Chapter 1

Introduction

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Chapter Outline

All these fifty years of conscious brooding have brought me no nearer to the answer to the question, 'What are light quanta?' Nowadays every Tom, Dick and Harry thinks he knows it, but he is mistaken.

Albert Einstein, 1954 [1]

1.1 PHYSICS OF LIGHT—AN HISTORICAL PERSPECTIVE

In the beginning there was light. And it was good. Not long thereafter people began to look for a comprehensive understanding of its nature. While the publication record starts off a little spotty, in the fifth century BC the Greek philosopher Empedocles concluded that light consists of rays that emanate from the eye. This point of view was questioned using what today might be characterized as a local realism argument by Euclid in his classic text on light propagation *Optica*. Euclid hypothesized that rays of light are emitted

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by external sources, but it was not until Ibn al-Haytham in 1000 AD that this view was put on a scientific footing.

The character of light itself was described by Descartes in the 17th century as "pressure" that was transmitted through space from a source to a detector. This idea was later developed by Huygens and Hooke into the wave theory of light. At about the same time, Gassendi put forward the contravening notion that light was a particle, an idea embraced and developed further by Newton. The differing perspectives of light as a particle versus a wave were generally considered resolved in favor of the wave picture by Young's double-slit experiment in 1803, and by Fresnel's experiments in diffraction. In the 1860s, further confirmation of this conclusion was framed in an elegant and deeply satisfying manner by the Maxwell equations: the prediction of polarized electromagnetic waves that propagate at what was understood to be the speed of light.

Problems with the waves-and-fluids view of electromagnetism arose in 1897, when J.J. Thomson discovered discrete particles carrying negative electric charge moving through vacuum. Then in 1900, in "an act of despair" Planck invoked quantized bundles of electromagnetic energy in the derivation of the blackbody radiation law [2,3], a step that not only embraced prior conjectures by Boltzmann in statistical mechanics, but also flew in the face of conventional understanding. It was originally considered an artifact of the derivation to be corrected later, but Einstein took the idea of light quanta more seriously in his 1905 description of the photoelectric effect [4]. Then in 1913 Bohr invoked the quantization of both energy and angular momentum to explain the discrete spectral emission lines observed in the Hydrogen-Balmer series. The wheels came completely off the wagon in 1924 when de Broglie hypothesized that not only light, but also particles of matter have wave-like properties. A flurry of subsequent discovery and advance that established the framework of quantum mechanics, most notably by Heisenberg, Born, Schrodinger, Pauli, and Dirac, culminated for the purposes of this book in 1927 when Dirac quantized the electromagnetic field, effectively developing a theory of light that encompassed the physical phenomenon that kicked off the entire revolution in the first place. The first direct detection of single photons was achieved in the 1930s. The atomic-cascade photon-pair source [5] developed in the 1950s and its use in the 1970s and 1980s [6–9] represents the first single-photon source. Then there was quantum light, and it was really good.

1.2 QUANTUM LIGHT

1.2.1 What is Non-Classical Light?

Before going too deeply into the details of single-photon technologies it is useful to at least provide a basic definition of what is meant by the term "quantum light." Quantum light, or "non-classical light," describes the broad class of states that cannot be emitted by "classical" sources such as discharge lamps or lasers.

Formally, the distinction between non-classical and classical light can be defined by writing the state in the Glauber-Sudarshan representation, in which the state is expanded in the basis of coherent states, weighted by a quasiprobability distribution [10]. If the quasiprobability is positive and bounded, then the light is considered classical, otherwise it is non-classical. Examples of classical light include thermal light emitted from a blackbody source, and coherent light emitted from a laser, while non-classical light includes squeezed states, photon-number (or Fock) states generally, and single-photon states specifically.

1.2.2 What is a Photon?

A photon is defined as an elementary excitation of a single mode of the quantized electromagnetic field [11]. The term "photon" was first introduced by Lewis in 1926 [12–14]. A mode k of the quantized electromagnetic field is labeled by its frequency ν_k, and a single photon in that mode has energy equal to $h\nu_k$, where h is the Planck constant. While this monochromatic definition of a photon implies delocalization in time, it is common to talk about propagating "single-photon states" that are localized to some degree in time and space. Mathematically, such states can be described as superpositions of monochromatic modes [11]. While there is some discussion in the literature about the definition of a "photon wavefunction" [15], here we adopt the following operational definition of a single-photon state: given a detector that can determine the number of incident photons (in some finite-width frequency range) with 100% accuracy, a single-photon state is an excitation of the electromagnetic field (localized to some degree in both space and time) such that the detector measures exactly one photon for each incident state. In other words, a single-photon state is one for which the photon-number statistics have a mean value of one and a variance of zero. It should be noted that since the results of quantum measurements may depend on the procedure and apparatus used, the physics of the measurement process itself should also be considered [16].

It is also worth noting the distinction between single-photon sources and classical sources of light in terms of photon statistics. While the distinction between non-classical and classical light is defined formally, a qualitative description is that the statistical variation of classical sources is at least that of a Poisson process, while emission from a single-photon source has lower variance. This is easily understood from the fact that a single-photon source is, by definition, unable to emit a second photon for some time following a previous photon (antibunching), and this enforces some degree of order to the source's output. In contrast, a classical thermal source has an increased likelihood of emitting additional photons near an existing one (bunching), and this tendency goes hand-in-hand with increased statistical fluctuations. The low-noise nature of single-photon sources is an obvious advantage in many measurement situations.

1.3 THE DEVELOPMENT OF SINGLE-PHOTON TECHNOLOGIES

The investigation of quantum mechanics for the advance of mankind's understanding and technological capability remains one of the prime motivators of current research in the physical sciences. Of the many strange properties of quantum mechanics, those relating to the so-called coherent quantum effects take the widest departure from our daily (macroscopic) experience: the possibility for physical objects to appear to simultaneously hold mutually exclusive properties is a confounding fact of the natural world. This capability has the potential to be an extremely powerful technological tool, and the exploitation of coherent quantum effects is at the frontier of research. And yet, the feature that conveys these wondrous capabilities is also their primary impediment: coherence in quantum systems is difficult to preserve in the presence of interactions with the environment. Thus, while quantum effects are studied in a wide array of media, optical quantum-mechanical phenomena are particularly robust and accessible in an experimental setting, which makes them among the most widely investigated.

Today, single-photon technologies are an area of intense and sustained interest. They represent a bridge between the "classical" world of our daily experience and the quantum realm where we may access the extraordinary phenomena therein. Single-photon technologies are critical for Bell tests probing fundamental questions about the nature of reality, and to research and development in quantum information science. One emergent example in this field is the generation of verifiable random numbers [18–20]. In a more prosaic but no less important sense, single-photon technologies operate at the fundamental limit of electromagnetic signal strength, and are thus used to make the most sensitive measurements in a wide range of applications, notably: astrophysics, molecular biology, health and safety monitoring, environmental sensing, and imaging. Given the broad scope and magnitude of these applications, it is not surprising that while some form of single-photon technology has been available for nearly 80 years [21–23], the literature record shows continued and robust activity in this field; a database search for papers on "single-photon detection" shows sustained growth over the past four decades, and a similar growth, although one that started more recently, in papers on "single-photon sources," as can be seen in (Fig. 1.1). We also see that interest in single-photon sources coincided with the advent of quantum cryptography, and while that field may appear to be maturing, the growth in interest in single-photon measurement and quantum-enabled metrology appears to be robust.

Much of the research in single-photon technologies actually focuses on states comprised of two photons. While at first blush this may seem counterintuitive, correlated-photon pairs offer a wealth of possibilities in single-photon technologies. Although the generation of photon pairs is typically governed by a spontaneous random process, as in a classical light source,

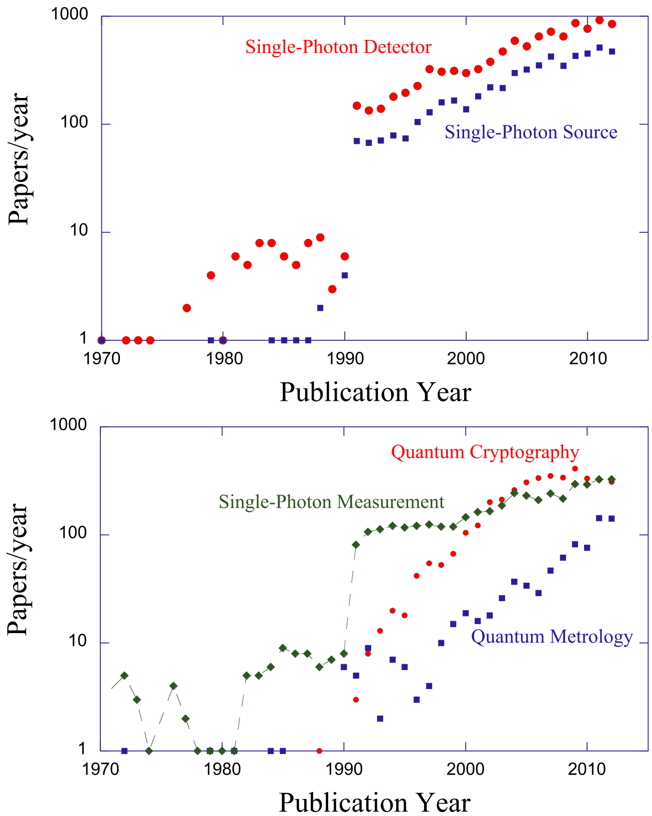

FIGURE 1.1 Growth of the field of single-photon source and detector technology as seen by the number of papers published each year using the indicated search terms in the publication database Web of Science [17]. Search terms: (a) "single-photon source" and "single-photon detector" and (b) "single-photon measurement," "quantum cryptography," and "quantum metrology." *Note:* The jump in the data at 1990 is an artifact due to the database methodology rather than an indication of a real change in the publication rates.

the pair-wise correlation of the two photons themselves is governed by strict conservation laws in a quantum-mechanical process. This fact allows one to produce light with non-classical properties by detecting one photon of the pair to indicate the existence of its correlated partner: a heralded single-photon state [24,25]. By extension, correlated pairs can be used as the basis for a primary standard technique [24,26] for calibrating single-photon detectors because they allow one to know when one and only one photon was incident on a detector under examination. Furthermore, such bipartite states provide a convenient way to study coherent quantum effects (e.g. entanglement) and have a variety of applications in quantum communication.

Figure 1.2 tells a nice story of the advance of photon-pair technology over the past five decades in terms of the detected-pair rate. The first pair sources were based on atomic cascades (c.f. Chapter 10), which improved from a few

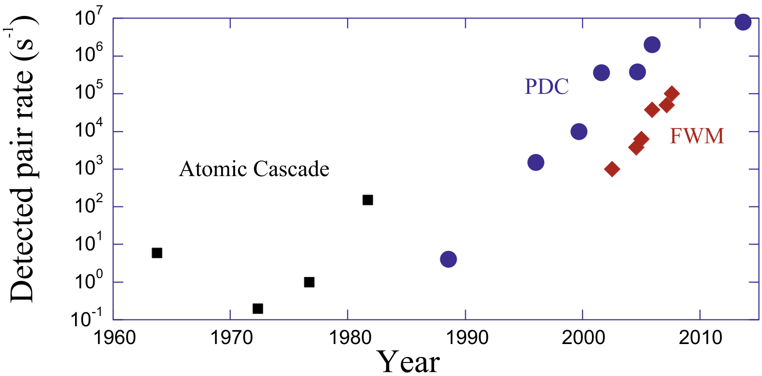

FIGURE 1.2 Detected photon-pair-rate progress. Detected photon-pair rates shown for atomic-cascade- (black squares), parametric-down-conversion- (blues dots), and fiber-four-wave-mixing-based sources (red diamonds) [6,7,9,27–35]. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this book.)

detected pairs/s in the 1960s to 150 pairs/s in the 1980s, and led to what is probably the most famous quantum-optics experiment to date: the test of Bell's theorem by Aspect *et al.* [9]. But those sources inherently emit into 4π steradians, meaning that the efficiency with which the emitted photons can be collected is severely limited. In contrast, the energy and momentum constraints governing the production of photon pairs in spontaneous parametric down-conversion (PDC) serve to concentrate the emission into a narrow range of angles, allowing for significantly more efficient collection of the pairs (c.f. Chapter 11). Indeed, although in the very first demonstration that PDC consisted of correlated pairs of photons, by Burham and Weinberg [36], the detection rate of $\approx 1\ s^{-1}$ was actually lower than that of Aspect *et al.*, the ratio of coincidence-to-accidentals (a measure of the overall collection efficiency, among other things) was more than 10 times higher. From that point there was exponential growth in the maximum reported detected-pair rate in PDC-based sources [33] until the late 2000s, where progress started to slow. Here it is important to note that Fig. 1.2 describes progress in both sources and single-photon detectors, and the apparent stall in progress in detected-pair rates was mostly due to detector limitations. By that time most photon-pair experiments used Si single-photon avalanche diodes (SPADs) for single-photon detection (c.f. Chapter 4). Initially SPADs were used in a passively quenched mode with a maximum count rate of $\approx 10^5\ s^{-1}$, later they were used in the actively quenched mode, which allowed count rates up to $\approx 10^6\ s^{-1}$, as can be seen from the graph, and recent reports make use of multiple actively quenched SPADs to achieve unprecedented detected-pair rates of $\approx 10^7\ s^{-1}$ [35]. In the past few years new detection technologies, such as multi-element and fast-gated SPADs (Chapters 4 and 7) and superconducting nanowire detectors (Chapter 6) capable of operating at rates approaching $\approx 10^9\ s^{-1}$ have been reported, and it is reasonable to expect corresponding advances in the detected-pair rate.

As mentioned above, collection efficiency continues to play, a critical limiting role in the overall performance of a correlated-pair source. Sources in which the emission is constrained to a well-defined spatial mode, as in four-wave-mixing (FWM) in single-mode fiber, have the potential to advance detected-pair rates even farther (Chapter 12). Figure 1.2 also shows exponential growth in rates from FWM sources, and these ideas have promoted the recent development of PDC in single-mode non-linear waveguides for correlated-pair generation (Chapter 11).

Heralded single-photon sources based on correlated photons are inherently probabilistic, and therefore have limited scalability in the context of real-world applications. Ideally, the next generation of sources would be deterministic on-demand sources that can produce a photon whenever required, and the most obvious approach is to use a single quantum emitter (e.g. a single two- or many-level system). Though seemingly straightforward, such sources are actually extremely challenging to implement. Using single atoms is a natural choice for such a system, but to address the collection problem seen by the original atom-based sources high-finesse cavities must be used to enhance the collection efficiency, and it is very difficult to maintain the coupling between a single emitter and the cavity. Nonetheless there have been a number of successes with both neutral alkali atoms, such as Cs and Rb [37–42], and Ca+ ions [43–45]. Solid-state single-photon emitters, such as quantum dots and color centers, are also attractive candidates. These systems are confined to a host material that can be used to form the optical cavity. For example, distributed-Bragg-reflection (DBR) mirrors on both sides of quantum dots can be used to define the emission mode, and these mirrors can be grown together with the dots. In more sophisticated designs, dots are integrated in pillars, micro-disks, or photonic-crystal cavities [46–52]. There are also efforts to build optical cavities around nitrogen-vacancy color centers in diamond [53,54] to improve coupling efficiency (Chapter 13). A common drawback of solid-state single-photon sources is their high rate of decoherence due to interactions between the emitter with host material. Current research is aimed at understanding and mitigating these effects [55].

Recently, the idea of using ensembles of emitters for generating single photons deterministically has been advanced (Chapter 14). In this scheme a collective excitation is generated in an ensemble of atoms, and later emitted when a read-out signal is applied to the ensemble, effectively acting as a quantum memory [56–59]. The use of an ensemble significantly enhances coupling of light to the emitters, meaning that an optical cavity is no longer necessary, while the deterministic character of the emission is preserved. Also note that a quantum memory used in conjunction with any photon-pair source is another path to deterministic single-photon generation [60–64]. The main distinction is whether the single photon is created externally and then stored in the memory, or created within the memory.

1.4 SOME APPLICATIONS OF SINGLE-PHOTON TECHNOLOGY

There are myriad applications that are enabled by, or that benefit from single-photon technologies. Currently quantum information is a particularly hot area, where examples of applications enabled by single-photon technology are quantum cryptography protocols [65–69], quantum communication and specifically quantum repeaters [70–74], and certain quantum computation protocols [75]. All these applications are being actively researched, in turn providing new and sometimes fundamental challenges for single-photon technology research. Clear demonstrations of how the performance of single-photon components affect quantum computation can be seen in recent work on boson sampling [76–79], an application in the field of linear-optics quantum computation. Another area of experimental research that relies on single-photon technology is the development of quantum receivers that can unambiguously discriminate between non-orthogonal states at error rates below the standard quantum limit, a fundamental measurement problem [80–82]. The latter is an example of a measurement that is not possible with a toolbox limited only to the classical world.

Single-photon technologies are also critical to fundamental tests of quantum mechanics that seek to determine whether or not non-local realism is absolutely required. Current efforts build on the Bell tests first implemented by Aspect, *et al.* [9] with atomic-cascade-based single-photon sources. However, the experimental implementation of tests of this type can have a number of so-called loopholes that may fail to conclusively exclude the possibility of alternate theories that offer a different perspective on the world than that suggested by quantum mechanics [83]. Currently there are intense efforts to close the remaining loopholes in such experiments, and this requires pushing the performance of single-photon devices to unprecedented levels [84–88]. Short of closing all the possible loopholes in a Bell test, other experimental tests can be performed to verify (or falsify) limited sub-classes of alternative theories, see for example [89]. Related to this are the emerging efforts to use the non-local realism of quantum mechanics and its indeterminism as a source of certifiable randomness [18–20], which may enable a whole new array of security related applications [90–94].

In addition to quantum-information, single-photon detectors are used for a wide variety of applications, including DNA sequencing [95–98], bioluminescence characterization [99], Förster resonance energy transfer for protein folding observation [100–102], light detection and ranging for remote sensing [103,104], and light ranging on shorter scales [105], optical time-domain reflectometry [106–112], picosecond imaging circuit analysis (PICA) [113–118], single-molecule spectroscopy [119–125] and fluorescence-lifetime measurements [126], medical applications such as diffuse optical tomography [127] and positron emission tomography [128], and finally, single-photon metrology [26, 129–136].

1.5 THIS BOOK

This book attempts to provide a comprehensive overview of the current state of technology and techniques that are available to facilitate and advance the design of experiments involving single photons. The book is broken into chapters focused on the design, performance, and ongoing research of available detectors and sources, grouped by their underlying physical principles.

Most chapters were written by active researchers who have contributed significantly to the field. To bridge gaps between the sub-fields, common concepts were identified. Chapter 2 introduces those basic properties and measurement metrics that are generally accepted for the characterization of single-photon sources and single-photon detectors. The discussion begins with the statistics of light and presents how those statistics are reflected in the measurements of single-photon sources and detectors. This allows a comparative understanding to be developed, along with an impression of how the field is progressing and what may be expected in the near future. The rest of the book is divided into two parts: Chapters 3 through 9 describe single-photon detectors, and the ways to characterize them, and Chapters 10 through 14 present various types of sources.

1.5.1 Single-Photon Detectors

Single-photon detectors were invented approximately 80 years ago with the advent of the photomultiplier tube (PMT), and ever since then detectors have been an active area of research and development. While there are a limited number of material systems used for single-photon detection, generally: photomultipliers, semiconductors, and superconductors, within each of these families are nearly innumerable variations designed to enhance various properties. Of course, the ideal detector has 100 % detection efficiency, photon-number-resolving (PNR) capability, arbitrarily accurate timing resolution, and no detrimental effects such as saturation, dark counts, etc. In fact, each of these ideal properties is nearly available in one type of detector or another, but not all in one detector at the same time. Unfortunately we are in little danger of ever achieving such a perfect detector. In reality, a detector represents a set of performance tradeoffs that must be selected based on the needs of a particular application. To aid with detector selection, Table 1.1 presents a survey of reported detector performance, and some relevant parameters. Refer to Chapter 2 for common definitions relevant to single-photon detectors.

TABLE 1.1 Comparison of Single-Photon Detectors [17] Based on Tables from [191,192] Using a Figure of Merit Given by the Ratio of the Detection Efficiency to the Product of the Dark-Count Rate and the Time Resolution (Assumed to be the Timing Jitter), $\eta/(D\delta t)$

Detector Type	Operation Temp. (K)	Detection Efficiency, Wavelength η(%), λ (nm)	Timing Jitter, δt(ns) (FWHM)	Dark-count Rate, D (ungated) (1/s)	Figure of Merit $\eta/(D\delta t)$	Max. Count Rate ($10^6/s$)	PNR Capability
PMT (visible–near-infrared) [137]	300	40 @ 500	0.3	100	1.3×10^7	10	some
PMT (infrared) [138]	200	2 @ 1550	0.3	200000	3.3×10^2	10	some
Si SPAD (thick junction) [139]	250	65 @ 650	0.4	25	6.5×10^7	10	none
Si SPAD (shallow junction) [140]	250	49 @ 550	0.035	25	5.6×10^8	10	none
Si SPAD (self-differencing) [141]	250	74 @ 600	–	2000	–	16	some
Si SPAD (linear-mode) [142]	78	56 @ 450	–	0.0008	–	0.01	full*
Si SPAD (cavity) [143]	78	42 @ 780	0.035	3500	3.4×10^6	10	none
Si SPAD (multipixel) [144,145]	290	40 @ 532	0.3	25000-500000	1×10^4	30	some
Hybrid PMT (PMT + APD) [146,147]	270	30 @ 1064	0.2	30000	5×10^4	200	none
Time multiplexed (Si SPAD) [148]	250	39 @ 680	0.4	200	5×10^6	0.5	some
Time multiplexed (Si SPAD) [149]	250	50 @ 825	0.5	150	7×10^6	2	some
Space multiplexed (InGaAs/InP SPAD) [150]	250	33 @ 1060	0.133	160000000	1.6×10^1	10	some
Space multiplexed (InGaAs/InP SPAD) [151]	250	2 @ 1550	–	–	–	0.3	none
InGaAs/InP SPAD (gated) [152]	220	20 @ 1545; 38 @ 1308	–	3300	–	5	none
InGaAs/InP SPAD (gated) [153]	200	10 @ 1550	0.370	91	3.0×10^5	0.01	none

InGaAs/InP SPAD (self-differencing) [154]	240	10 @ 1550	0.055	16000	1.1×10^5	100	none
InGaAs/InP SPAD (self-differencing) [155]	240	10 @ 1550	–	–	–	–	full
InGaAs/InP SPAD (self-differencing) [156]	243	26 @ 1550	0.1	170000	4.5×10^6	1000	none
InGaAs/InP SPAD (sinusoidal gating) [157]	223	12 @ 1550	0.37	1570	5.8×10^7	43	none
InGaAs/InP SPAD (harmonic subtraction) [158]	251	25 @ 1310	0.077	313000	5.4×10^5	100	none
InGaAs/InP SPAD (discharge pulse counting) [159]	243	7 @ 1550	–	40000	–	10	none
InGaAs NFAD (monolithic negative feedback) [160,161]	243	6 @ 1550	0.4	28000	–	10	some
InGaAs (self-quenching & self-recovery) [162]	160	11.5 @ 1550	–	3300000	–	3	none
CIPD (InGaAs) [163]	4.2	80 @ 1310	–	–	–	0.001	full
Frequency up-conversion [164]	300	8.8 @ 1550	0.4	13000	1.7×10^4	10	none
Frequency up-conversion [165,166]	160	56 to 59 @ 1550	–	460000	–	5	none
Frequency up-conversion [167]	300	20 @ 1306	0.62	2200	1.5×10^5	10	none
VLPC [168]	7	88 @ 694	40	20000	1.1×10^3	10	some
VLPC [169]	7	40 @ 633	0.24	25000	6.7×10^4	10	some
SSPM [170]	6	76 @ 702	3.5	7000	3×10^4	30	full
TES(W) [171]	0.1	50 @ 1550	100	3	1.7×10^6	0.1	full
TES(W) [172,217]	0.1	95 @ 1556	4	–	–	0.1	full
TES(Ha) [173]	0.1	85 @ 850	28	–	–	0.1	full
TES (Ti) [174–176,216]	0.1	89 to 98 @ 850	100	–	–	1	full
Waveguide-SNSPD [177]	2	91(on-chip); 2 @ 1550	0.02	6000	1.7×10^5	1000	none

(Continued)

TABLE 1.1 (*Continued*)

Detector Type	Operation Temp. (K)	Detection Efficiency, Wavelength $\eta(\%)$, λ (nm)	Timing Jitter, δt(ns) (FWHM)	Dark-count Rate, D (ungated) (1/s)	Figure of Merit $\eta/(D\delta t)$	Max. Count Rate ($10^6/s$)	PNR Capability
NbTi-SNSPD [178]	2.3	74 @ 1550	0.07	100	1×10^8	–	none
WSi-SNSPD [179]	0.25	93 @ 1550	0.15	0.1(intrinsic); 1000	6.2×10^6	25	none
Parallel SNSPD [180]	2	2 (device) @ 1300	0.05	0.15	2.7×10^9 (device)	1000	some
Multi-element SNSPD [181]	2.5	76 @ 1550	0.07	10000	1.1×10^6	800	some
Series SNSPD [182]	1.2	1 @ 1300	0.08	5	2.5×10^7	100	some
STJ [183–185]	0.4	45 @ 350	2000	–	–	0.01	full
QD (resonant tunnel diode) [186]	4	12 @ 550	150	0.002	4×10^9	0.25	full
QDOGFET (field-effect transistor) [187–189]	4	2 @ 805	10000	150	10	0.05	full
SPT (single-photoelectron transistor) [190]	4	1 @ 1300	–	–	–	–	full

*PNR should be possible, but none has been demonstrated as of yet. While most parameter values are for the detector as a complete system, a few parameter values as indicated are given just for the intrinsic device.

Maximum count rate is a rough estimate from the detector's output pulse width or count rate that yields 100% dead time. The photon-number-resolving (PNR) capability is defined here as: none) for devices that are typically operated as a photon or no photon device; some) for devices that are made from multiple detectors that individually have no PNR capability and thus are limited in the photon number that can be resolved to the number of individual detectors; and full) for devices whose output is inherently proportional to the number of photons even if their proportional response ultimately saturates at high photon levels.

Chapter 3 reviews the PMT, the first detector able to detect single optical photons. Given its large active area, fast response, reliability, and response efficiency over a wide range of optical spectrum, the PMT remains one of the most widely used detectors. Two distinct disadvantages of the PMT, the bulk vacuum tube and the lower detection efficiency, particularly at near infrared and longer wavelengths, have motivated the development of solid-state alternatives.

Chapter 4 presents a comprehensive review, from fabrication to operation, of the most commonly used alternative to the PMT (certainly they are the most used in quantum information applications), the semiconductor-based detector. This is largely due to their higher detection efficiency, particularly in the red and near-infrared spectral regions, along with other advantages such as the compactness, low power dissipation, lower cost, and reliability.

Chapter 5 describes a variety of solid-state detectors that go beyond the mechanisms of typical semiconductor-based devices. These include the visible-light photon counter (VLPC) and the solid-state photomultiplier (SSPM), which have been in existence for some time, but have not been particularly accessible to many researchers. These devices have the advantage of high detection efficiency and high maximum rates, and some PNR capability. Also included in this chapter are devices that use quantum dots, photoconductive gain, and electrical readout of photo-generated carriers as a means to detect single photons. In addition to the potential for PNR detection, these latter schemes may even allow for the possibility of recording the spin of a incident photon. Such transfer of a photonic quantum state to a material system would represent a unique capability that could open the door to a whole new category of applications.

Chapter 6 reviews one of today's most promising single-photon-detection technologies, cryogenic-based detection, in the form of the superconducting transition-edge-sensor (TES) and the superconducting nanowire single-photon detector (SNSPD). Both of these detectors have demonstrated detection efficiencies approaching unity. In addition, TES detectors can provide information about the number of photons that arrive simultaneously, and can do so up to large numbers of photons. We refer to this as full PNR capability. The SNSPD, the younger of these two technologies and known for low timing jitter and high count rates, is now being used to provide PNR capability by means of multiplexing. And the advent of commercially available cryogen-free cooling systems has greatly improved the convenience of these detectors, albeit at high capital cost. SNSPDs generally operate at somewhat more accessible temperatures than TES ($\approx$1 K rather than $\approx$0.1 K) and the development of devices with higher operating temperatures is an active area of research, offering the potential to move them out of the laboratory environment and introducing them to a wider range of applications.

Chapter 7 discusses the hybrid detection systems, whereby multiple technologies are combined to provide additional detection capabilities. These include using multiplexed detection techniques to provide PNR capability where the individual detector(s) has(have) none. In addition, these techniques can be

TABLE 1.2 Comparison of Single-Photon Sources.

Source Type	Prob. or Det.	Temp. (K)	Wavelength Range General	Wave-Length Tunability Specific	Inherent Band-width	Emission Efficiency	Output Spatial Mode	$g^{(2)}(0)$	Refs.
Faint laser Two photon	P	300	vis-IR	nm	GHz	1	single	1	
(heralded)– atomic cascade	P	–	vis-UV	MHz	atomic line	0.0001	multi	–	[9]
PDC bulk	P	300	vis-IR	nm	nm	0.6	multi	0.0014	[193–195]
periodically poled	P	300 to 400	vis-IR	nm	nm	0.84	multi/single*	–	[84–88]
waveguide (periodically poled)	P	300 to 400	vis-IR	nm	nm	0.8	single	–	[196]
gated	D	300	vis-IR	nm	nm	0.27	single	0.02	[197, 198]
multiplexed (free-space, chip)	D	300	vis-IR	nm	nm	0.1	single	0.08	[199, 200]
FWM									
DSF	P	4 to 300	IR	nm	nm	0.02	single	–	[201]
BSMF	P	300	vis-IR	nm	nm	0.26	single	0.022	[202]
PCF	P	300	vis-IR	10 nm	nm	0.18	single	0.01	[203]
SOI waveguide	P	300	IR	10 nm	nm	0.17	single	-	[204]
Laser-PDC hybrid	P	300	vis-IR	nm	nm	–	single	0.37	[205]
Isolated system–									
Single Molecule	D	300	500 nm to 750 nm	30 nm	30 nm	0.04	multi	0.09	[206–208]
Color center (NV)	D	300	640 nm to 800 nm	nm	nm	0.022	multi	0.07	[209]

QD (GaN)	D	200	340 nm to 370 nm	nm	nm	–	multi	0.4	[210]
QD (CdSe/ZnS)	D	300	500 nm to 900 nm	nm	15 nm	0.05	multi	0.003	[211]
QD (InAs) in pillar cavity	D	5	920 nm to 950 nm	10 GHz	1 GHz	0.05	single	0.02	[212]
QD (InGaAs) in pillar cavity	D	10	932 nm	10 GHz	1 GHz	0.25	single	0.15	[54]
QD in tapered pillar	D	5	915, 950 nm	10 GHz	1 GHz	0.01	single	0.008	[52,213]
Single ion in cavity	D	≈0	atomic line	MHz	5 MHz	0.08	single	0.015	[44]
Single Atom in cavity	D	≈0	atomic line	MHz	10 MHz	0.05	single	0.05	[39,214]
Ensemble–									
Rb, Cs	D	10^{-4}	atomic line	MHz	10 MHz	0.2	single	0.25	[56,57]

Sources are characterized as probabilistic (P) or deterministic (D) (remembering the caveat that a deterministic source can in practice lose some or much of its determinism and operate in a more probabilistic fashion due to issues such as low emission efficiency)

*While bulk and periodically poled PDC sources are generally inherently multimode, they can be engineered to emit with high overlap to a single-spatial mode [215].

The wavelength range possible for each method is given, along with how far an individual source can be tuned. The inherent bandwidth indicates the typical spectral width of the emitted photons. The emission efficiency is the overall extraction efficiency of the source from generation of the photons to emission of the light, including any spectral filtering that would be necessary for typical quantum-information applications (the efficiency of the detector used to measure the source is not included). Note that for two-photon sources, the second-order correlation function $g^{(2)}(0)$ typically increases as the generation rate increases, so the values here are for the lower end of the generation ranges.

used to circumvent other deficiencies, such as dead time and maximum count rates. Another hybrid scheme is the use of frequency up-conversion, which transfers photons of an IR wavelength to the visible where Si SPADs have much better characteristics.

Because of the complexity of a detector's response, in many cases they need to be characterized by the end user. Chapter 8 addresses the important question of how one calibrates the detection efficiency of a single-photon detector and documents the issues relevant to achieving high accuracy. While knowing the absolute detection efficiency is critical both to metrology and to many quantum information applications, determining a device's efficiency can be challenging because many other properties of a detector must also be understood and characterized to achieve a highly accurate calibration. In addition to the usual challenges associated with high accuracy metrology, we should bear in mind that while each single-photon detection is a classical event, the measurement itself is a quantum process. The interface between these two regimes requires particular care and Chapter 9 analyzes single-photon detection, and the quantum process by which that measurement takes place.

1.5.2 Single-Photon Sources

Contemporary single-photon sources can be broadly categorized as either probabilistic or deterministic, with a probabilistic source being based on two-photon emission where one of the photons is used to herald the other as the "single-photon emission." Although many applications require an on-demand (i.e. deterministic) source of single photons, and this has led to intense research into developing truly deterministic single-photon sources, we note that photon-pair-based heralded single-photon sources are still the most widely used in applications such as quantum information, quantum-enabled measurement, and single-photon detector calibration. Table 1.2 provides a survey of reported performance for a variety of source technologies. The meaning of the relevant parameters used to describe a source is introduced in Chapter 2. The physics of different source types is discussed in Chapters 10 through 14.

Chapter 10 discusses the historic motivation and development of single-photon sources for testing the most fundamental of quantum mechanical features: wave-particle duality and entanglement. This application illustrates the fundamental distinction between a weak light pulse and a true single-photon source. The full appreciation of this distinction is key to understanding a broad range of applications in quantum information.

Spontaneous PDC is the most studied photon-pair production process and the most used for single-photon generation in quantum information applications. In particular, PDC-based single-photon sources offer the highest detected photon-pair rates (Fig. 1.2). Chapter 11 presents a comprehensive and detailed description of PDC-based single-photon sources over their 40 years development. An alternative and more recently developed type of photon-pair-based heralded single-photon source relies on four-wave mixing in single-mode optical fibers. The advantage of such a source is that the generation, extraction, encoding, delivery, and detection of photon pairs can be achieved all within the fiber, which greatly simplifies the design and operation of end-user applications. Such advantage of the four-wave mixing method has led to its use in a number of labs. Chapter 12 covers four-wave mixing sources and their applications in quantum information science.

"Single-emitter" quantum systems as on-demand sources of single photons are discussed in Chapter 13. While each of these single-emitter approaches uses a different material system (single atoms and ions, quantum dots, color centers, mesoscopic quantum wells, etc.), most rely on similar principles of operation. When single-photon emission is desired, some external control is used to put the system into an excited state that will emit a single photon upon relaxation to some lower energy state. Commonly, coupling emitters to optical cavities is employed to enforce high emission efficiency into a single spatial mode.

Chapter 14 introduces a different kind of on-demand single-photon source. This method uses collective excitations in ensembles of atoms with two metastable ground states and at least one excited state. All the atoms are first optically prepared in one of the ground states. A weak coupling pulse probabilistically transfers an ensemble into a superposition state, in which one atom of the ensemble ends up in the second ground state, but importantly, which atom was transferred cannot be determined, even in principle. This collective excitation can be stored in the ensemble until a single photon is required. Then, by applying a strong coupling pulse, the single ensemble excitation can be deterministically converted into a single photon. Sources of this type offer many advantages and conveniences over other on-demand sources.

1.6 CONCLUSIONS

Single-photon technology has had a short, but very eventful history. The concept of a photon was brought forth less than one century ago to address fundamental physics problems of the time. Since then, the field has experienced rapid and accelerating development. At the same time, the list of applications that require either single photons or single-photon detection has grown. In the following chapters the major technologies and applications are discussed in detail. Obviously, this book does not, and cannot, describe all related technologies and applications.

The development of single-photon sources and single-photon detectors have been closely interrelated, as a comprehensive understanding of detectors is not possible without studying sources at the same time, and vice versa. Our hope is that we have compiled a useful guide to the current state of the field, and one that would provide a curious reader enough background knowledge to aid their own research, as well as with the motivation to pursue these wonderful tools for the betterment of humanity.

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