Contents

| Cont | ributors | S | | xiii |
|-------|----------|-------------|---|----------|
| Volu | mes in | series | | xvii |
| Prefa | ice | | | xxi |
| | | | | |
| | | | | |
| 1. | Intro | ductio | Photographic Tubes were statut simmen of | 1 |
| | 1.1 | | of Light—an Historical Perspective | 1 |
| | 1.2 | , | m Light | 2 |
| | 1.2 | 1.2.1 | What is Non-Classical Light? | 2 |
| | | | What is a Photon? | 3 |
| | 1.3 | The De | velopment of Single-Photon Technologies | 4 |
| | 1.4 | Some A | pplications of Single-Photon Technology | 8 |
| | 1.5 | This bo | | 9 |
| | | 1.5.1 | Single-Photon Detectors | 9 |
| | | 1.5.2 | Single-Photon Sources | 16 |
| | 1.6 | Conclus | | 17 |
| | | Referen | ces | 18 |
| | | | | |
| 2. | Phot | ton Stat | tistics, Measurements, and | |
| | | | ents Tools | 25 |
| | 2.1 | Quantiz | zed Electric Field & Operator Notation | 26 |
| | 2.2 | | Characteristics | 28 |
| | | 2.2.1 | State Vector | 28 |
| | | 2.2.2 | Density Matrix and Photon Number Probabilities | 29 |
| | | 2.2.3 | Purity | 30 |
| | | 2.2.4 | Source Efficiency and Generation Rate | 31 |
| | | 2.2.5 | Second-Order Coherence, $g^{(2)}$ | 32 |
| | | 2.2.6 | Relating $g^{(2)}$ to $P(n)$ | 34 |
| | | 2.2.7 | Ideal and Non-Ideal Single-Photon Sources | 37 |
| | | 2.2.8 2.2.9 | To measure $P(n)$ or $g^{(2)}$? Hanbury Brown-Twiss Interferometer | 38 38 |
| | | 2.2.10 | Bunching, Antibunching, and Poissonian | 30 |
| | | 2.2.10 | Photon Statistics | 42 |
| | | 2.2.11 | High-Order Coherences | 44 |
| | | 2.2.12 | Indistinguishability | 45 |
| | | 2.2.13 | Other Sources | 47 |

and the particular services and remaining

| | 2.3 | Detecto | or Properties | 52 |
|----|-----|-------------------|---|----------|
| | | 2.3.1 | Detection Efficiency | 53 |
| | | 2.3.2 | POVM Elements | 55 |
| | | 2.3.3 | Photon-Number-Resolving (PNR) Capability | 56 |
| | | 2.3.4 | Timing Latency and Rise Time | 62 |
| | | 2.3.5 | Timing Jitter | 62 |
| | | 2.3.6 | Dead Time, Reset Time, and Recovery Time | 64 |
| | | 2.3.7 | Dark Count Rate | 65 |
| | | 2.3.8 | Background Count Rate | 65 |
| | | 2.3.9 | Afterpulse Probability | 65 |
| | | 2.3.10 | Active Area | 66 |
| | | 2.3.11 Referen | Operating Temperature of Active Area ces | 66 66 |
| 3. | Pho | tomulti | plier Tubes | 69 |
| | 3.1 | Introduc | ction | 69 |
| | 3.2 | Brief Hi | | 69 |
| | 3.3 | | e of Operation | 71 |
| | | 3.3.1 | Photoelectron Emission and Photocathodes | 72 |
| | | 3.3.2 | Secondary Emission, Dynodes | 73 |
| | 3.4 | | Counting with Photomultipliers | 76 |
| | 3.5 | Conclus | | 82 |
| | | Referen | ces | 82 |
| 4. | Sem | icondu | ctor-Based Detectors | 83 |
| | 4.1 | Photon | Counting: When and Why | 84 |
| | 4.2 | Why Se | miconductor Detectors for Photon Counting? | 85 |
| | 4.3 | Principl | e of Operation of Single-Photon Avalanche Diodes | 85 |
| | 4.4 | Perform | ance Parameters and Features of SPAD Devices | 87 |
| | | 4.4.1 | Photon Detection Efficiency | 88 |
| | | 4.4.2 | Dark Count Rate (DCR) | 88 |
| | | 4.4.3 | Afterpulsing | 89 |
| | | 4.4.4 | Timing Jitter | 90 |
| | | 4.4.5 | Crosstalk | 92 |
| | | 4.4.6 | Fill-Factor | 93 |
| | | 4.4.7 | Microelectronic Structure of a SPAD: Outline and Basic Features | 93 |
| | 4.5 | Circuit I | Principles for SPAD Operation | 94 |
| | 4.6 | | SPAD Devices | 98 |
| | | 4.6.1 | Planar SPAD Devices Fabricated in a Custom | |
| | | | Technology | 98 |
| | | 4.6.2 | Non-Planar SPAD Devices Fabricated in a | |
| | | | Custom Technology | 102 |
| | | 4.6.3 | High-Voltage, Complementary Metal-Oxide | |
| | | | Semiconductor (HV-CMOS) SPADs | 104 |
| | | 4.6.4 | Standard Deep-Submicron CMOS SPADs | 106 |
| | 4.7 | Silicon | SPAD Array Detectors | 108 |

| Cont | ents | | vii |
|------|------|---|--------------------------|
| | 4.8 | SPADS for the Infrared Spectral Range 4.8.1 Infrared SPADs 4.8.2 Basic InGaAs/InP SPAD Design Concepts 4.8.3 DE and DCR Modeling and Performance | 113 113 114 115 |
| | 4.9 | 4.8.4 Timing Jitter 4.8.5 Afterpulsing 4.8.6 Comparison of InGaAs/InP SPADs and Si SPADs Active Gating Techniques for InGaAs SPADs | 117 118 119 120 |
| | | 4.9.1 Introduction 4.9.2 Sampling 4.9.3 Cancellation 4.9.4 Introduction to High-Speed Periodic Gating | 120 122 123 125 |
| | | 4.9.4 Introduction to High-Speed Periodic Gating 4.9.5 Sine-Wave Gating 4.9.6 Self-Differencing 4.9.7 Harmonic Subtraction | 127 129 131 |
| | | 4.9.8 Summary | 132 |
| | 4.10 | Future Prospects for Silicon SPADs | 134 |
| | 4.11 | Future Prospects for InGaAs SPADs References | 135 137 |
| 5. | Nove | el Semiconductor Single-Photon Detectors | 147 |
| | 5.1 | Introduction | 147 |
| | 5.2 | Solid-State Photomultipliers and Visible-Light Photon | 140 |
| | | Counters 5.2.1 Introduction | 148 148 |
| | | 5.2.2 VLPC Structure and Operation | 150 |
| | | 5.2.3 SSPM and VLPC Performance | 154 |
| | | 5.2.4 Quantitative Model and its Current Limitations | 161 |
| | | 5.2.5 New Opportunities for VLPCs | 163 |
| | | 5.2.6 Conclusions | 166 |
| | 5.3 | Quantum-Dot-Based Detectors | 166 |
| | | 5.3.1 Detector Designs and Principles of Operation | 167 |
| | | 5.3.2 Photon-Number-Resolving Detection | 172 |
| | | 5.3.3 Modeling Photoconductive Gain | 175 |
| | | 5.3.4 Conclusions References | 179 180 |
| | | 8.3.2 Correlated-Photon-Pair Calibration Metrod | |
| 6. | | ectors Based on Superconductors | 185 |
| | 6.1 | Introduction | 186 |
| | 6.2 | Superconducting Nanowire Single-Photon Detectors | 187 |
| | | 6.2.1 Operating Principle6.2.2 Principal Strengths, Weaknesses | 187 191 |
| | | 6.2.2 Principal Strengths, Weaknesses6.2.3 Areas of Research | 191 |
| | 6.3 | Transition-Edge Sensors | 194 |
| | | 6.3.1 Operating Principle | 195 |
| | | 6.3.2 Principal Strengths and Weaknesses | 199 |
| | | 6.3.3 Research Areas | 199 |

Viii Contents

| | 6.4 | Superconducting Tunnel Junction Detectors 6.4.1 Operating Principle | 201 201 |
|----|------|---|------------|
| | | 6.4.2 Strengths and Weaknesses | 201 |
| | | 6.4.3 Research Areas | 204 |
| | 6.5 | Microwave Kinetic-Inductance Detectors | 204 |
| | 0.5 | 6.5.1 Operating Principle | 205 |
| | | 6.5.2 Strengths and Weaknesses | 206 |
| | | 6.5.3 Research Areas | 207 |
| | 6.6 | Conclusions and Perspective | 208 |
| | 0.0 | References | 209 |
| 7. | Hyb | orid Detectors | 217 |
| | 7.1 | Introduction | 218 |
| | 7.2 | Space-Multiplexed Detectors | 219 |
| | | 7.2.1 Introduction | 219 |
| | | 7.2.2 Theory of Operation | 220 |
| | | 7.2.3 Experimental Implementations of | |
| | | Space-Multiplexed Detectors | 231 |
| | 7.3 | Time-Multiplexed Detectors | 236 |
| | | 7.3.1 Introduction | 236 |
| | | 7.3.2 Fiber-Loop Detectors | 237 |
| | | 7.3.3 Weak-Homodyne Detection | 241 |
| | 7.4 | Up-Conversion Detectors | 243 |
| | | 7.4.1 Introduction | 243 |
| | | 7.4.2 Theory of Single-Photon Up-Conversion | 244 |
| | | 7.4.3 Up-Conversion Techniques | 245 |
| | | 7.4.4 Pulsed Up-Conversion | 249 |
| | | 7.4.5 Ultrafast Up-Conversion | 250 |
| | 7.5 | Conclusion | 253 |
| | | References | 253 |
| 8. | Sing | gle-Photon Detector Calibration | 257 |
| | 8.1 | Introduction | 257 |
| | 8.2 | Definitions | 259 |
| | 8.3 | Calibration Methods | 260 |
| | | 8.3.1 Radiant Power Measurements (Substitution Method) | 261 |
| | | 8.3.2 Correlated-Photon-Pair Calibration Method | 262 |
| | 8.4 | Practical Considerations | 263 |
| | | 8.4.1 Semiconductor Single-Photon Avalanche Diodes | 264 |
| | | 8.4.2 Transition Edge Sensors | 275 |
| | 8.5 | Conclusion | 279 |
| | | References | 280 |
| 9. | Qua | antum Detector Tomography | 283 |
| | 9.1 | Introduction | 283 |
| | 9.2 | Quantum Tomography: Prelude | 286 |
| | | 9.2.1 State Tomography | 287 |

Contents

| | | 9.2.2 Process Tomography | 288 |
|-----|------|--|-----|
| | 9.3 | Detector Tomography | 288 |
| | | 9.3.1 General Introduction | 289 |
| | | 9.3.2 Photon-Number-Resolving Detectors | 291 |
| | | 9.3.3 Reconstruction without Phase-Sensitivity | 293 |
| | | 9.3.4 Reconstruction with Phase-Sensitivity: the Challenge | 295 |
| | 9.4 | Experimental Implementations of Detector Tomography | 297 |
| | | 9.4.1 Experimental Setup | 298 |
| | | 9.4.2 Q-Function | 300 |
| | | 9.4.3 Reconstructed POVM Elements | 301 |
| | | 9.4.4 Conditioning and Regularization | 305 |
| | | 9.4.5 Robustness of Detector Tomography | 307 |
| | | 9.4.6 Wigner Functions | 308 |
| | 9.5 | Conclusions | 310 |
| | 3.3 | References | 311 |
| | | | |
| 10. | The | First Single-Photon Sources | 315 |
| | 10.1 | Introduction | 316 |
| | 10.2 | Feeble Light vs. Single Photon | 318 |
| | | 10.2.1 In Search of Feeble Light's Wave-Like Properties: | |
| | | A Short Historical Review | 318 |
| | | 10.2.2 Quantum Optics in a Nutshell | 319 |
| | | 10.2.3 One-Photon Wavepacket | 321 |
| | | 10.2.4 Quasi-Classical Wavepacket | 326 |
| | | 10.2.5 The Possibility of an Experimental Distinction | 328 |
| | | 10.2.6 Attenuated Continuous Light Beams | 329 |
| | | 10.2.7 Light From a Discharge Lamp | 331 |
| | | 10.2.8 Conclusion: What is Single-Photon Light? | 333 |
| | 10.3 | Photon Pairs as a Resource for Single Photons | 334 |
| | | 10.3.1 Introduction | 334 |
| | | 10.3.2 Non-Classical Properties in an Atomic Cascade | 335 |
| | | 10.3.3 Anticorrelation for a Single Photon on a Beamsplitter | 336 |
| | | 10.3.4 The 1986 Anticorrelation Experiment | 339 |
| | 10.4 | Single-Photon Interferences | 344 |
| | | 10.4.1 Wave-Particle Duality in Textbooks | 344 |
| | | 10.4.2 Interferences with a Single Photon | 344 |
| | 10.5 | Further Developments | 346 |
| | | 10.5.1 Parametric Sources of Photon Pairs | 346 |
| | | 10.5.2 Other Heralded and "On-Demand" | |
| | | Single-Photon Sources | 347 |
| | | 10.5.3 "Delayed-Choice" Single-Photon Interference | |
| | | Experiments | 348 |
| | | References | 348 |
| 11. | Para | metric Down-Conversion | 351 |
| | 11.1 | Introduction | 352 |
| | 11.2 | Single Photons from PDC: Theory | 353 |
| | | 11.2.1 Classical Description of PDC | 354 |

| | | 11.2.2 Quantum Mechanical Description of PDC | 33/ |
|-----|--------------|--|--------------------------|
| | | 11.2.3 Heralding Single Photons from PDC | 360 |
| | | 11.2.4 Heralding Pure Single-Photon Fock States | 362 |
| | 11.3 | Bulk-Crystal PDC | 367 |
| | 11.5 | | |
| | | 11.3.1 Birefringent Phase-Matching | 367 |
| | | 11.3.2 Heralded Single Photons from Triggered PDC | 372 |
| | 11.4 | Periodically-Poled Crystal PDC | 379 |
| | | 11.4.1 Quasi-Phase-Matching | 379 |
| | | 11.4.2 Periodic Poling | 383 |
| | | 11.4.3 Optimal Focus Parameters for Heralding Efficiency | 384 |
| | | | |
| | | 11.4.4 Number Purity | 388 |
| | | 11.4.5 Spectral Purity | 390 |
| | | 11.4.6 Non-Uniform Periodic Poling | 391 |
| | 11.5 | Waveguide-Crystal PDC | 392 |
| | | 11.5.1 History and Experimental Implementations | 393 |
| | | 11.5.2 Theory of PDC in Waveguides | 394 |
| | | | |
| | | | 399 |
| | | 11.5.4 Electric Field Modes in Waveguides | 401 |
| | 11.6 | Comparison of Experimental Single-Photon Sources | |
| | | Using PDC | 403 |
| | 11.7 | Overview of the Most Commonly Used Nonlinear | |
| | | Materials and Their Properties | 404 |
| | 11.8 | Conclusion | 404 |
| | 11.0 | | |
| | | References | 404 |
| | | | |
| 12. | Four | -Wave Mixing in Single-Mode Optical Fibers | 411 |
| | | | |
| | 12.1 | Introduction | 412 |
| | 12.2 | Photon-Pair Generation in Optical Fibers | 413 |
| | | 12.2.1 Classical Four-Wave Mixing Theory and | |
| | | Phase-Matching Requirements | 413 |
| | | 12.2.2 Quantum Theory of Four-Wave Mixing | 416 |
| | | | 410 |
| | | 12.2.3 Cross-Polarized Four-Wave Mixing in | |
| | | Birefringent Fibers | 419 |
| | | 12.2.4 Raman Scattering | 420 |
| | 12.3 | Heralded Single-Photon Sources Based on sFWM | 422 |
| | | | |
| | | | |
| | | 12.3.1 Photon-Pair Generation in the Anomalous | 125 |
| | | 12.3.1 Photon-Pair Generation in the Anomalous Dispersion Regime | 425 |
| | | 12.3.1 Photon-Pair Generation in the Anomalous Dispersion Regime12.3.2 Photonic Crystal Fiber Sources in the Normal | |
| | | 12.3.1 Photon-Pair Generation in the Anomalous Dispersion Regime 12.3.2 Photonic Crystal Fiber Sources in the Normal Dispersion Regime | 425 427 |
| | 12.4 | 12.3.1 Photon-Pair Generation in the Anomalous Dispersion Regime12.3.2 Photonic Crystal Fiber Sources in the Normal | |
| | 12.4 | 12.3.1 Photon-Pair Generation in the Anomalous Dispersion Regime 12.3.2 Photonic Crystal Fiber Sources in the Normal Dispersion Regime | |
| | | 12.3.1 Photon-Pair Generation in the Anomalous Dispersion Regime 12.3.2 Photonic Crystal Fiber Sources in the Normal Dispersion Regime Quantum Interference Between Separate Spectrally Filtered Fiber Sources | 427 |
| | 12.4 12.5 | 12.3.1 Photon-Pair Generation in the Anomalous Dispersion Regime 12.3.2 Photonic Crystal Fiber Sources in the Normal Dispersion Regime Quantum Interference Between Separate Spectrally Filtered Fiber Sources Intrinsically Pure-State Photons | 427 |
| | | 12.3.1 Photon-Pair Generation in the Anomalous Dispersion Regime 12.3.2 Photonic Crystal Fiber Sources in the Normal Dispersion Regime Quantum Interference Between Separate Spectrally Filtered Fiber Sources Intrinsically Pure-State Photons 12.5.1 Generation of Spectrally Uncorrelated Two-Photon | 427 430 436 |
| | | 12.3.1 Photon-Pair Generation in the Anomalous Dispersion Regime 12.3.2 Photonic Crystal Fiber Sources in the Normal Dispersion Regime Quantum Interference Between Separate Spectrally Filtered Fiber Sources Intrinsically Pure-State Photons 12.5.1 Generation of Spectrally Uncorrelated Two-Photon States Through Group Velocity Matching | 427 |
| | | 12.3.1 Photon-Pair Generation in the Anomalous Dispersion Regime 12.3.2 Photonic Crystal Fiber Sources in the Normal Dispersion Regime Quantum Interference Between Separate Spectrally Filtered Fiber Sources Intrinsically Pure-State Photons 12.5.1 Generation of Spectrally Uncorrelated Two-Photon States Through Group Velocity Matching 12.5.2 A Temporal Filtering Approach for Attaining | 427 430 436 436 |
| | | 12.3.1 Photon-Pair Generation in the Anomalous Dispersion Regime 12.3.2 Photonic Crystal Fiber Sources in the Normal Dispersion Regime Quantum Interference Between Separate Spectrally Filtered Fiber Sources Intrinsically Pure-State Photons 12.5.1 Generation of Spectrally Uncorrelated Two-Photon States Through Group Velocity Matching | 427 430 436 |
| | | 12.3.1 Photon-Pair Generation in the Anomalous Dispersion Regime 12.3.2 Photonic Crystal Fiber Sources in the Normal Dispersion Regime Quantum Interference Between Separate Spectrally Filtered Fiber Sources Intrinsically Pure-State Photons 12.5.1 Generation of Spectrally Uncorrelated Two-Photon States Through Group Velocity Matching 12.5.2 A Temporal Filtering Approach for Attaining | 427 430 436 436 |

| Contents | xi |
|----------|----|
| | |

| | 12.7 | Applications of Fiber Photon Sources—All-Fiber | |
|------|------|---|-----|
| | | Quantum Logic Gates | 454 |
| | 12.8 | Photonic Fusion in Fiber | 458 |
| | 12.9 | Conclusion | 460 |
| | | References | 461 |
| 13. | Sing | le Emitters in Isolated Quantum Systems | 467 |
| | 13.1 | Introduction | 468 |
| | 13.2 | Single Photons from Atoms and Ions - A. Kuhn | 468 |
| | | 13.2.1 Emission into Free Space | 469 |
| | | 13.2.2 Cavity-Based Single-Photon Emitters | 471 |
| | 13.3 | 13.2.3 Photon Coherence, Amplitude, and Phase Control Single Photons from Semiconductor | 485 |
| | | Quantum Dots - G. S. Solomon | 492 |
| | | 13.3.1 Introduction | 492 |
| | | 13.3.2 InAs-Based Quantum-Dot Formation | 493 |
| | | 13.3.3 Exciton Energetics | 494 |
| | | 13.3.4 Optically Accessing Single Quantum Dots | 497 |
| | | 13.3.5 Single Photons From Single Quantum Dots | 499 |
| | | 13.3.6 Weak QD-Cavity Coupling | 502 |
| | | 13.3.7 Quantum-Dot Photon Indistinguishability | 505 |
| | 13.4 | Single Defects in Diamond - C. Santori | 511 |
| | | 13.4.1 Introduction | 511 |
| | | 13.4.2 The Nitrogen-Vacancy Center | 511 |
| | | 13.4.3 Other Defects | 521 |
| | | 13.4.4 Optical Structures in Diamond | 522 |
| | | 13.4.5 Quantum Communication | 525 |
| | 12 - | 13.4.6 Summary | 526 |
| | 13.5 | Future Directions | 526 |
| | | References | 527 |
| 14. | Gen | eration and Storage of Single Photons in | |
| | Coll | ectively Excited Atomic Ensembles | 541 |
| | 14.1 | Introduction | 541 |
| | 14.2 | Basic Concepts | 543 |
| | 14.3 | From Heralded to Deterministic Single-Photon Sources | 545 |
| | 14.4 | Interference of Photons from Independent Sources | 550 |
| | 14.5 | Conclusion and Outlook | 555 |
| | Appe | | 556 |
| | | A Write Process | 556 |
| | | B Read Process | 559 |
| | Refe | rences | 560 |
| Inde | PY | | E62 |
| | muex | | 563 |