

Contents

Acknowledgements	V
Preface	XI
1 Introduction	1
1.1	Definition and Characteristics of Single-Photon Sources 1
1.2	Single-Photon Generation with Atom-Like Systems 2
1.3	Applications of Single Photons 6
1.3.1	Quantum Erasure through Optical Interference 6
1.3.2	Secure Communication 8
1.3.3	Creating Entanglement between Matter Qubits 9
1.4	History of Single-Photon Generation 12
1.5	Outline 15
2 Single Photon Generation from a Two-Level Quantum Emitter in a Cavity	17
2.1	The Jaynes–Cummings Hamiltonian 17
2.1.1	Electromagnetic Field Quantization 18
2.1.1.1	3D Translational Symmetry: Uniform Dielectric 20
2.1.1.2	2D Translational Symmetry: Slab Waveguide 21
2.1.1.3	1D Translational Symmetry: Waveguide 22
2.1.2	Light-Matter Interaction 23
2.1.2.1	Minimal Coupling Hamiltonian and Multipole Expansion 23
2.1.2.2	Jaynes–Cummings Hamiltonian, Rotating Wave Approximation 24
2.2	Quantum Emitter Coupling to a Radiation Continuum 25
2.2.1	General Case 26
2.2.2	One-Dimensional Continuum 28
2.3	Cavity Coupling to a Radiation Continuum 28
2.4	Quantum Emitter Decay via a Cavity 31
2.5	The Strong and Weak Coupling Regime, Purcell Effect 37
2.5.1	Strong Coupling Regime 38
2.5.2	Weak Coupling Regime, Purcell Factor 39
2.5.3	Comparison of the Purcell Effect from a 3D Cavity, 1D Waveguide and Homogeneous Dielectric 40

2.6	Single-Photon Source Based on a Two-Level Quantum Emitter	42
2.6.1	Emitted Photon Waveform	42
2.6.2	Efficiency	43
2.7	Interaction of Single Photons with Loaded or Unloaded Cavities	43
2.7.1	Description of the Problem	44
2.8	No Atom Present	45
2.8.1	Atom Present	45
2.8.2	Differential Transmission between the “Atom” and “No Atom” Case	46
2.8.2.1	Small Detuning	47
2.8.2.2	Large Detuning	48
3	Coherent Photon Emission from a Three-Level Lambda System in a Cavity	49
3.1	Coherently Driven Λ -Systems: Background	50
3.2	Adiabatic Approximation	51
3.3	Control Pulse Engineering for Fast Single-Photon Generation/Trapping	53
3.4	Non-ideal Systems: Trapping/Generation Efficiency	56
3.4.1	Claims	58
3.4.2	Proof	59
3.5	Λ -System with Several Excited States	61
4	Effects of Decoherence	65
4.1	Introduction	65
4.2	Decoherence Processes Affecting Solid-State Single-Photon Sources	66
4.3	T_1 , T_2 and T_2^*	67
4.3.1	Definition of the Random Process	67
4.3.2	A Pure Dephasing (T_2) Process	68
4.3.3	A Population Relaxation (T_1) Process	70
4.4	Example: A Fluctuating Electric Field from Charge Traps	72
4.5	Photons Emitted by a Two-Level System with Pure Dephasing	74
4.6	Time-Jitter Process	77
4.7	Nonradiative Decay	82
4.8	Relaxation between Two Excited States	83
4.9	Pure Dephasing in the Three-Level Raman Scheme	86
4.10	Phonon Sidebands and Broadening	94
4.10.1	Franck–Condon Picture	94
4.10.2	Continuum of Phonon Modes	97
4.10.3	Implications of Phonon Sidebands for Applications	99
4.10.4	Phonon Broadening and Relaxation	101
5	Experimental Techniques	103
5.1	Microphotoluminescence Setups	103
5.1.1	Cryostats	103
5.1.2	Excitation Methods	105
5.1.3	Scanning Methods	106

5.1.4	Navigation	106
5.1.5	Spectrometers	107
5.1.6	Lifetime Measurements	107
5.2	Photon Correlation Measurements	108
5.2.1	Experimental Issues	109
5.2.2	Theory	110
5.2.2.1	$g^{(2)}(0) > 1$	112
5.2.2.2	$g^{(2)}(0) = 1$	112
5.2.2.3	$g^{(2)}(0) < 1$	112
5.3	Measuring Coherence Properties	113
6	Atom-Like Systems in Solids Useful for Single-Photon Generation	115
6.1	Semiconductor Quantum Dots	115
6.1.1	Introduction	115
6.1.2	Growth and Isolation	116
6.1.3	Single-Electron Energy Levels	119
6.1.4	Excitation Methods	122
6.1.5	Multi-Particle States	123
6.1.6	Exciton Fine Structure	127
6.1.7	Radiative Decay Rates	130
6.1.8	Single-Photon Generation with Quantum Dots	131
6.1.8.1	Photon Correlation Measurements	131
6.1.8.2	Quantum Efficiency	132
6.1.8.3	Indistinguishability	133
6.1.8.4	Emission Wavelength	136
6.1.8.5	Electrically Driven Devices	136
6.1.8.6	Temperature Dependence	137
6.1.9	Photon Pair Sources	137
6.1.10	Quantum Dots as Spin Qubits	139
6.1.11	Integration into Microcavities	142
6.1.12	Summary	143
6.2	The Nitrogen-Vacancy Center in Diamond	143
6.2.1	Introduction	143
6.2.2	Geometry and Single-Electron Orbitals	145
6.2.3	Detailed Level Structure of NV^-	147
6.2.4	Optical Transitions and Phonon Sidebands	154
6.2.5	Single-Photon Generation Experiments	158
6.2.6	Optical Initialization, Readout, and Manipulation of Electron Spins	159
6.2.7	NV Centers as Spin Qubits	161
6.2.8	Spin Coherence Lifetimes	162
6.2.9	Coupling to Microcavities	163
6.2.10	NV Fabrication and Stability	165
6.2.11	Summary	166
6.3	Semiconductor Donors and Acceptors	166
6.3.1	Effective Mass Theory for Shallow Impurities	166

6.3.1.1	Neutral Donor (D^0) Ground States	166
6.3.1.2	Neutral Acceptor (A^0) Ground States	167
6.3.2	Neutral Donor-Bound-Exciton (D^0X) States	168
6.3.3	Spectroscopy of a D^0 - D^0X Λ -Type System	172
6.3.4	Shallow Donors and Acceptors as Spin Qubits	173
6.3.5	Single-Photon Generation with Shallow Donors and Acceptors	174
6.4	Summary and Comparison Table	174
7	Survey of Microcavity Geometries	177
7.1	Planar Distributed Bragg Reflector (DBR) Microcavity	178
7.2	Pillar Microcavities	180
7.3	Microdisk Cavities	182
7.4	Photonic Crystals	184
8	Applications	187
8.1	BB84 Quantum Key Distribution	187
8.2	Quantum Repeater with Nested Purification Protocol	192
8.3	Quantum Information Processing	193
8.3.1	QIP in Quantum Networks	193
8.3.1.1	Single Node Preparation and Measurement Techniques	194
8.3.1.2	Coherent Manipulation of a Single Node	195
8.3.1.3	Photon-Induced Controlled Phase Gates between Two Nodes	196
8.3.2	Entanglement Distribution: Cluster State Formation	197
8.3.3	Single Photon Nonlinear Optics	198
	References	201
	Index	219