

Contents

<i>Preface</i>	<i>page xv</i>
1 Quantized electromagnetic field and coherent state representations	1
1.1 Quantization of the electromagnetic field	1
1.2 State space for the electromagnetic field – Fock space and Fock states	5
1.3 Quadratures of the field	6
1.4 Coherent states	7
1.5 Mixed states of the radiation field	12
1.6 Diagonal coherent state representation for electromagnetic fields – <i>P</i> -representation	15
1.7 The Wigner function for the electromagnetic field	18
1.8 Bosonic systems with finite mass – coherent states and phase-space representations	22
Exercises	24
References	26
2 Nonclassicality of radiation fields	28
2.1 The Mandel Q_M parameter	28
2.2 Phase-dependent measure of nonclassicality – squeezing parameter S	29
2.3 Single-mode squeezed states – squeezed vacuum	31
2.4 Squeezed coherent state	37
2.5 Other measures of nonclassicality	39
2.6 Mixed nonclassical states – degradation in squeezing	43
Exercises	45
References	47
3 Two-mode squeezed states and quantum entanglement	49
3.1 The two-mode squeezed states	49
3.2 Nonclassicality of the two-mode squeezed vacuum	50
3.3 Quantum phase-space distributions and quadrature distributions	52
3.4 Cauchy–Schwarz inequalities for nonclassicality in two-mode states	54
3.5 Conditional measurements on the two-mode squeezed vacuum	55
3.6 Quantum entanglement in the two-mode squeezed vacuum	56
3.7 Peres–Horodecki separability criterion for continuous variable systems	56
3.8 Generation of two-mode nonclassical and entangled states – optical parametric down-conversion	58

3.9	Parametric amplification of signals	60
3.10	Type-II optical parametric down-conversion – production of entangled photons	61
3.11	Four-photon entanglement using optical parametric down-conversion	63
3.12	Two-mode mixed nonclassical states	65
3.13	Entanglement in two-mode mixed Gaussian states	66
3.14	Application of entanglement to the teleportation of a quantum state	67
3.15	Nonclassical fields in optical fibers	69
	Exercises	72
	References	74
4	Non-Gaussian nonclassical states	76
4.1	Schrödinger cat state and the cat paradox	76
4.2	Photon-added and -subtracted states	82
4.3	Single-photon-added coherent and thermal states	84
4.4	Squeezing and sub-Poissonian properties of single-photon-added states	86
4.5	Experimental realization of photon-added nonclassical non-Gaussian states	88
4.6	Single-photon-subtracted states	89
4.7	Single-photon-subtracted two-mode states with vortex structure	93
4.8	Pair-coherent states	97
	Exercises	101
	References	102
5	Optical interferometry with single photons and nonclassical light	103
5.1	Transformation of quantized light fields at beam splitters	103
5.2	Beam splitter transformation equivalent to evolution under a Hamiltonian	105
5.3	Transformation of states by the beam splitter	105
5.4	Transformation of photon number states by a beam splitter	106
5.5	Single photons at beam splitters	107
5.6	Pairs of single photons at beam splitters	108
5.7	Generalization of the Hong–Ou–Mandel interference to N photons from both ports of the beam splitter	109
5.8	Transformation of a two-mode squeezed state by a 50-50 beam splitter	109
5.9	Generation of two-mode entangled states by the interference of coherent fields and single photons	110
5.10	Beam splitter as an attenuator	111
5.11	Transformation of quantized light fields by phase shifters	112
5.12	The Mach–Zehnder interferometer	113
5.13	Wheeler’s delayed choice gedanken experiment	117
5.14	Interaction-free measurements	117

5.15	Two-photon Mach–Zehnder interferometer	119
5.16	Multiphoton interference and engineering of quantum states	121
5.17	Mach–Zehnder interferometer with two-mode squeezed vacuum as input	123
5.18	Balanced homodyne interferometers for measuring the squeezing of light	125
5.19	Manipulation of quantum states by homodyning and feed-forward	126
5.20	Quantum state tomography	128
5.21	Sensitivity of an optical interferometer	129
5.22	Heisenberg limited sensitivity of interferometers based on parametric amplifiers or four-wave mixers	131
5.23	The quantum statistics of fields at the output ports	133
	Exercises	134
	References	136
6	Polarization and orbital angular momentum of quantum fields	138
6.1	Characterization of the polarization properties of quantized fields	138
6.2	Polarization of quantized fields – Stokes operators	139
6.3	Action of polarizing devices on quantized fields	141
6.4	Description of unpolarized light beyond Stokes parameters	143
6.5	Stokes operator tomography	144
6.6	Orbital angular momentum of fields – HG and LG modes	146
6.7	Orbital Stokes operators and the Poincaré sphere	149
6.8	Mixed states of orbital angular momentum	151
6.9	Entangled states of the orbital angular momentum	152
6.10	Transformation of entanglement between polarization and orbital angular momentum q -plates	154
	Exercises	155
	References	156
7	Absorption, emission, and scattering of radiation	158
7.1	The interaction of radiation and matter in the electric dipole approximation	158
7.2	Rates for the absorption and emission of radiation	159
7.3	Single-mode limit – Einstein’s B coefficient and the absorption coefficient $\alpha(\omega)$	165
7.4	Scattering of radiation	166
7.5	Quantum interferences in scattering	169
7.6	Radiative decay of states – Weisskopf–Wigner theory	170
7.7	Control of spontaneous emission through the design of the electromagnetic vacuum	174
	Exercises	177
	References	178

8 Partial coherence in multimode quantum fields	179
8.1 Correlation functions for electromagnetic fields	179
8.2 Young's interferometer and spatial coherence of the field	181
8.3 Photon-photon correlations – intensity interferometry	184
8.4 Higher-order correlation functions of the field	187
8.5 Interferometry in the spectral domain	188
8.6 Squeezing spectrum and spectral homodyne measurement	191
8.7 Coherence effects in two-photon absorption	192
8.8 Two-photon imaging – ghost imaging using $G^{(2)}$	194
Exercises	197
References	198
9 Open quantum systems	200
9.1 Master equation description of open systems	200
9.2 Dissipative dynamics of harmonic oscillators	204
9.3 Dissipative dynamics of a two-level system	206
9.4 Dissipative dynamics of a multilevel system	208
9.5 Time correlation functions for multilevel systems	210
9.6 Quantum Langevin equations	212
9.7 Exactly soluble models for the dissipative dynamics of the oscillator	213
9.8 Exact dissipative dynamics of a two-level system under dephasing	215
Exercises	218
References	219
10 Amplification and attenuation of quantum fields	220
10.1 Quantum theory of optical amplification	220
10.2 Loss of nonclassicality in the amplification process	223
10.3 Amplification of single-photon states	229
10.4 Amplification of entangled fields	230
10.5 Realising a phase-insensitive amplifier from a phase-sensitive amplifier	232
10.6 Degradation of nonclassicality and entanglement due to the absorption of quantum fields	233
10.7 Loss of coherence on interaction with the environment	235
Exercises	238
References	240
11 Quantum coherence, interference, and squeezing in two-level systems	242
11.1 Two-level approximation: atomic dynamics in a monochromatic field	242
11.2 Application of atomic coherence – Ramsey interferometry	247
11.3 Atomic coherent states	249
11.4 Minimum uncertainty states for two-level systems – spin squeezing	252
11.5 Atomic squeezed states by nonlinear unitary transformations	254
11.6 Atomic squeezed states produced by supersensitivity of Ramsey interferometers	256

11.7 Phase-space representation for a collection of two-level systems	258
11.8 Phase-space description of EPR correlations of spin systems	262
Exercises	264
References	265
12 Cavity quantum electrodynamics	267
12.1 Exact solution of the Jaynes–Cummings model: dressed states	268
12.2 Collapse and revival phenomena in JCM	271
12.3 Dispersive limit of the JCM	273
12.4 Dissipative processes in cavity QED – the master equation	275
12.5 Spectroscopy of the ladder of dressed states	277
12.6 Multi-atom effects in cavity QED	284
12.7 Effective dipole–dipole interaction in a dispersive cavity from Lamb shift of the vacuum	288
12.8 Atomic cat states using multi-atom dispersive JCM	290
12.9 Application of atomic cat states in Heisenberg limited measurements	293
12.10 Engineering anti-Jaynes–Cummings interaction	296
12.11 QED in coupled cavity arrays – single-photon switch	298
Exercises	300
References	301
13 Absorption, emission, and scattering from two-level atoms	304
13.1 Effects of relaxation: optical Bloch equations	304
13.2 Absorption and amplification of radiation by a strongly pumped two-level system	309
13.3 Resonance fluorescence from a coherently driven two-level atom	314
13.4 Quantum dynamics of the two-level atom and spectrum of fluorescence	317
Exercises	325
References	327
14 Quantum interference and entanglement in radiating systems	328
14.1 Young's interference with microscopic slits – atoms as slits	328
14.2 Spatial bunching and antibunching of photons	330
14.3 Interference in radiation from two incoherently excited atoms	333
14.4 Atom–photon entanglement	337
14.5 Atom–atom entanglement via detection of spontaneously emitted photons	338
14.6 Multi-atom entanglement	341
14.7 Quantum entanglement in Dicke states and superradiance	343
14.8 Multi-path quantum interference as the source of Dicke superradiance	345
14.9 Entanglement of photons produced in an atomic cascade	348
Exercises	351
References	352

15 Near field radiative effects	354
15.1 Near field radiative effects – coupling between dipoles	354
15.2 Radiative coupling between dipoles and dynamics	358
15.3 Vacuum-induced deterministic entanglement	360
15.4 Two-photon resonance induced by near field radiative effects	362
15.5 The dipole blockade	365
Exercises	368
References	368
16 Decoherence and disentanglement in two-level systems	370
16.1 Decoherence due to the interaction of a two-level system with the environment	370
16.2 Disentanglement in two-level systems	371
16.3 Decoherence-free subspace	373
16.4 Protection of decoherence due to dephasing via dynamical decoupling	374
16.5 Control of the spectral density of environment for protection against decoherence	378
16.6 Modulation produced protection against disentanglement in cavity QED	380
Exercises	382
References	383
17 Coherent control of the optical properties	385
17.1 A simple model for coherent control	385
17.2 Dark states and coherent population trapping	394
17.3 EIT in single-atom fluorescence	397
17.4 Control of two-photon absorption	400
17.5 Vacuum-induced coherence and interference	404
Exercises	409
References	410
18 Dispersion management and ultraslow light	413
18.1 Group velocity and propagation in a dispersive medium	413
18.2 Electromagnetically induced waveguides	417
18.3 Storage and retrieval of optical pulses	418
18.4 Adiabats and storage and retrieval of pulses	423
18.5 Non-EIT mechanisms for ultraslow light	426
Exercises	429
References	430
19 Single photons and nonclassical light in integrated structures	432
19.1 Quantum optics in a coupled array of waveguides	432
19.2 The Hong–Ou–Mandel interference in a system of two coupled waveguides	434

19.3 Single-photon transport and coherent Bloch oscillations in a coupled array	436
19.4 The Anderson localization of quantum fields in coupled waveguide arrays	442
19.5 Discrete quantum walks via waveguide couplers on a chip	447
Exercises	452
References	453
20 Quantum optical effects in nano-mechanical systems	455
20.1 The radiation pressure on the nano-mechanical mirror	455
20.2 Basic quantum Langevin equations for the coupled system of cavity and NMO	457
20.3 Steady-state solution of quantum Langevin equations in the mean field limit and bistability	459
20.4 Quantum fluctuations in optomechanical systems	461
20.5 Sideband cooling of the nano-mechanical mirror	463
20.6 Normal-mode splitting	466
20.7 Squeezing of a nano-mechanical oscillator	471
20.8 Electromagnetically induced transparency (EIT) in the mechanical effects of light	475
20.9 Quantized states of the nano-mechanical mirror coupled to the cavity	481
Exercises	485
References	487
<i>Index</i>	489