermal source . . . 41
3.4 Interference experiments . . . 43
3.5 Modelling single photon experiments . . . 46
3.5.1 Polarization of a single photon . . . 47
3.5.2 Some mathematics . . . 49
3.5.3 Polarization states . . . 50
3.5.4 The single photon interferometer . . . 51
3.6 Intensity correlation, bunching, anti-bunching . . . 53

3.7 Single photon Rabi frequencies 56
Bibliography 57

4 Quantum models of light **60**
4.1 Quantization of light 60
4.1.1 Some general comments on quantum mechanics 60
4.1.2 Quantization of cavity modes 61
4.1.3 Quantized energy 62
4.1.4 The quantum mechanical harmonic oscillator 63
4.2 Quantum states of light 64
4.2.1 Number or Fock states 64
4.2.2 Coherent states 65
4.2.3 Mixed states 68
4.3 Quantum optical representations 68
4.3.1 Quadrature amplitude operators 68
4.3.2 Probability and quasi-probability distributions 70
4.3.3 Photon number distributions, Fano factor 75
4.4 Propagation and detection of quantum optical fields 77
4.4.1 Propagation in quantum optics 77
4.4.2 Detection in quantum optics 81
4.4.3 An example: The beamsplitter 82
4.5 Quantum transfer functions 84
4.5.1 A linearized quantum noise description 84
4.5.2 An example: The propagating coherent state 86
4.5.3 Real laser beams 87
4.5.4 The transfer of operators, signals and noise 88
4.5.5 Sideband modes as quantum states 90
4.6 Quantum correlations 92
4.6.1 Photon correlations 92
4.6.2 Quadrature correlations 93
4.7 Summary: The different quantum models 95
Bibliography 97

5 Basic optical components **99**
5.1 Beamsplitters 99
5.1.1 Classical description of a beamsplitter 99
5.1.2 The beamsplitter in the quantum operator model 102
5.1.3 The beamsplitter with single photons 104
5.1.4 The beamsplitter and the photon statistics 106
5.1.5 The beamsplitter with coherent states 108
5.1.6 The beamsplitter in the noise sideband model 110
5.1.7 Comparison between a beamsplitter and a classical current junction . 111
5.2 Interferometers 112
5.2.1 Classical description of an interferometer 113
5.2.2 Quantum model of the interferometer 115

5.2.3 The single photon interferometer . . . 115
5.2.4 Transfer of intensity noise through the interferometer . . . 116
5.2.5 Sensitivity limit of an interferometer . . . 117
5.3 Cavities . . . 119
5.3.1 Classical description of a linear cavity . . . 121
5.3.2 The special case of high reflectivities . . . 125
5.3.3 The phase response . . . 126
5.3.4 Spatial properties of cavities . . . 128
5.3.5 Equations of motion for the cavity mode . . . 132
5.3.6 The quantum equations of motion for a cavity . . . 133
5.3.7 The propagation of fluctuations through the cavity . . . 133
5.3.8 Single photons through a cavity . . . 137
5.4 Other optical components . . . 138
5.4.1 Lenses . . . 138
5.4.2 Crystals and polarizers . . . 140
5.4.3 Modulators . . . 141
5.4.4 Optical fibres . . . 143
5.4.5 Optical noise sources . . . 143
5.4.6 Nonlinear processes . . . 144
Bibliography . . . 145

6 Lasers and Amplifiers **147**
6.1 The laser concept . . . 147
6.1.1 Technical specifications of a laser . . . 148
6.1.2 Rate equations . . . 150
6.1.3 Quantum model of a laser . . . 154
6.1.4 Examples of lasers . . . 156
6.1.5 Laser phase noise . . . 161
6.2 Amplification of optical signals . . . 162
6.3 Parametric amplifiers and oscillators . . . 164
6.3.1 The second-order non-linearity . . . 165
6.3.2 Parametric amplification . . . 167
6.3.3 Optical parametric oscillator . . . 168
6.3.4 Pair production . . . 169
6.4 Summary . . . 171
Bibliography . . . 171

7 Photodetection techniques **173**
7.1 Photodetector characteristics . . . 173
7.2 Detecting single photons . . . 174
7.3 Photon sources and analysis . . . 178
7.4 Detecting photocurrents . . . 180
7.4.1 The detector circuit . . . 184
7.5 Spectral analysis of photocurrents . . . 187
Bibliography . . . 197

8 Quantum noise: Basic measurements and techniques **200**
8.1 Detection and calibration of quantum noise . . . 200
8.1.1 Direct detection and calibration . . . 200
8.1.2 Balanced detection . . . 204
8.1.3 Detection of intensity modulation and SNR . . . 205
8.1.4 Homodyne detection . . . 206
8.1.5 Heterodyne detection . . . 210
8.2 Intensity noise . . . 211
8.3 The intensity noise eater . . . 212
8.3.1 Classical intensity control . . . 213
8.3.2 Quantum noise control . . . 216
8.4 Frequency stabilization, locking of cavities . . . 221
8.4.1 How to mount a mirror . . . 225
8.5 Injection locking . . . 226
Bibliography . . . 229

9 Squeezing experiments **232**
9.1 The concept of squeezing . . . 232
9.1.1 Tools for squeezing, two simple examples . . . 232
9.1.2 Properties of squeezed states . . . 238
9.2 Quantum model of squeezed states . . . 242
9.2.1 The formal definition of a squeezed state . . . 242
9.2.2 The generation of squeezed states . . . 245
9.2.3 Squeezing as correlations between noise sidebands . . . 247
9.3 Detecting squeezed light . . . 250
9.3.1 Reconstructing the squeezing ellipse . . . 253
9.3.2 Summary of different representations of squeezed states . . . 254
9.3.3 Propagation of squeezed light . . . 254
9.4 Four wave mixing . . . 260
9.5 Optical parametric processes . . . 263
9.6 Second harmonic generation . . . 267
9.7 Kerr effect . . . 275
9.7.1 The response of the Kerr medium . . . 275
9.7.2 Fibre Kerr Squeezing . . . 277
9.7.3 Atomic Kerr squeezing . . . 279
9.8 Atom-cavity coupling . . . 280
9.9 Pulsed squeezing . . . 283
9.9.1 Quantum noise of optical pulses . . . 283
9.9.2 Pulsed squeezing experiments with Kerr media . . . 285
9.9.3 Pulsed SHG and OPO experiments . . . 287
9.9.4 Soliton squeezing . . . 288
9.9.5 Spectral filtering . . . 289
9.9.6 Nonlinear interferometers . . . 290
9.10 Amplitude squeezed light from diode lasers . . . 292
9.11 Twin photon beams . . . 294

9.12 Polarization squeezing . . . 295
9.13 Quantum state tomography . . . 298
9.14 Summary of squeezing results . . . 300
9.14.1 Loopholes in the quantum description . . . 303
Bibliography . . . 303

10 Applications of squeezed light **310**
10.1 Optical communication . . . 310
10.2 Spatial squeezing and quantum imaging . . . 313
10.3 Optical sensors . . . 315
10.4 Gravitational wave detection . . . 321
10.4.1 The origin and properties of GW . . . 321
10.4.2 Quantum properties of the ideal interferometer . . . 323
10.4.3 The sensitivity of real instruments . . . 328
10.4.4 Interferometry with squeezed light . . . 333
Bibliography . . . 338

11 QND **343**
11.1 The concept of QND measurements . . . 343
11.2 Classification of QND measurements . . . 346
11.3 Experimental results . . . 348
11.4 Single photon QND . . . 350
Bibliography . . . 353

12 Fundamental tests of quantum mechanics **355**
12.1 Wave-Particle duality . . . 355
12.2 Indistinguishability . . . 358
12.3 Nonlocality . . . 362
12.3.1 Einstein-Podolsky-Rosen Paradox . . . 362
12.3.2 Generation of entangled CW beams . . . 365
12.3.3 Bell inequalities . . . 367
12.4 Summary . . . 371
Bibliography . . . 371

13 Quantum Information **374**
13.1 Photons as qubits . . . 374
13.2 Postselection and coincidence counting . . . 376
13.3 True single photon sources . . . 377
13.3.1 Heralded single photons . . . 377
13.3.2 Single photons on demand . . . 379
13.4 Characterizing photonic qubits . . . 381
13.5 Quantum key distribution . . . 382
13.5.1 QKD using single photons . . . 383
13.5.2 QKD using continuous variables . . . 385
13.5.3 No cloning . . . 387

13.6 Teleportation 387
13.6.1 Teleportation of photon qubits 388
13.6.2 Continuous variable teleportation 390
13.7 Quantum computation 395
13.8 Summary 400
Bibliography 401

14 Summary and outlook **404**

15 Appendices **407**
Appendix A: Gaussian functions 407
Appendix B: List of quantum operators, states and functions 408
Appendix C: The full quantum derivation of quantum states 410
Appendix D: Calculation of of the quantum properties of a feedback loop 412
Appendix E: Symbols and abbreviations 414

Index **416**