## Contents

### Part I  Cavity QED

1  **Cavity Induced Interfacing of Atoms and Light**  
   Axel Kuhn  
   1.1 Introduction ........................................ 3  
   1.2 Cavities for Interfacing Light and Matter .......... 4  
      1.2.1 Atom-Photon Interaction in Resonators ........... 5  
      1.2.2 Single-Photon Emission .......................... 9  
   1.3 Cavity-Enhanced Atom-Photon Entanglement .......... 18  
   1.4 Photon Coherence, Amplitude and Phase Control .... 21  
      1.4.1 Indistinguishability of Photons .................. 21  
      1.4.2 Arbitrary Shaping of Amplitude and Phase ....... 23  
   1.5 Cavity-Based Quantum Memories ........................ 28  
   1.6 Future Directions .................................... 34  
   References .............................................. 35  

2  **A Highly Efficient Single Photon-Single Quantum Dot Interface**  
   Loic Lanco and Pascale Senellart  
   2.1 Motivations .......................................... 39  
   2.2 Efficient Quantum Dot-Photon Interfacing .......... 41  
      2.2.1 Basics of Cavity-QED in a Quantum Dot-Micropillar Device ......................... 41  
      2.2.2 Deterministic QD-Cavity Coupling  
           Through In Situ Lithography ....................... 43  
      2.2.3 Critical Parameters: Beyond the Purcell Factor .......... 45  
   2.3 Ultrabright Single Photon Sources .................. 46  
      2.3.1 Why Are Bright Single Photon Sources Desirable? .. 46  
      2.3.2 Demonstration of Single Photon Sources  
           with Record Brightness ............................ 47  
      2.3.3 Purity of the Single Photon Emission ............ 49
2.3.4 High Indistinguishability Through a Control of the QD Environment .......................... 51
2.3.5 Electrically Controlled Sources ................................ 54
2.3.6 Implementation of an Entangling CNOT Gate .............. 56
2.4 Nonlinear Optics with Few-Photon Pulses ....................... 59
  2.4.1 Motivations: Photon Blockade and Photon Routing ....... 59
  2.4.2 Observation of Nonlinearities at the Few-Photon Scale .... 61
  2.4.3 Device Optimization: Towards a Single-Photon Router? .... 63
  2.4.4 Resonant Excitation: Application to Fast Optical Nanosensing ................................ 64
2.5 Future Challenges .................................................. 65
References ........................................................................ 67

Part II Light Meets a Single Atom

3 Photon-Atom Coupling with Parabolic Mirrors ................. 75
  Markus Sondermann and Gerd Leuchs
  3.1 Coupling to an Atom: The Role of Dipole Radiation ......... 75
    3.1.1 General Considerations ....................................... 75
    3.1.2 Defining a Coupling Efficiency ......................... 77
  3.2 Dipole-Mode Generation with a Parabolic Mirror ........... 78
    3.2.1 Finding the Optimum Field Mode ....................... 78
    3.2.2 Generation and Characterization of Field Modes Tailored for Efficient Free-Space Coupling .... 81
  3.3 Overview of Experiments on Photon-Atom Coupling in Free Space ........................................ 82
    3.3.1 Shifting the Phase of a Coherent Beam ................. 83
    3.3.2 Extinction of a Weak Coherent Beam ................... 84
    3.3.3 Absorption of Single Photons ............................ 85
  3.4 Absorbing a Single Photon: Temporal Mode Shaping ....... 87
    3.4.1 Choosing the Right Mode ................................... 87
    3.4.2 Generation of Exponentially Increasing Pulses ........ 88
    3.4.3 An Analogous Experiment: Coupling to a Resonator .... 89
  3.5 Trapping Ions in Parabolic Mirrors ............................ 90
    3.5.1 Parabolic Mirror Ion Trap ................................ 90
    3.5.2 Fluorescence Collection ................................... 92
  3.6 Experimental Determination of the Coupling Efficiency .... 92
  3.7 Outlook ............................................................. 95
References ........................................................................ 95
4 Free Space Interference Experiments with Single Photons and Single Ions .............................................................. 99
   Lukáš Slodička, Gabriel Hétet, Markus Hennrich and Rainer Blatt
   4.1 Coupling to a Single Ion in Free Space ......................... 100
      4.1.1 Electromagnetically Induced Transparency from a Single Atom in Free Space ................................. 101
      4.1.2 Single Ion as a Mirror of an Optical Cavity .......... 108
   4.2 Probabilistic Entanglement Between Distant Ions .......... 111
      4.2.1 Single-Photon and Two-Photon Protocols............... 111
      4.2.2 Generation of Entanglement by a Single Photon Detection ....................................................... 114
      4.2.3 Experimental Realization .................................. 115
      4.2.4 Summary ....................................................... 120
   References ..................................................................... 121

5 Single Photon Absorption by a Single Atom: From Heralded Absorption to Polarization State Mapping .................. 125
   Nicolas Piro and Jürgen Eschner
   5.1 Introduction ........................................................... 126
   5.2 Single Photon-Single Atom Interaction and Entanglement Schemes ...................................................... 127
      5.2.1 Single Photon Absorption Schemes ....................... 127
      5.2.2 Photon-Atom State Transfer and Entanglement Swapping Schemes .............................................. 129
   5.3 Experimental Setup .................................................. 130
   5.4 Experimental Progress .............................................. 132
      5.4.1 Single Photon Absorption by a Single Ion ............ 132
      5.4.2 Polarization Control in the Absorption Event ...... 134
      5.4.3 Photon-to-Ion State Transfer by Heralded Absorption .............................................................. 138
   5.5 Conclusions and Outlook ........................................... 138
   References ..................................................................... 140

Part III Light Meets Many Atoms

6 Narrowband Biphotons: Generation, Manipulation, and Applications ................................................................. 145
   Chih-Sung Chuu and Shengwang Du
   6.1 Introduction ........................................................... 145
   6.2 Monolithic Resonant Parametric Down-Conversion with Cluster Effect .................................................... 146
      6.2.1 Single-Mode Output .......................................... 147
      6.2.2 Experimental Realization ................................... 148
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.3 Backward-Wave Biphoton Generation</td>
<td>149</td>
</tr>
<tr>
<td>6.3.1 General Formalism: Free Space</td>
<td>150</td>
</tr>
<tr>
<td>6.3.2 General Formalism: Resonant SPDC</td>
<td>153</td>
</tr>
<tr>
<td>6.3.3 Single-Mode Output</td>
<td>155</td>
</tr>
<tr>
<td>6.3.4 Experimental Challenge</td>
<td>156</td>
</tr>
<tr>
<td>6.4 Spontaneous Four-Wave Mixing with Electromagnetically</td>
<td>157</td>
</tr>
<tr>
<td>Induced Transparency</td>
<td></td>
</tr>
<tr>
<td>6.4.1 Damped Rabi Oscillation Regime</td>
<td>160</td>
</tr>
<tr>
<td>6.4.2 Group Delay Regime</td>
<td>162</td>
</tr>
<tr>
<td>6.5 Manipulation of Narrowband Single Photons</td>
<td>165</td>
</tr>
<tr>
<td>6.6 Applications</td>
<td>173</td>
</tr>
<tr>
<td>6.7 Summary</td>
<td>179</td>
</tr>
<tr>
<td>References</td>
<td></td>
</tr>
<tr>
<td>7 Generation, Characterization and Use of Atom-Resonant</td>
<td>183</td>
</tr>
<tr>
<td>Indistinguishable Photon Pairs</td>
<td></td>
</tr>
<tr>
<td>Morgan W. Mitchell</td>
<td></td>
</tr>
<tr>
<td>7.1 Introduction</td>
<td>183</td>
</tr>
<tr>
<td>7.1.1 CESPDC Sources</td>
<td>184</td>
</tr>
<tr>
<td>7.1.2 Atomic Frequency Filters</td>
<td>185</td>
</tr>
<tr>
<td>7.2 Atom-Resonant Indistinguishable Photon Pairs</td>
<td>186</td>
</tr>
<tr>
<td>in a Single Mode</td>
<td></td>
</tr>
<tr>
<td>7.2.1 Type-I CESPDC Source</td>
<td>186</td>
</tr>
<tr>
<td>7.2.2 A FADOF at the Rb D1 Line</td>
<td>187</td>
</tr>
<tr>
<td>7.2.3 Spectral Purification of Degenerate Photon Pairs</td>
<td>190</td>
</tr>
<tr>
<td>from Type-I CESPDC</td>
<td></td>
</tr>
<tr>
<td>7.2.4 Interference of Biphoton Amplitudes</td>
<td>193</td>
</tr>
<tr>
<td>from Distinct Sources</td>
<td></td>
</tr>
<tr>
<td>7.2.5 Full Reconstruction of the Biphoton Wave-function</td>
<td>196</td>
</tr>
<tr>
<td>7.3 Generation of Spectrally-Pure, Atom-Resonant NooN States</td>
<td>197</td>
</tr>
<tr>
<td>7.3.1 NooN States</td>
<td>197</td>
</tr>
<tr>
<td>7.3.2 Type-II CESPDC Source</td>
<td>198</td>
</tr>
<tr>
<td>7.3.3 Induced Dichroism Atomic Filter</td>
<td>202</td>
</tr>
<tr>
<td>7.3.4 Spectral Purity Measurement</td>
<td>203</td>
</tr>
<tr>
<td>7.3.5 Quantum-Enhanced Sensing of Atoms Using Atom-Tuned NooN States</td>
<td>204</td>
</tr>
<tr>
<td>7.4 Conclusions</td>
<td>208</td>
</tr>
<tr>
<td>References</td>
<td>211</td>
</tr>
</tbody>
</table>
Part IV Storage and Retrieval of Non-classical States

8 On-Demand Release of a Heralded Quantum State from Concatenated Optical Cavities
Jun-ichi Yoshikawa, Kenzo Makino and Akira Furusawa

8.1 Introduction 217
8.2 Working Principle 220
8.3 Experimental Demonstration for a Heralded Single-Photon State 222
  8.3.1 Experimental Methods 223
  8.3.2 Experimental Results 228
8.4 Summary 229
References 239

9 Quantum Light Storage in Solid State Atomic Ensembles
Hugues de Riedmatten and Mikael Afzelius

9.1 Introduction 241
9.2 Rare-Earth-Ion Doped Crystals 243
9.3 Quantum Memory Protocols 245
9.4 State of the Art 249
9.5 Quantum Light Sources Compatible with Solid State Quantum Memories 251
  9.5.1 Characterizing Photon Pair Sources 253
  9.5.2 A Quantum Light Source Compatible with Nd Doped Crystals 255
  9.5.3 A Quantum Light Source Compatible with Pr Doped Crystals 257
9.6 Quantum Light Storage Experiments 259
  9.6.1 Quantum Entanglement Storage in Nd:YSO Crystals 259
  9.6.2 Quantum Storage of Heralded Single Photon in a Pr³⁺:Y2SiO5 Crystal 263
9.7 Prospects for Spin-Wave Storage with Quantum Light 266
9.8 Outlook 268
References 268

Part V New Sources of Entangled Photon Pairs

10 Engineering of Quantum Dot Photon Sources via Electro-elastic Fields
Rinaldo Trotta and Armando Rastelli

10.1 Engineering of Quantum Dot Photon Sources via Electro-elastic Fields 277
| 10.2 | Hybrid Semiconductor-Piezoelectric Quantum Dot Devices: The First High-Speed, Wavelength-Tunable, and All-Electrically-Controlled Source of Single Photons | 280 |
| 10.3 | Independent Control of Different Quantum Dot Parameters via Electro-elastic Fields | 284 |
| 10.3.1 | Independent Control of Charge State and Emission Energy | 284 |
| 10.3.2 | Independent Control of Exciton and Biexciton Energy | 286 |
| 10.4 | Controlling and Erasing the Fine Structure Splitting for the Generation of Highly Entangled Photon Pairs | 288 |
| 10.4.1 | Controlling and Erasing the Exciton Fine Structure Splitting via Electro-elastic Fields | 289 |
| 10.4.2 | Generation of Highly Entangled Photon Pairs via Electro-elastic Tuning of Single Semiconductor QDs | 293 |
| 10.5 | Conclusions and Outlook | 298 |
| References | 299 |

| 11 | Resonant Excitation and Photon Entanglement from Semiconductor Quantum Dots | 303 |
| Ana Predojević | 303 |
| 11.1 | Introduction | 303 |
| 11.2 | On-Demand Generation of Photon Pairs Using Single Semiconductor Quantum Dots | 304 |
| 11.2.1 | Quantum Dots and Polarization Entanglement | 305 |
| 11.2.2 | Resonant Excitation | 307 |
| 11.2.3 | Theoretical Description of the Two-Photon Excitation Process | 309 |
| 11.3 | Measurements Under Resonant Excitation | 313 |
| 11.3.1 | Coherent Control | 313 |
| 11.3.2 | Photon Statistics Under Resonant Excitation | 314 |
| 11.3.3 | Time-Bin Entanglement | 316 |
| 11.4 | Future Directions | 321 |
| References | 321 |

| Part VI | Distinguishability of Photons |
| 12 | Generation and Application of Frequency-Uncorrelated Photon Pairs | 327 |
| Tian-Ming Zhao, Xiao-Hui Bao, Bo Zhao and Jian-Wei Pan | 327 |
| 12.1 | Introduction | 327 |
| 12.2 | Single Photon Wavepacket Generation by SPDC | 329 |
12.3 Group Velocity Mismatching .......................... 330
12.4 Narrowband Entanglement Sources .................. 334
12.5 Applications ............................................. 338
12.6 Conclusions ............................................... 341
References ...................................................... 341

13 Single Semiconductor Quantum Dots in Microcavities: Bright Sources of Indistinguishable Photons .............. 343
C. Schneider, P. Gold, C.-Y. Lu, S. Höfling, J.-W. Pan and M. Kamp
13.1 Introduction ............................................... 343
13.2 A Pedestrian’s Guide to Two Photon Interference .... 344
13.2.1 Quantum Dot Single Photon Source .............. 344
13.2.2 Photon Interference with Quantum Light ........ 345
13.3 A Bright Quasi-planar Single Photon Source ....... 347
13.4 Emission of Single and Indistinguishable Photons from Single Quantum Dots .................................. 349
13.4.1 Single Photon Emission from Single QDs ......... 349
13.4.2 Two Photon Interference with Single Photons ... 353
13.5 Two Photon Interference from Remote, Single Quantum Dots ................................................. 356
13.5.1 Conclusion .............................................. 359
References ...................................................... 360

Part VII Beyond Photons

14 Towards Quantum Repeaters with Solid-State Qubits: Spin-Photon Entanglement Generation Using Self-assembled Quantum Dots ................................. 365
Peter L. McMahon and Kristiaan De Greve
14.1 Introduction ............................................... 365
14.2 Quantum Repeaters ........................................ 366
14.2.1 Motivation for Quantum Repeaters .............. 367
14.2.2 Design of Quantum Repeaters ........................ 373
14.3 Quantum Dots as Building Blocks for Quantum Repeaters ......................................................... 380
14.3.1 Quantum Dots as Quantum Memories .......... 381
14.3.2 Quantum Dots as Photon Sources .............. 387
14.3.3 Entanglement Between a Spin in a Quantum Dot and an Emitted Photon ......................... 388
14.4 Conclusion ............................................... 396
References ...................................................... 398

Index .......................................................... 403
Engineering the Atom-Photon Interaction
Controlling Fundamental Processes with Photons, Atoms and Solids
Predojević, A.; Mitchell, M.W. (Eds.)
2015, XVII, 405 p. 155 illus., 112 illus. in color., Hardcover
ISBN: 978-3-319-19230-7