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Single-Photon Sources and Detectors Dictionary

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Abstract

We present a dictionary that defines terms and metrics relevant to the characterization of single-photon detectors and sources, with the goal of promoting better understanding and communication and providing a useful reference for the quantum and single-photon communities. Clear definitions can accelerate technology development and device interoperability. The resulting common language also allows commercial devices to be compared directly and helps clarify to users what performance they can expect.

Keywords

Detectors; Quantum; Single-photon; Sources.

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Preface

The intention of this dictionary is to define relevant terms and metrics used in the characterization of single-photon detectors and sources with the goal of promoting better understanding and communication across the single-photon technology community. With the recent emergence and growth of a "quantum-component industry," the need for common definitions of terms is clear and pressing. For example, a recent (2022) workshop sponsored by the Quantum Economic Development Consortium [1] identified the need for a common set of definitions for single-photon device performance metrics [2]. There are some pre-existing documents relevant to this need, but they are focused on somewhat different purposes or on a specific application. For example, the ETSI (European Telecommunications Standards Institute) Quantum Key Distribution Vocabulary [3, 4] focuses specifically on the application of quantum key distribution (a scheme for secure communications based on fundamental quantum properties), and there is a vocabulary resource under the auspices of the CIE (International Commission on Illumination) [5] that is intended for the illumination industry. It is also worth noting that there are several publications that contain compendiums of definitions relevant to single-photon technologies [6–8]. Our effort is intended to complement and build on these reference documents, to create a dictionary independent of a particular application (for long-term relevance), and to promote clarity and understanding when terms and metrics relevant to single-photon sources or detectors are used.

This document also seeks to dispel common misconceptions and to make a few subtle distinctions that will benefit the community. Thus, this document may form the basis for a future standards document. With that as a goal, we facilitated a thorough peer-review by the Quantum Economic Development Consortium, representatives of other National Metrology Institutes, fellow colleagues at the National Institute of Standards and Technologies, and the larger single-photon community. We hope that this document will promote a community-wide consensus on the definitions herein and help facilitate the growth of the single-photon industry.

As the community makes use of this document, we expect additional gaps in terminology to be identified along with needs for further clarification. Please send such comments, suggestions, and concerns to singlephotondictionary@nist.gov. A link to the latest version will be available at https://www.nist.gov/itl/single-photon-sources-and-detectors-dictionary.

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1. List of Acronyms

- PNR: photon-number resolving
- N.B.: *nota bene (N.B.)*; Latin for “observe carefully”
- N/A: not applicable

1.1. For sources

- CAR: coincidences to accidentals ratio
- CW: continuous wave
- JSA: joint spectral amplitude
- (S)FWM: (spontaneous) four-wave mixing
- (S)PDC: (spontaneous) parametric down-conversion
- WCP: weak coherent pulse
- WCS: weak coherent state

1.2. For detectors

- SNSPD: superconducting-nanowire single-photon detector
- SPAD: single-photon avalanche diode
- TES: transition-edge sensor
- PMT: photomultiplier tube
- APD: avalanche photodiode
- VLPC: visible-light photon counter
- SDE: system detection efficiency
- POVM: positive operator valued measure
- FWHM: full width at half maximum
- PDP: photon detection probability
- DTF: dead time fraction

2. Single-Photon Sources

2.1. Introduction

2.1.1. Foreword

Before diving into detailed definitions, we begin with some context, motivation, and general issues that have guided our efforts to define relevant and self-consistent terms for characterizing the performance of single-photon devices. Often, when device performance is stated, parameters important for understanding device operation, and critical for comparing to other published results, are omitted, or when they are stated, the specific meaning of the definition may be unclear and one is left to guess the intended meaning of the metric presented. Some of the confusion is due to the significant overlap in terminology across a variety of related fields such as radiometry, photometry, quantum communication, and optics in general. Some examples are the term "brightness", which has multiple meanings, or the use of the term "photon counting detector" for detectors that can only distinguish zero photons from more than zero. To facilitate the development of quantum technologies, there is a need for a unified and self-consistent set of performance-parameter definitions. This need is of increasing importance as single-photon technology advances and diversifies, and as a quantum industry emerges.

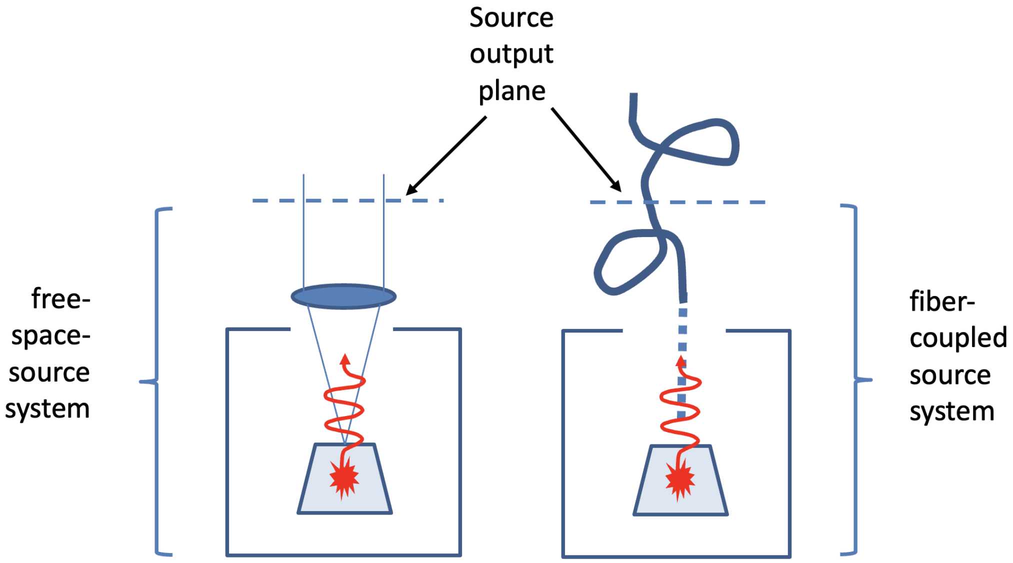

Figure 1. Examples of source output planes for free-space and fiber-coupled sources. While the choice of the output plane's location is somewhat arbitrary, it should be clearly stated. The optical path to the output plane may or may not contain various components such as lenses, spectral filters, and apertures, as well as pumping optics as might be required for quantum-dot or spontaneous parametric down conversion (SPDC) and spontaneous four-wave mixing (SFWM) sources.

2.1.2. On modes

By “well-defined mode,” we mean with respect to all possible degrees of freedom, i.e., temporal, spatial, spectral, polarization, etc. The term “single mode” is typically used in reference to some conveniently defined low-order mode to which other modes are orthogonal. When this term is used, the details of the mode shape should be stated. When a mode is defined only with respect to a particular degree of freedom, that should be clearly stated by using modifiers, as in “a well-defined spatial mode” or “a well-defined temporal mode.”

2.1.3. On Photon-number states vs. Fock states

For clarity, the term or “Fock state” is reserved for a state with a specific number of photons in a well-defined mode [9]. In practice, photons may be distributed over a variety of modes. The term “photon-number state” is an operational term that refers to the state detected by a photon-number-resolving detector, which may not properly resolve modes. Thus, all Fock states are photon-number states, but a photon-number state may be a mixture of Fock states in distinct modes.

2.1.4. Dictum on output plane (or surface)

The output plane (or surface) of a single-photon source or system must be defined when specifying metrics such as extraction efficiency or coupling efficiency. For example, a free-space source’s output plane might be defined as the outer surface of a component, such as a window, lens, or filter, whereas a fiber- or waveguide-source’s output plane might be specified within the guiding structure, which also defines the output mode(s). See diagram in figure 1.

2.2. Definition of sources

2.2.1. Single-photon sources

A single-photon source is a light source capable of emitting a single excitation of a mode, or a single excitation spread across several modes, of the electromagnetic field. This excitation is called a photon. The output of an ideal single-photon source will satisfy the autocorrelation condition $g^{(2)}(0) = 0$, where $g^{(2)}(0)$ is described below. A source with $g^{(2)}(0) < 1$ (anti-bunched) typically indicates that the source has some single-photon component. More strictly, $g^{(2)}(0) < 1$ requires some non-classical component and is a sufficient criterion for labeling a source as non-classical. A source is classified as non-classical based on its Glauber-Sudarshan representation [10].

In practice, when dealing with the possibility of more than one single-photon source (such as an ensemble of emitters), the threshold $g^{(2)}(0) < 1/2$ is used to define the source as being predominantly just one single-photon emitter [11].

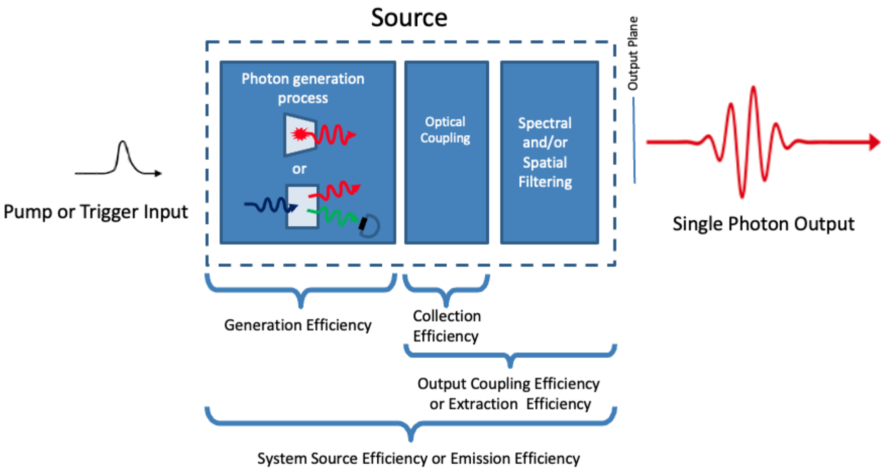

Figure 2. Illustration of conceptual components and sub-components of source efficiency. The order of optical coupling and spectral or spatial filtering need not necessarily be as illustrated and may not even be distinct. For example, some filtering may be inherent in the design of the generation process. We also note that optical coupling can be subdivided into terms such as optical collection at the first lens and optical transport through the rest of the system. A single quantum emitter and a heralded single-photon source are illustrated as examples of the single-photon generation process.

N.B. For emitters of higher-order photon-number states, the criterion $g^{(2)}(0) < 1/2$ does not apply.

The underlying physical processes for single-photon sources include:

- Optical nonlinearities, such as:
    Spontaneous parametric down-conversion (SPDC)
    Spontaneous four-wave mixing (SFWM)
- Emission from a single emitter, such as
    Ions
    Atoms
    Quantum dots
    Color-center defects
- Quantum-memory-based emission

2.2.2. Weak classical sources

A weak classical source is a faint or attenuated coherent source (e.g. a laser) or thermal (or pseudo-thermal) source and is commonly used as a substitute for a single-photon source. Such a source will always exhibit a second-order autocorrelation function $g^{(2)}(0) \geq 1$. Weak classical sources can be attenuated such that their probability of producing a single-photon output state is higher than their probability of producing multi-photon output states (though both will be smaller than the probability of a zero-photon, vacuum-state output). List of other related names:

- Weak coherent state (WCS)
- Weak coherent pulse (WCP)
- Weak classical source or state
- Attenuated or weak laser source
- Pseudo-single-photon source
- Pseudo-thermal state
- Weak thermal state

2.2.3. Probabilistic vs. deterministic single-photon source

Single-photon sources are often categorized as deterministic or probabilistic. These terms are used to distinguish the underlying photon-emission processes, and are not necessarily representative of the source's output properties. An example of a deterministic single-photon source is a single quantum system that is triggered (or excited or armed) by some controllable event and is guaranteed (or nearly guaranteed) to emit a single photon in response to the trigger, such as a single excitation of a quantum dot. A probabilistic single-photon source is one where the photon production mechanism is inherently probabilistic, e.g., those based on processes like spontaneous parametric down-conversion or spontaneous four-wave mixing, which are governed by Bose statistics [12, 13].

The use of these terms warrants a significant caveat: When referring to any real source, the difference becomes less clear. For example, a source built around a deterministic process still requires optics to collect the single-photon emission and those optics will introduce loss. Thus, an "inherently deterministic source" becomes, to some degree, probabilistic in its implementation. Similarly, an inherently probabilistic source can become more deterministic when paired with multiplexing techniques [8]. Thus, the terms probabilistic and deterministic should be used carefully and it is preferable to state the single-photon probability.

2.2.4. Single-emitter single-photon source

A single-emitter single-photon source is a source based on a single isolated quantum system, such as a single atom, color center, or quantum dot, which emits single photons after excitation.

2.2.5. Pulsed single-photon source

A pulsed single-photon source is a source whose single-photon-emission probability modulates between zero and some non-zero value. Note that the pump pulse duration is not the same as the duration of the single-photon emission because they are two distinct processes.

2.2.6. Source repetition rate

Source repetition rate is the rate of attempts to produce a single photon. This is distinct from the single-photon generation rate.

2.2.7. Continuous-wave single-photon source

Continuous-wave sources are sources whose single-photon-emission probability is intended to be constant over time. Note that the duration of a single photon's temporal mode is finite in continuous-wave sources.

2.2.8. Photon-pair source (or pair source or correlated-photon-pair source)

A photon-pair source is a source that creates photons two at a time. Typically, such sources are based on spontaneous parametric down-conversion (SPDC), spontaneous four-wave-mixing (SFWM), or a process involving a two-photon cascade. Such sources are often used as the basis of a heralded single-photon source or as a two-photon source. Measurements of both photons of a pair show non-classical correlation in some parameter.

2.2.9. Heralded single-photon source

A heralded single-photon source is a single-photon source that uses the detection of one photon of a pair to declare (herald, announce) the presence of the correlated (conjugate, partner) photon. The declaring photon is referred to as the herald (or heralding) photon, and the partner photon emitted from the source is referred to as the heralded photon. This is often a probabilistic source and can produce high-quality single photons, albeit at arbitrary times (although using pulsed sources can provide some order to that arbitrariness).

N.B. Sometimes "herald rate" is referred to as "heralding rate," but "herald rate" is preferred.

2.2.10. Herald(ing) event

A herald(ing) event is a detection event of the herald(ing) detector during an attempt or trial. Ideally, a herald(ing) event occurs when a herald photon, such as that from a pair source, is incident on the herald(ing) detector. A herald event could also be caused by a detector dark count or by light from another source incident on the detector.

N.B. A herald(ing) event may contain more than one photon.

2.2.11. Heralded event

A heralded event is an event conditioned on the detection registered by a herald(ing) detector.

2.2.12. Memory-based source

A memory-based source is a single-photon source in which a photon is stored in a memory or delay, and released on demand. The single photon may be stored in a controllable media such as a solid-state [14] or vapor ensemble [15, 16] or in a controllable delay or switched storage ring [17]. One early example of the latter is an "on pseudo-demand" single-photon source [18]. Similarly, such a source could be an n-photon source.

2.2.13. Blockade-based source

A blockade-based source is a single-photon source that relies on a "turnstile" mechanism (e.g., Rydberg blockade, strongly-coupled-cavity-based photon blockade) whereby only a single-photon or single-electron excitation is passed at a time through some media. This mechanism is distinct from memory-based sources in which a single photon is stored and released on demand [19, 20].

2.2.14. Multiplexed-based source

A multiplexed source is composed of several individual sources that are combined through switching to make a composite system with a single output that has higher overall single-photon performance, i.e., single-photon fidelity closer to one. Multiplexing is often used to combine probabilistic pair sources, typically using heralding and switching, in a way that results in a more deterministic source of photons [8]. Such multiplexing may use time, space, or frequency degrees of freedom or some combination thereof.

2.3. Efficiencies and rates

2.3.1. On probabilities, rates, and efficiencies

Probability, rate, and efficiency are often used somewhat interchangeably and without being accurately defined, and this can lead to confusion. While the definitions of probabilities (unitless) and rates (per unit time) may seem fairly clear, the closely related term efficiency may be defined as a unitless ratio, or can have units related to parameters such as pump power. Similarly, a rate is sometimes used as a probability (as in quantum bit error rate). This section addresses these sticky issues and proposes an organization of definitions that will help provide clarity and self-consistency in the context of a single-photon sources. We begin with discussion and definitions of probabilities and efficiencies.

When stating probabilities care must be taken to clearly define a “trial,” because probabilities in a physical system always imply a set of trials. In a pulsed system, a trial is often naturally defined by the pump pulse and the probability of generating a photon due to a pulse is generally understood. However, in continuous-wave (CW) operation, the trial needs to be explicitly defined. If a trial is difficult to define (as in some CW cases), it may be clearer to use rates instead of probabilities. Below we give specific examples of using both rates and probabilities to define efficiency-related terms.

N.B. Trial vs. Attempt: Though often used synonymously, we find it beneficial to emphasize the following distinction: An attempt is a physical process initiated for the purpose of generating a photon, while a trial is a logical event that is specified arbitrarily by the user and allows probability to be defined. For example, when attempting to generate a single photon using a continuous pump source, the attempt can be considered as continuous, whereas a trial can be defined by a stated time interval or, in the case of photon pair generation, the detection of a herald.

We categorize source efficiencies into two broad areas: those related to photon generation, and those related to transporting photons generated by a source to the source’s output where they can be used (See figure 2).

- Generation: Conversion of one resource into another resource (e.g., from input photons to output photons, or input power to output power). This conversion is not necessarily linear, for example in an FWM-based source where the output power P_{out} is proportional to the square of the input power, P_{in} (or “P_{pump}” is often appropriate) thus the units of these generation-related efficiency terms may vary.
- Transport: Output coupling efficiency η_{source}, as defined by $1 - \mathscr{L}$, where $\mathscr{L}$ is the optical loss and is defined as the output single-photon rate divided by the input single-photon rate, or their equivalent powers: $P_{\text{out}}/P_{\text{in}}$. In this example, “efficiency” is unitless and can also be defined as the output-coupling probability for a single photon. Note that for multi-photon states loss applies to each photon in that state independently.

Note that both generation and transport processes can be combined in terms such as “single-photon emission efficiency”.

N.B. All probabilities may be seen as “efficiencies,” but not all efficiencies are probabilities. For example, nonlinear conversion efficiency can be specified as pairs per second per pump-power squared, which is not unitless and is thus not a probability.

N.B. Here and throughout, the units of rate can be 1/s, as in events per second or photons per second, but not Hz due to the inherent stochastic nature of processes involved, rather than a periodic or cyclic function [21].

2.3.2. Generation efficiency (or single-photon generation efficiency):

Generation efficiency is an umbrella for terms used to define the probability of creating exactly one photon per trial, and possibly per some other parameter. In the context of sources, generation efficiency and generation rate are sometimes used interchangeably. This adds confusion related to the distinction between rate and probability, as described above. Possible generation parameters (that go in the denominator of the generation efficiency) include pump power (or pump-power squared for processes such as four-wave mixing (FWM)), pump pulse, time bin, spectral bandwidth, or mode (spatial, spectral, temporal, polarization).

Note: generation efficiency does not include losses associated with extracting the photon from the medium where it is generated. Generation efficiency is sometimes referred to as the “internal conversion efficiency,” where optical coupling losses into and out of the conversion medium are not included. The multitude of efficiency-related terms has been a source of confusion; care should be taken to carefully define the specific term(s) used.

We also note that one should be aware of the possible presence of multi-photon emission and its potential contribution to errors in evaluating the generation efficiency.

N.B. Generation efficiency is often associated with of the term “brightness,” which generates additional confusion as described below.

N.B. The term “generation efficiency” may also be used to describe generation of photon pairs as well as single photons.

Examples of generation efficiencies (“internal” may be added to any of these terms to emphasise that coupling losses are not included):

Generation Efficiency or Rate	per trial	as rate	Typical Use
per attempt	[unitless]	photons/s	any source
per time bin	[unitless]	photons/s	any source
per pump power	1/W	photons/s/W	heralded SPDC sources
per pump-power squared	1/W^2	photons/s/W^2	heralded SFWM sources
per solid angle	1/sr	photons/s/sr	sources with significant solid angle
per spectral band	1/nm	photons/s/nm	sources with broad spectral output
per pump photon	[unitless]	N/A	
per electron	[unitless]	N/A	quantum dots

Table 1. Examples of units for efficiencies and rates.

- Generation efficiency per pump power - typically used with pair sources
- Generation efficiency per pump power squared - typically used for FWM pair sources
- Generation efficiency per pump photon, or electron, or pump pulse
- Generation efficiency per spectral band
- Generation efficiency per steradian - typically used for sources whose emission covers some significant solid angle, rather than a single mode.
- Generation efficiency per attempt - typically used for optical- or electrical- pulse-pumped sources
- Generation efficiency per time bin – for a defined duration of a trial - typically used for CW sources

We note that these last two items can be unitless, but the “attempt,” “trial,” or “time bin” must be clearly defined, rather than leaving it to be understood or simply implied.

We also note that efficiencies may be per some additional parameter or multiple parameters, such as photon rate per pump power per bandwidth, as further listed in Table 1. In this table, the focus is on single-photon sources rather than pair sources. If pairs are of interest, that should be clearly stated (for instance, by using pair-generation probability).

While these ratios are designed to capture a simple linear dependence on the denominator, nonlinear effects (such as saturation) may occur and these linear relations are not universal. Thus, the parameters at which the metric was measured should be stated.

Illustrative examples:

- Example 1: SPDC pumped with a pulsed laser. The pump pulses naturally define the attempts and time bins. The generation efficiency of the photon pairs may be reported as pair-generation probability per pump energy (1/J) (or pairs generated per attempt per pump energy (pairs per Joule)). It is also acceptable to report pair-generation probability per average pump power (1/W) (or pairs generated per attempt per average pump power (pairs per Watt)).

- Example 2: SPDC pumped with a CW laser. As there are multiple possibilities for time scales (such as coherence time, or resolution of the timing electronics), the choice of time bin may not be obvious and can be application dependent. Given this ambiguity, we recommend reporting generation efficiency as a rate. For instance, for SPDC this can be pairs produced per second per pump power (pairs/s/W). Alternatively, generation efficiency may also be reported as a probability, such as the probability of down-converting a single pump photon into a photon pair.
- Example 3: An electrically-triggered quantum-dot single-photon source. The generation efficiency can be reported as photon probability per attempt (unitless), where the attempt is defined by the electrical trigger.

2.3.3. Single-photon generation probability

The probability of generating exactly one photon per specified trial in a defined mode or modes. When specifying the single-photon generation probability of a source, care should be taken to not include any coupling loss required for collection of the light; these losses are generally characterized as part of emission efficiency.

Single-photon generation probability is also a special case of generation efficiency that is defined per trial and is unitless.

2.3.4. Single-photon generation rate

Single-photon generation rate is the number of single photons generated by a source in a defined mode or modes per unit time. This does not include any losses after generation.

N.B. In practice, determining the generation rate typically requires measuring detection rates and correcting for losses, output coupling efficiencies, and detection efficiencies.

N.B. There is a subtlety concerning optical losses associated with the photon-generation process. For a source process based on a single quantum system like a quantum dot, optical losses should not be included in the generation efficiency. However, for a source based on photon-pair generation with a heralding detector, loss in the herald(ing) channel is inherently included in the generation efficiency because a photon whose herald is not detected is not counted as a successful photon generation event.

2.3.5. Single-photon probability

The single-photon probability is the probability of a photon in a defined mode or modes.

N.B. Single-photon probability should not be confused with the single-photon generation probability.

2.3.6. Multi-photon probability and n-photon probability

The n-photon probability is the probability of n photons in a defined mode or modes. The n-photon probability is the probability of a specific number of photons, while the multi-photon probability is generally understood as the total probability of more than one photon.

2.3.7. Multi-photon generation probability and n-photon generation probability

Like single-photon generation probability, the multi-photon generation probability is the probability of generating more than one photon per trial in a defined mode or modes. The n-photon generation probability refers to the generation probability of a specific number of photons, while multi-photon generation probability refers to a total probability of more than one photon.

2.3.8. Pair generation probability

The pair-generation probability is the probability of generating a photon pair in defined output mode(s) per specified trial. As in the case of single-photon generation probability, this parameter includes just the generation process and specifically excludes any coupling loss required for the collection of the light.

2.3.9. Background emission probability

Background emission probability is the probability, in a specified trial, of unwanted photons at the output of the source into the desired output mode(s). It does not include backgrounds originating outside the source (e.g. in the detector). Examples of background photons include fluorescence, Raman processes, thermal photons, etc. For heralded sources, background emission also includes photons that were created in a pair but ultimately are unheralded at the output due to loss in the herald(ing) channel/detection process.

N.B. In some cases, it may be useful to break down the total background probability into specific underlying processes. In such cases, the total probability and its component parts should be stated, along with any assumptions or additional measurements made.

2.3.10. Output coupling efficiency or extraction efficiency

Output coupling efficiency or extraction efficiency is the fraction of light generated by a source that is emitted into a defined spatial mode or modes at a defined output surface (see Dictum on output plane (or surface)). This includes all filtering and other losses from the point of generation to the output surface. (If spectral or temporal modes are of interest, then they also must be defined.)

N.B. For quantum dot sources, the “collection efficiency at the first lens” is an additional definition that is sometimes used, which effectively defines the output plane as the first lens.

N.B. For heralded sources, output coupling or extraction efficiency is synonymous to heralded efficiency.

2.3.11. Emission efficiency or total (source) system efficiency

Emission efficiency or total (source) system efficiency is the probability (often for a single-emitter source) that a photon is emitted at the output plane from the source in a specific mode and in a defined trial. It is the product of generation efficiency and output coupling efficiency.

2.3.12. Emission rate

The number of single photons emitted by a source in a defined mode at the output plane per unit time. It is the product of generation rate and output coupling efficiency.

2.3.13. Emission probability, or single-photon emission probability

See emission efficiency.

2.3.14. Extraction efficiency

See output coupling efficiency.

2.3.15. Brightness

While “brightness” has been used to describe the performance of single-photon sources, there are conflicting ways to define and quantify “brightness” in the single-photon community. In addition, and adding further confusion, the larger field of optics has a number of sub-fields that use a range of definitions for brightness. These various definitions overlap and often conflict and therefore, in the context of single-photon sources, we discourage the use of the term “brightness” without any modifiers. To avoid (and ideally resolve) this conflict, we recommend an appropriate term from Sec. 2.3, which contains self-consistent terms that apply to a broad range of single-photon sources.

2.3.15.1. Confusion surrounding the term “brightness”

The problem with “brightness” begins with the fact that it is used by many disparate fields, from the human-vision-related field of photometry, to radiometry, to many colloquial and popular uses; this issue is well documented. Beyond conflicts between fields, there are conflicts even within a field, such as single-photon applications. Examples of such problems include:

- Within the laser community, confusion surrounding the term “brightness” has been noted [22]
- The US Federal Glossary of Telecommunication Terms (FS-1037C) emphasizes that “brightness” relates to human perception [23]:
- Terms like “brightness” and “intensity” encompass a range of meanings that are larger than what is used in the single-photon community. For example, in many contexts multi-photon emission is “brighter” or “more intense” than single-photon emission but would be considered to have a lower single-photon “brightness.” In that case, using “brightness” to describe the intensity of the source is not consistent with having brightness represent the single-photon generation probability. Beyond this technical issue, brightness is often conflated with the “suitability” or “goodness” of a source, but this is subjective and dependent on the specific application, such as whether it is a single- or multi-photon application.
- Brightness may be a generation rate, which is normalized by some parameter(s).
- While brightness may be presented as a unitless probability in pulsed excitations (i.e., per trial) it is difficult to find an appropriate or equivalent definition for continuous-wave cases.

For these reasons we discourage the use of “brightness” (certainly it should not be used in the context of single-photon sources without modifiers) and instead recommend more robustly and specifically defined terms such as the list of probability and efficiency related terms elsewhere in Sec. 2.3.

We note that the adjective “bright” is sometimes used to describe a source, where a “bright source” is typically understood to be a source with high emission rate. However, because of the multiple connotations of “brightness,” we recommend against using the phrase “bright source,” but instead encourage describing the source as having a high emission rate or high efficiency, both of which are clear and well-defined.

2.3.15.2. Single-photon brightness

Because “brightness” is used differently in many different situations, we advise against its use as an unmodified term (see Brightness). “Single-photon brightness” is somewhat clearer but is still ambiguous. Thus, we also recommend against its use, preferring instead terms such as single-photon generation probability, single-photon emission probability, single-photon generation rate, etc., as they are clear and self-explanatory.

2.4. Efficiencies and rates - for heralded sources

Here we present terms related to heralded sources, which we summarize in Table 2. In a heralded source, the declaring photon is referred to as the herald (or heralding) photon, and the partner photon emitted from the source is referred to as the heralded photon.

2.4.1. Heralded sources with PNR and non-PNR heralding

In heralded sources, heralding may use either non-PNR or PNR detectors. Because a non-PNR detector only distinguishes between no photons and a non-zero number of photons, the heralding event would not differ if one or more photons are present in the heralded arm. Also, any dark-count or afterpulsing event in the heralding detector will result in a heralding event. Hence, heralding and heralded rates and efficiencies for non-PNR detectors will be affected by these situations.

In contrast, a PNR heralding detector distinguishes between number states so that a herald event can be chosen to be a specific number of detected photons. Due to detection loss and noise, an *n*-photon herald event may not be due to *n* photons.

We summarize the differences between PNR and non-PNR heralding and its impact on rates and efficiencies in Table 2.

	Non-PNR Herald Detector	**PNR Herald Detector**
Herald(ing) rate: The measured number of herald events per unit time from a pair source.	A herald event from a non-PNR detector counts any multi-photon outputs as just a single photon.	A herald event from a PNR detector is tagged with its photon number.
Heralded rate: The number of heralded (single) photons from the output of a pair source per unit time. N.B. The heralded rate will be lower than the herald(ing) rate due to losses in the heralded channel. N.B. The heralded rate does not include unheralded events (emissions not associated with a herald event).	Any event heralded by a non-PNR herald detector, including noise, is assumed to be a single photon.	An event from a PNR herald detector can be chosen to be a specific number of photons. N.B. Due to detection loss and noise, an *n*-photon herald event may not be due *n* photons.

Table 2. Herald(ing) - Heralded table.

2.4.2. Herald(ing) efficiency or herald(ing) probability

Herald(ing) efficiency (or herald(ing) probability) is the probability per trial to have a herald event (a detection event in the herald detector) in a pair source.

N.B. The heralding probability includes the herald detector's efficiency.

2.4.3. Heralded efficiency (or heralded probability)

Heralded efficiency relates to the probability per specified trial that a photon exists at the output plane when a herald event is registered. In different applications, though, it is important to know the heralded efficiency of the setup with or without the efficiency of detecting the heralded photon; whether or not the detection efficiency for the heralded photon is included should be clearly stated. Thus, we suggest the use of the two terms heralded source efficiency and heralded efficiency as detected.

N.B. A clear definition of the source output surface is required.

2.4.3.1. Heralded source efficiency

The heralded source efficiency is the probability the heralded photon is at the source output plane when a herald event is registered.

2.4.3.2. Heralded efficiency as detected

The heralded efficiency as detected is the heralded efficiency that includes the heralded-channel detector efficiency and any losses beyond the source output plane or surface. This is in contrast to heralded source efficiency, which excludes detection efficiency and other losses beyond the output plane of the heralded source.

2.4.3.3. Klyshko efficiency

While "Klyshko efficiency" is often used similarly to "heralded efficiency as detected," we believe it is useful to distinguish between the two terms. The Klyshko efficiency is an idealized case of the heralded efficiency as detected because it assumes no optical or detector backgrounds. Thus background would have to be subtracted to approach the idealized Klyshko efficiency [24–26].

2.4.4. Herald(ing) rate

Herald(ing) rate is a rate defined as the measured number of herald events per unit time from a pair source.

2.4.5. Heralded rate

Heralded rate is a rate defined as the number of heralded events from the output of a pair source per unit time.

The heralded rate does not include unheralded events (emissions not associated with a herald event).

N.B. The heralded rate will be less than or equal to the herald rate.

2.5. Characterization metrics other than signal efficiencies, rates, and probabilities

2.5.1. Coincidences-to-accidentals ratio (CAR)

Coincidences-to-accidentals ratio (CAR) is the ratio of the true-coincidence count rate to the accidental-coincidence count rate from a pair source or heralded source: $\mathrm{CAR} = (C-A)/A$, where C is the total (raw) coincidence rate, $C-A$ is the coincidence rate due to detection of photons created as a pair, sometimes called the true coincidence rate, and A is the measured accidental-coincidence-count rate [8]. We note that "accidentals" refers to coincident detections not due to photons created as a pair.

Because these rates depend critically on the width of the coincidence detection window, the width of the window should be specified, as well as the coincidence rate in that specified window.

In general, the CAR is related to the second-order cross-correlation between the heralding and heralded outputs of a pair source. In the special case of a background-free single-mode source, the CAR is related to the squeezing parameter, and at low squeezing CAR can be approximated with the heralded autocorrelation function.

2.5.2. Fidelity of a single photon (unheralded or heralded)

Fidelity of a single photon is the overlap of the output state of a single-photon source to a single photon in a single mode, $|1\rangle$. $\mathscr{F} = \langle 1|\hat{\rho}|1\rangle$, where $\hat{\rho}$ is the density matrix of the state. The reference location and any corrections applied to calculate the extracted fidelity should be specified, e.g., at the source output, at the detector, correcting for system detection efficiency, etc., along with any assumptions made. This omits multi-mode states, which may sometimes be of use.

N.B. Related term: Infidelity: $\overline{\mathscr{F}} = 1-\mathscr{F}$.

2.5.3. Indistinguishability

The indistinguishability of two unentangled (separable) photons is the normalized overlap integral, $I = |\langle\psi_1|\psi_2\rangle|^2$, of their wavefunctions, $|\psi_1\rangle$ and $|\psi_2\rangle$ [27]. Perfect indistinguishability, where the overlap integral $I = 1$, implies the photons' ability to completely interfere with each other, e.g., in a Hong-Ou-Mandel (HOM) interferometer. It should be stated whether indistinguishability is measured for subsequent pulses of the same source or for different sources [27–30].

N.B.: In cases where the source exhibits non-stationary behavior, such as random fluctuations in its photon-emission probability or blinking, the time-delay-dependent HOM interference should be reported rather than just the interference visibility at zero time delay.

2.5.4. Coalescence

Coalescence is a phenomenon where single photons entering the two input ports of a beamsplitter tend to bunch as they exit the output ports of the beamsplitter. The degree to which they bunch quantifies the coalescence. For indistinguishable single-photons that arrive simultaneously the bunching is complete and the coalescence is 1, while for completely distinguishable inputs the coalescence is 0. Because coalescence applies only to single photons, statistical effects of multi-photon emission must be excluded for practical single-photon sources with a multi-photon component [31].

The coalescence probability, C (which ranges from 0 to 1), is related to the visibility of Hong-Ou-Mandel [28] interference of single photons [32] and is typically measured by comparing a pair of distinguishable and indistinguishable inputs in a HOM measurement: $C = (g^{(2)}(0)_{\text{dist}} - g^{(2)}(0)_{\text{indist}})/g^{(2)}(0)_{\text{dist}}$, where the subscripts refer to $g^{(2)}$ for distinguishable and indistinguishable inputs.

2.5.5. Multi-photon component

Multi-photon component is the fraction of the total photon state made up of Fock states of more than one photon.

2.5.6. Mean photon number

The mean photon number μ is the average number of photons per trial (or time period): [33]

$$\mu = \sum_{n=0}^{\infty} n p_n \tag{1}$$

where p_n are the probabilities of n-photon states. For a source with Poisson statistics p_n is given by:

$$p_n = \frac{\mu^n e^{-\mu}}{n!}. \tag{2}$$

For a thermal source p_n is given by:

$$p_n = \frac{\mu^n}{(\mu+1)^{n+1}} \tag{3}$$

2.5.7. Output noise factor

Output noise factor is the ratio of the background counts to the total output counts (sum of background counts and true counts) in the output mode of a photon source.

2.5.8. Schmidt number

Schmidt number is a representation of the effective (minimal) number of thermal modes (spatial and/or temporal-spectral) into which photons are emitted. It is defined by $\aleph = 1/\sum\lambda_i^2$, where λ_i are the weights of individual modes resulting from a Schmidt decomposition of an entangled state [34], where $\lambda_i = \mu_i/\sum\mu_i$, μ_i is the mean photon number of the thermal mode i that describes the field (c.f. Eq. 3). Note that the Schmidt number is not to be confused with the total number of occupied optical modes found from Schmidt decomposition [27, 30].

2.5.9. Source timing jitter

Source timing jitter is the variation of the emission time of the temporal envelope of the output pulse. It is distinct from the variation due to inherent quantum mechanical uncertainty within that envelope.

2.6. Second-order correlation function, $g^{(2)}$

2.6.1. General definition

The second-order correlation function, $g^{(2)}$, is a description of the spatial and temporal correlation of the electromagnetic field(s) either between a pair of modes or within a single mode. The most general form for $g^{(2)}$, can be written as [10]

$$g_{j,k}^{(2)}(\vec{r}_1,t_1,\vec{r}_2,t_2) = \frac{\langle \hat{a}_j^\dagger(\vec{r}_1,t_1)\hat{a}_k^\dagger(\vec{r}_2,t_2)\hat{a}_j(\vec{r}_2,t_2)\hat{a}_k(\vec{r}_1,t_1)\rangle}{\langle \hat{a}_j^\dagger(\vec{r}_1,t_1)\hat{a}_j(\vec{r}_1,t_1)\rangle\langle \hat{a}_k^\dagger(\vec{r}_2,t_2)\hat{a}_k(\vec{r}_2,t_2)\rangle}, \tag{4}$$

where j and k refer to the modes measured at the locations $\vec{r}_1$ and $\vec{r}_2$ at the times t_1 and t_2, and $a_j^\dagger$ and a_j are the creation and annihilation operators for modes j, k (note, $\hat{a}(\vec{r},t)$, $\hat{a}^\dagger(\vec{r},t)$ are Fourier transforms of $\hat{a}(\vec{k},\omega)$, $\hat{a}^\dagger(\vec{k},\omega)$, respectively.) For $j = k$, this represents a second-order autocorrelation that is useful for characterizing a single-photon source. When $j \neq k$, the cross-correlation function is suitable for describing the joint temporal and spatial properties of pair and/or multi-mode sources, e.g., joint temporal intensity distribution.

There are nuances in the use of the above equation for the characterization of single-photon sources. For example, these nuances lead to distinguishing definitions for the second-order correlation function for CW and pulsed single-photon sources.

N.B. When stating $g^{(2)}$ measurement results, any corrections or adjustments due to effects such as detector background or dark count rates, should be clearly indicated.

2.6.2. $g^{(2)}$ for CW single-photon sources

For a single-photon source with stationary (unchanging in time) statistics, such as a CW source, the second-order correlation function's properties only depend on the time delay $\tau = t_2 - t_1$.

$$g^{(2)}(\tau) = \frac{\langle \hat{a}^\dagger(t)\hat{a}^\dagger(t+\tau)\hat{a}(t+\tau)\hat{a}(t)\rangle}{\langle \hat{a}^\dagger(t)\hat{a}(t)\rangle^2}, \tag{5}$$

where, for simplicity, the subscript "1" of t_1 is omitted. Variants specific to pair sources are the heralded $g^{(2)}_{\mathrm{h}}(0)$, measured conditioned on a heralding event, and the unheralded $g^{(2)}_{\mathrm{unh}}(0)$, measured unconditionally. Note that pulsed sources are not stationary, so special treatment is required.

Note that pulsed sources are not stationary, so a special treatment is required.

2.6.3. $g^{(2)}$ for pulsed sources

For a periodic pulsed source with a period T, $|a(t)\rangle = |a(t+MT)\rangle$, where M is an integer enumerating the pulses. Therefore, the second-order correlation of a single-mode source in a general form reads:

$$g^{(2)}(\Delta M, \tau_1, \tau_2) = \frac{\langle \hat{a}^\dagger(MT+\tau_1)\hat{a}^\dagger((M+\Delta M)T+\tau_2)\hat{a}((M+\Delta M)T+\tau_2)\hat{a}(MT+\tau_1)\rangle}{\langle \hat{a}^\dagger(MT+\tau_1)\hat{a}^\dagger(MT+\tau_1)\rangle\langle \hat{a}((M+\Delta M)T+\tau_2)\hat{a}((M+\Delta M)T+\tau_2)\rangle}, \tag{6}$$

where ΔM is an offset counting the number of pulses between the two detection events, $0 \le \tau_1, \tau_2 < T$ are time offsets between the detection events and the start of the prior period (cf. [35]). To describe the correlation between outputs of a pulsed source, integration over τ_1, τ_2 is common. In doing so, the integration limits for τ_1 and τ_2 must be identical. This discrete version of $g^{(2)}$ reads [7]:

$$g^{(2)}(\Delta M) = \frac{\langle \hat{a}^\dagger(M)\hat{a}^\dagger(M+\Delta M)\hat{a}(M+\Delta M)\hat{a}(M)\rangle}{\langle \hat{a}^\dagger(M)\hat{a}^\dagger(M)\rangle\langle \hat{a}(M+\Delta M)\hat{a}(M+\Delta M)\rangle}. \tag{7}$$

N.B. Note that in literature the $g^{(2)}$ of pulsed sources is often measured as a function of τ, c.f. $g^{(2)}$ for CW sources. In this case, an extra averaging is performed over $\tau_2 - \tau_1 = \tau$ isolines, which does not directly correspond to underlying physical processes in pulsed sources. For example, there is no expectation that the shape of the zero-offset peak ($\Delta M = 0$) should be the same as other peaks, because the zero-peak may be driven by quantum dynamics, whereas other peaks are uncorrelated (coincidental) detection events [31].

2.6.4. $g^{(2)}(\tau = 0)$

The second-order correlation of a single-photon source with itself, $g^{(2)}(\tau = 0)$ (also often written $g^{(2)}(0)$), where $\tau = t_2 - t_1$, is an important quantity that can be used to characterize the photon number statistics of a state of light. $g^{(2)}(\tau = 0)$ is related to single-photon purity. In this special case, $\vec{r}_1 = \vec{r}_2$, the spatial modes are identical, $j = k$, and $t_1 = t_2 = t$. Thus, Eq. 4 reduces to: [7]

$$g^{(2)}(0) = \frac{\langle \hat{n}(t)(\hat{n}(t) - 1) \rangle}{\langle \hat{n}(t) \rangle^2}, \tag{8}$$

where $\hat{n}$ is the photon-number operator.

We relate photon-number statistics with $g^{(2)}(0)$. For three common source statistics, the functional forms of second-order correlations are distinct:

- For a source with Poisson statistics, the second-order correlation equals 1 and is independent of τ. The arrival or detection of any one photon is independent of the time of arrival or detection of any other photon.
- For a source with thermal statistics, the likelihood of a photon arrival event is increased near the arrival of another photon (bunching). For a single-mode source with thermal statistics $g^{(2)}(0) = 2$.
- Finally, a source designed to emit a single photon at a given time necessarily has a lower likelihood of emitting a second photon at the same time as the first photon. For any single-photon state $\hat{n} = 0$ or 1, and Eq. 8 reduces to $g^{(2)}(0) = 0$. The second-order correlation for an ideal single-photon source is zero at $\tau = 0$.

In general, it can be shown that $g^{(2)}(0) < 1$ is a sufficient condition for the state to be nonclassical. In addition, $g^{(2)}(0) < 1/2$ is often defined as the threshold for a single photon source as opposed to more than one single photon source [11].

We note also that the correlation treatment depends on the type of source, specifically whether it is CW or pulsed. In practice, this function is measured in a specified time-bin, defined either as $|t_1 - t_2| < \tau_0/2$ or floor(t_1/τ_0) − floor$(t_2/\tau_0) = 0$, where τ_0 is a time interval that can, for example, include the entire single-photon wavefunction for pulsed sources, and floor(x) indicates rounding down to the nearest integer.

2.6.5. Single-photon purity ($g^{(2)}(0)$)

Single-photon purity, $\mathscr{P}$, is a metric characterizing the extent to which a single-photon source emits more than one photon. It is closely related to the value of the second-order autocorrelation function at zero time delay $g^{(2)}(\tau = 0)$, specifically, $\mathscr{P} = 1 - g^{(2)}(0)$ [36]. Note that with photon bunching it is possible for the single-photon purity to be negative.

N.B. The single-photon purity should not be confused with the quantum state purity that is defined as $\mathscr{P}_\mathrm{q} = \mathrm{Tr}\{\hat{\rho}^2\}$ [37], which distinguishes pure states from mixed states (where $\hat{\rho}$ is the density matrix of the state). For example, the Fock state $|2\rangle$ has $\mathscr{P}_\mathrm{q} = \mathrm{Tr}\{\hat{\rho}^2\} = 1$, but is not a pure single-photon state.

2.6.6. Second-order cross-correlation $g^{(2)}$, or joint temporal intensity (distribution)

The $g^{(2)}$ can be used to describe correlations between different light fields, particularly those related through some underlying physical process. It is also referred to as joint temporal intensity in cases where it is useful to describe simultaneous emission of photons, for example, from a SPDC or SFWM pair source, subsequent emission of photons from a cascade source, or some more complicated distribution due to memory/storage processes.

2.6.7. Conditional second-order auto-correlation function $g^{(2)}$

Conditional $g^{(2)}|_{\mathrm{X}(t)}$ describes the state of the light field when a certain condition $\mathrm{X}(t)$ has occurred. Typically, the condition is a detection of a heralding photon at time t emitted from a probabilistic (pair) source using SPDC or FWM. This auto-correlation is given by [38]

$$g^{(2)}_{\quad \mathrm{X}(t)}(\Delta M, \tau_1, \tau_2) = \frac{\langle \hat{a}^\dagger(t_i+\tau_1)\hat{a}^\dagger(t_j+\tau_2)\hat{a}(t_j+\tau_2)\hat{a}(t_i+\tau_1)\rangle_{j-i=\Delta M}}{\langle \hat{a}^\dagger(t_i+\tau_1)\hat{a}(t_i+\tau_1)\rangle_i \langle \hat{a}^\dagger(t_j+\tau_2)\hat{a}(t_j+\tau_2)\rangle_j}, \tag{9}$$

where t_i, t_j are times when the conditional events $\mathrm{X}(t)$ occur, and the averaging is done over all such events; $\tau_1 = t_1 - t_i$ and $\tau_2 = t_2 - t_j$ t_1 and t_2 are defined as in Eq. 4. Formally, this equation is similar to Eq. 7, but instead of periodic emission attempts of a pulsed source, events $\mathrm{X}(t)$ occur at random times. Instead of periodic time intervals, the first argument of this function, ΔM, uses the enumerated events that satisfy condition X. Therefore, ΔM in 7 is a time interval (measured by a periodic process) whereas ΔM in 9 is not a time interval. Integration over τ_1 and τ_2 can be used to obtain the discrete version of the auto-correlation, similarly to Eq. 7:

$$g^{(2)}_{\quad \mathrm{X}(t)}(\Delta M) = \frac{\langle \hat{a}^\dagger(I)\hat{a}^\dagger(J)\hat{a}(J)\hat{a}(I)\rangle_{j-i=\Delta M}}{\langle \hat{a}^\dagger(I)\hat{a}^\dagger(I)\rangle\langle \hat{a}(J)\hat{a}(J)\rangle}, \tag{10}$$

where I, J label integration areas (histogram peaks) around i, j occurrences of $\mathrm{X}(t)$.

Probabilistic single-photon sources typically have classical statistics when the condition (detection of a heralding photon) is ignored. However, their statistics become similar to a single-photon source if the autocorrelation is conditioned on the detection of a heralding photon. Note that probabilistic sources cannot achieve unit purity, because the probability of generating an extra pair of photons does not depend on the condition of generating one pair.

N.B. The unconditional $g^{(2)}$ applied to one of the outputs of the probabilistic source in some cases can be used to verify the number of modes in the output. Particularly in SPDC and FWM, the unconditional $g^{(2)}(0) = 1 + 1/\aleph \geq 1$, where $\aleph$ is the Schmidt number (the effective number of thermal modes) of the source's output, whereas the conditional $g^{(2)}(0) < 1$.

2.6.8. N-order correlation function, $g^{(N)}$

Similar to the second-order correlation function, higher-order correlations can be defined. These can be relevant for sources with significant multi-photon emission.

N.B. Although it is typically the case that conditional correlation functions of $(N-1)^{\text{th}}$ order and non-conditional correlation functions of the N^{th} order both require N^{th}-order coincidence measurements, at least one argument of those correlation functions is different: a time interval in case of the unconditional $g^{(N)}$ vs. a difference in condition event numbers for the conditional $g^{(N-1)}|_{X(t)}$.

2.7. Other correlation metrics

2.7.1. Joint spectral amplitude (JSA)

The joint spectral amplitude (JSA) of a source of photon pairs describes the frequency correlations within the spectral distributions of photons in a pair. It can be used to describe the two-photon wavefunctions as in the equation below, where $f(w_1, w_2)$ is the JSA.

$$|\mathrm{SPDC}\rangle = \int\int d\omega_1 d\omega_2 f(\omega_1, \omega_2) \hat{a}^{\dagger}_{\omega_1} \hat{a}^{\dagger}_{\omega_2} |0\rangle \tag{11}$$

A common use of the JSA is to determine the Schmidt number, of the photons in the pair state produced. Related terms are separability and factorizability [30], which are closely related to the field of entanglement and are beyond the current scope of this document.

2.7.2. Joint spectral intensity (JSI)

Joint spectral intensity (JSI) is the magnitude squared of the joint spectral amplitude (JSA), i.e., $\mathrm{JSI} = |\mathrm{JSA}|^2$

N.B. While alternative terms such as joint spectral distribution and joint temporal distribution are sometimes used, their use is discouraged, as the use of “distribution” in those instances does not specify whether intensity or amplitude is meant.

2.7.3. Joint photon-number distribution

The joint photon-number distribution represents the correlation of photon numbers of two outputs of one or more source(s).

2.7.4. Joint temporal intensity

See second-order cross-correlation, $g^{(2)}$.

2.8. Squeezing and its relation to single-photon generation

2.8.1. Single-photon sources and squeezing

In general, squeezing is the reduction in uncertainty in one variable, such as quadrature, phase, or photon number, at the expense of an increase in uncertainty of its conjugate variable, while maintaining the product of the two (the Heisenberg uncertainty limit) [39]. For example: $\Delta x \Delta p \geq \hbar/2$. Its primary application to single-photon generation is the use of two-mode squeezed vacuum from SPDC or FWM, which can be used to generate single photons with high probability via heralding (see multiplex-based sources). Below we define some squeezing-related terms relevant to the generation of single photons.

2.8.2. Single-mode squeezed vacuum

Single-mode squeezed vacuum is a state whose uncertainty in one quadrature of the field is reduced (squeezed) and is smaller than the value of the vacuum state (and the uncertainty in its conjugate quadrature must be increased to obey the uncertainty principle). It is referred to as a vacuum state because the mean value of both quadratures is zero, however, its mean photon number is not. Squeezed vacuum is typically realized by the production of photon pairs into a single mode, generated via an SPDC or FWM process. When the mean photon number is small, the degree of squeezing is small. In the ideal case, which assumes no losses, the photon number distribution of such a state consists only of even photon numbers.

2.8.3. Two-mode squeezed vacuum

Two-mode squeezed vacuum is the production of photon pairs into two distinct modes, typically from an SPDC or FWM source. The photon numbers per trial in each mode are highly correlated and lead to observation of difference-photon-number squeezing, while excess noise is seen in the photon-number sum. With heralding, a source of two-mode squeezed vacuum can be used to generate single photons with high probability.

2.8.4. Squeezing parameter

Squeezing is typically parameterized in terms of one or two modes and the squeezing strength λ_{sq} (which ranges from 0 to 1), and for two mode squeezing it is defined for the output-beam wavefunction as [40]:

$$|\psi\rangle = \sqrt{1-\lambda_{\text{sq}}^2} \sum_{n=0}^{\infty} \lambda_{\text{sq}}^n |n,n\rangle \tag{12}$$

with the squeezing parameter r contained in the squeezing strength $\lambda_{\mathrm{sq}} = \tanh(r)$ and n being the number of signal and idler photons that are in each single mode. The probability of generating two photon pairs is directly linked to the probability of generating one pair, namely, its square [8]. In all sources, there exists some loss between the generation of the squeezed states and where they are measured, thus squeezing should be specified as "as measured" or "as inferred" back to the point of generation (stating all the loss and background assumptions made). The mean photon number of a two-mode squeezed state depends on the squeezing parameter: $\mu = \sinh^2(r)$.

3. Single-Photon Detectors

3.1. Single-photon detector

A single-photon detector is a device that is able to produce a measurable output signal, distinguishable from noise, due to a single photon incident on the detector's input plane (see Dictum on input plane). We acknowledge that while there is a continuum to the definition of "measurable," most single-photon-detection applications require some reasonable signal-to-noise ratio in the signal produced from a single incident photon.

In some cases the term "sensor" has been used to refer to an entire single-photon detection system, while in other cases the term "sensor" has been used to refer solely to the sub-component with which light interacts, distinct from other parts of the system. This usage varies in different fields, and for this reason the use of the term "sensor" is discouraged.

3.1.1. Examples of single-photon detectors

Examples of single-photon detectors include:

- superconducting nanowire single-photon detector (SNSPD)
- transition edge sensor (TES)
- photomultiplier tube (PMT)
- single-photon avalanche diode (SPAD)
- avalanche photodiode (APD)
- visible-light photon counter

Note that APDs and SPADs are generally not considered to be synonymous; SPADs are APDs specifically designed for single-photon sensitivity enabled by Geiger-mode operation.

3.1.2. Dictum on input plane (or surface)

The input plane of a single-photon detector or single-photon detection system, Fig. 3, must be clearly defined when specifying detector metrics such as efficiency or dark count rate. For example: a free-space detector's input plane might be defined as the outer surface of a component, such as a specific surface of a window or lens; a fiber- or waveguide-coupled detector's input plane might be within the fiber/waveguide, or the surface of the active area of the single-photon detector.

3.1.3. Dictum on input angle (or solid angle)

The detector's angular acceptance and whether it is multimode or single mode, should also be specified.

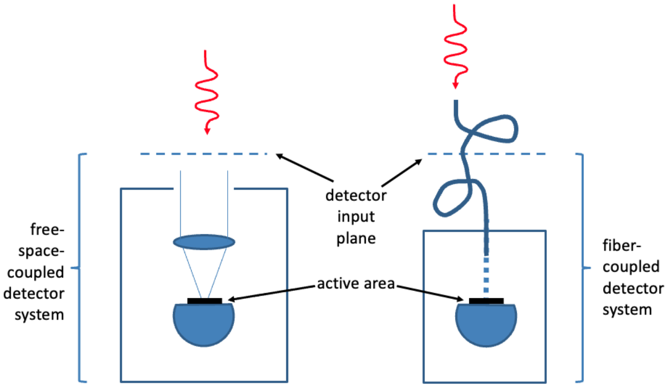

Figure 3. Examples of detector input planes shown for free-space- and fiber-coupled detectors. While the input plane location is somewhat arbitrary, it should be clearly stated. Optical paths may or may not contain components such as lenses, spectral filters, apertures, and fibers.

3.1.4. Active area

The active area of a detector is the area of the optically sensitive region of the detector and is defined by the projection of the absorption region onto the input plane (or surface). See Fig. 3.

3.2. Photon-number-resolving detectors

A photon-number-resolving (PNR) detector produces an output that is inherently representative of the number of photons input to the detector (over some range of photon numbers). From that output, an integer number of detected photons can be determined with some level of uncertainty, usually significantly less than one.

N.B. Sometimes these detectors are referred to as "intrinsic photon-number-resolving detectors" to distinguish them from quasi-photon-number-resolving detectors.

3.3. Non-photon-number-resolving detectors

Non-photon-number-resolving detectors are devices that typically operate as a "photon versus no-photon" detector (with some threshold used to distinguish between photon and no photon) are non-photon-number resolving (non-PNR). Often such detectors are also referred to as "click detectors," "click/no-click detectors," "on/off detectors," or "threshold detectors."

3.4. Quasi-photon-number-resolving detectors

A quasi-photon-number-resolving (quasi-PNR) detector is a device based on temporally and/or spatially multiplexed detectors (such as in a detector array or through the use of a beamsplitter-detector tree) that individually have no photon-number-resolving capability, and this may affect the n-photon efficiency. Such systems work best when the number of photons is much lower than the number of multiplexed detectors.

3.5. Detector tomography

Detector tomography is a detector characterization that allows reconstruction of a single-photon detector's positive operator-valued measure (POVM). This method is often used to determine the full output distribution of the detector for specific input photon numbers [7].

3.6. Positive operator valued measure (POVM)

A POVM is an ensemble of positive semi-definite matrices that sum to the identity matrix. A phase-independent single-photon detector's POVM is a single matrix that represents the probabilities of all the possible detector outcomes dependent on the input optical field, particularly the input photon number (0, 1 , 2, . . .). The diagonal elements of the POVM matrix are the probabilities of n incident photons being detected as n photons and can be simpler to refer to rather than the entire POVM matrix. These individual elements are sometimes referred to as the n-photon efficiency or the n-photon fidelity [41]. To avoid confusion with other uses of fidelity, the former is preferred.

N.B. The POVM of a phase-independent detector relates the output of a detector (typically a PNR output) to the input photon number and may be represented by the phase independent terms (diagonal elements in the number-state basis). While the general framework of POVMs does include phase-dependent outcomes, most single-photon detectors are not phase sensitive [7, 42].

3.7. Detection event

A detection event is the occurrence of a measurable output signal distinguished from noise from a single-photon or PNR detector. A detection event need not be initiated by a photon. A detection event may also be referred to as a "count."

3.8. Single-photon-detector output signal

Single-photon-detector output signal is a classically measurable electrical signal from a single-photon or PNR detector.

3.9. Detector timing jitter

Detector timing jitter is the variation in the time delay between when light arrives at the detector input plane and when a signal is output from the detector (this overall time delay is known as detector latency). As the details of the distribution of timing jitter are important for various applications, detector timing jitter is quoted in multiple ways and thus should be clearly specified. Most common are full width at half maximum (FWHM), and full width at 1% maximum (FW1%M). In the literature, timing jitter is also referred to as "detector timing resolution." Care should be taken to distinguish between timing-variation contributions due to the optical input and variations due to the detector or the timing electronics.

3.10. Detector timing resolution

See detector timing jitter.

3.11. Detector latency

Detector latency is the time delay between when a photon arrives at the detector input plane and when a signal is output from the detector.

3.12. Single-photon-detector output electrical noise

The single-photon-detector output electrical noise refers to noise fluctuations in the signal output from a detector or detection system. This is the noise from which the detection signal is discriminated, for example, at the input of a comparator (see discrimination threshold).

Output electrical noise is a concern when discriminating analog signals from no detection or from among photon-number values. Examples of these fluctuations may include electrical noise that becomes an effective noise floor, or variations in the gain of the electrical portion of the detection system. Measurement times or bandwidths should be specified for noise measurements. This output electrical noise is distinguished from other single-photon-detector noise (see single-photon-detector noise).

3.13. Discrimination threshold

Discrimination threshold is a criterion for distinguishing detection events in the output of a detector. Typically, a discrimination threshold is used to identify detection events in an analog signal, and thus to generate a digital count (e.g., to distinguish one or more from zero, or to distinguish n from m in a photon number resolving detector). Note: discrimination thresholds need not be just a single measured parameter, but may be a compound parameter. Some detectors, such as those with number-resolving capability, will have multiple relevant thresholds to distinguish between specific numbers of photons registered.

3.14. Double counts

Double counts refers to a detection event due to a single photon that causes at least two counts on a photon counting circuit. This can occur due to noise on a detector's output signal in combination with a discrimination threshold circuit, causing a single detection event to produce a signal that crosses the discrimination threshold multiple times. Double counting can also occur due to poor termination of electrical cabling, resulting in the reflection of electrical output pulses. Double counting is generally due to issues external to the detector itself.

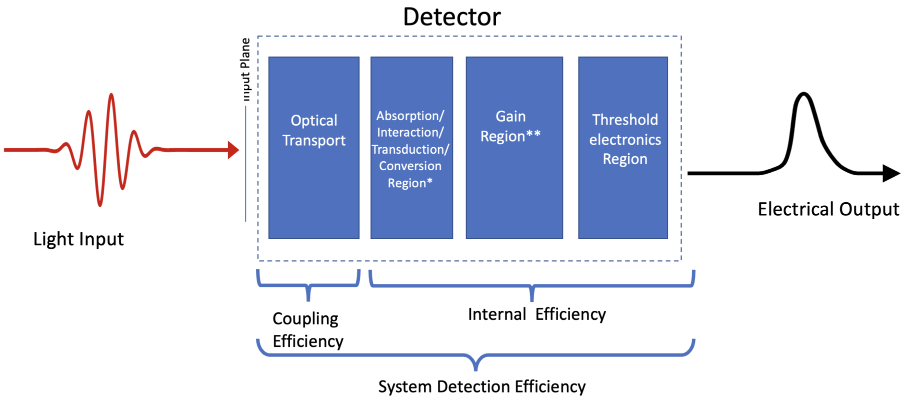

Figure 4. Illustration of conceptual components and sub-components of detection efficiency.
*Phenomena related to quantum efficiency and absorption efficiency happen here.
**Phenomena such as those related to avalanche or triggering efficiency in a SPAD or breaking of superconductivity in an SNSPD happen here

3.15. Detection efficiency

Detection efficiency is typically used to define some portion of the system detection efficiency; it is the probability of a single-photon detector to produce a measurable signal at some specific point in the circuitry due to one photon incident on the detector's input plane. Of course, efficiency depends on the wavelength of the incident photon and thus the wavelength (or wavelength range) should be specified. Detection efficiency also depends on the detection rate, particularly at high count rates, and thus the count rate at which the efficiency is measured should be specified. One particularly useful approach is to use the detection efficiency extrapolated to zero incident flux, the "zero-flux efficiency." This value has practical utility as it can be estimated without any assumptions on the specific operation of the detector. On the other hand, details of the operation can be used to extract an idealized efficiency of the detector when it is in a fully armed state (i.e., not affected by a prior detection event).

Care must be taken to distinguish "detection efficiency," which often refers to just a portion of a detector system, from "system detection efficiency," as often "system detection efficiency" is what is meant when "detection efficiency" is used. Detection efficiency is often sub-divided as the product of a variety of efficiencies and phenomena relevant to the detector under consideration, with examples listed below.

- Coupling efficiency:

The probability that a photon incident on the detector's input plane enters the detector's absorption region.

- Absorption efficiency:
  The probability that a photon coupled to the absorption region is absorbed therein. Hypothetically the absorption process can be distinct from the transduction process, for example in a detector that relies on recoil instead of absorption. Also note that the 2-D projection of the absorption region on the input plane is often what is meant by the detector's "active area."
- Internal efficiency:
  The probability that an absorbed photon produces a measurable output signal at a specified point in the detection system (which could be the output).
- Photon detection probability (PDP):
  Historically used with SPADs, this term is synonymous with internal efficiency, but is easily confused with "system detection efficiency." Its use is discouraged in favor of "internal efficiency."
- Triggering efficiency:
  Typically for single-photon avalanche diodes; the probability that a photo-generated carrier(s) triggers a detectable avalanche. Two equivalent terms are "breakdown probability" and "avalanche probability."

N. B. The corrected detection rate is typically used to calculate the detection efficiency.

N. B. For all the efficiencies in this document the modifier "spectral" can be used to explicitly include variations of efficiency(ies) with wavelength, but care should be taken to avoid confusion with spectral-density-related terms.

3.16. System detection efficiency (SDE)

System detection efficiency is the probability of a complete single-photon detection system to indicate a detection event due to one photon incident at the system's input plane (see "Input plane" dictum). This efficiency includes, but is not limited to, optical path loss, quantum efficiency of the active area, and electronic signal-detection efficiencies. It is distinguished from "detection efficiency," which can be the efficiency of just one component of the entire detection system, such as the active area without any optical-path or electronic-readout efficiencies. Operation conditions, such as detector count rate, should be specified when reporting a system detection efficiency. As efficiency is dependent on operating conditions and history, relevant conditions should be specified. One preferred practice is to extrapolate to an efficiency at zero count rate (the zero-flux efficiency) and then provide count-rate-dependent corrections (see dead-time fraction).

N. B. System detection efficiency is the product of the coupling efficiency and the internal efficiency.

3.17. Zero-flux efficiency

Zero-flux efficiency is the detection efficiency extrapolated to the zero-light or zero-flux level. This is a useful benchmark for comparison because it is less arbitrary than the efficiency at some specific count rate and it avoids count-rate dependent complications.

3.18. Quantum efficiency

Quantum efficiency is the probability of transducing a photon to some primary quantum excitation. Examples of primary quantum excitations include generation of: an electron-hole pair (as in a SPAD or analog photodiode) or a photoelectron (as in a PMT); a hot electron in a superconducting detector; an atomic excitation; or a recoil in an opto-mechanical device. In most cases, the quantum efficiency is the same as the absorption efficiency.

N.B. Quantum efficiency differs from internal efficiency in that the internal efficiency includes both the gain and transduction mechanisms that convert the primary quantum excitation to a measurable output signal.

3.19. Gated detector

A gated detector is a detection system that is actively enabled and disabled in time; the system is actively switched between a single-photon-sensitive state (SDE > 0) and a non-single-photon-sensitive state (SDE $= 0$), independent of prior detection events. One common method to achieve this is to actively modulate the internal gain mechanism of the detector. Note that this gating mechanism is distinguished from a system that simply blocks an active detector's output. Similarly, gating is distinguished from recovery time, when the detection efficiency drops to zero due to a preceding detection event.

N.B. When a gated detector is operated in such a way that only one detection event is possible during a gate (for example, because the gate is shorter than the recovery time of the detector), it often makes sense to define detector characteristics such as the dark count rate or the afterpulse probability on a per-gate basis.

N.B. The detection efficiency of a gated detector has temporal dependence, thus when quoting the detection efficiency of a gated detector it is necessary to specify whether the quoted efficiency is the peak detection efficiency observed in a detection gate, the average efficiency over an entire detection gate, or some convolution of the temporal dependence of the incident optical signal and the detection efficiency.

3.20. Polarization-dependent detection efficiency

The dependence of the single-photon detection efficiency on the polarization of the photons at the input plane. While the full Poincaré-sphere dependence can be mapped, often just the maximum-to-minimum response is quoted.

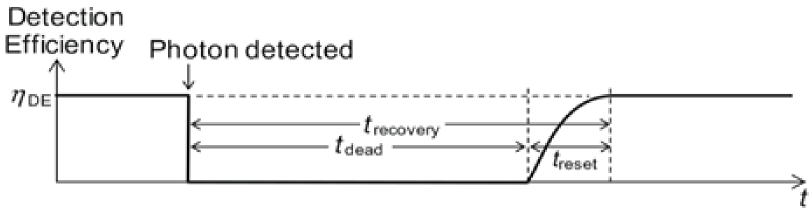

Figure 5. Illustration of detection efficiency as a function of time after a detection event.

3.21. Recovery time

The recovery time of a single-photon detector is the total amount of time required after a detection event for the detection efficiency to return to its nominal steady-state value (or to within a stated percentage of that steady-state value). The recovery time is often defined as the sum of the dead time and the reset time (see Fig. 5).

N.B. Recovery time, dead time, and reset time apply to the behavior of the detection efficiency. The electronic output of the detector can differ from the above depending on the design of the detector's electronics.

3.22. Dead time

The dead time is the duration of time, beginning at the start of a detection event, during which a detection system is incapable of producing a measurable output signal due to a photon that arrives during the dead time; during the dead time the detection efficiency is zero (see Fig. 5).

3.23. Dead-time fraction (DTF)

The dead-time fraction [27] is the fraction of events missed due to detector dead time and reset time. This is most directly determined by comparing the detection efficiency at the count rate of interest to the detection efficiency extrapolated to the zero-incident-light level (the zero-flux efficiency). For detection systems in which the reset time is small compared to the dead time (as in some actively quenched and reset SPADs), counts missed during the reset time are usually neglected an the dead-time fraction (DTF) is written as:

$$\mathrm{DTF} = 1 - \frac{1}{1 + R\, t_{\mathrm{dead}}}, \tag{13}$$

where R is the detected photon rate and t_{dead} is the detector dead time, (see Fig. 5). The dead-time fraction defined above assumes a continuous source, from which photons may arrive at any time.

3.24. Quench time

Quench time is the time between the initiation of an avalanche and its termination due to some quenching mechanism (e.g. a change in the bias voltage that results in the termination of avalanche-current flow) in a single-photon avalanche diode system. This may be governed by passive or active feedback circuitry or by a repetitive gate.

3.25. Hold-off time

Typically used in actively quenched single-photon avalanche diode systems, the hold-off time is the time after an avalanche is quenched when the bias voltage is intentionally held below breakdown to allow trapped charges to be released. This is a common technique used to reduce afterpulsing.

3.26. Reset time

Reset time is the time following the dead time during which the detection efficiency of single-photon detector is increasing from zero back to its steady-state value (see Fig. 5). In a system that resets passively (e.g. through a passive circuit element) the detection efficiency typically approaches its nominal steady-state value asymptotically, and therefore the reset time may be defined as the time to reach some percentage of the steady-state value.

3.27. Twilight events

Twilight events are any detection events that occur during the reset time. Such events can result in irregular detector behavior, such as a lower detection efficiency, latency that differs from normal, and increased afterpulsing[43, 44].

3.28. Charge persistence

Charge persistence in single-photon avalanche diodes (SPADs) refers to the phenomenon of charge carriers that are generated by light but remain in a SPAD during the dead time long enough that they are present when the device is reset, potentially resulting in a twilight event. This phenomenon is distinguished from afterpulsing in that there need not be a prior avalanche that generated the carrier(s), specifically, charge persistence can be the result of photo-absorption during the dead time [45, 46].

3.29. Raw detection rate

The raw detection rate is the raw (uncorrected) number of detection events per unit time. This includes all detection events, whether due to photons or other causes.

3.30. Corrected detection rate

The corrected detection rate is the number of detection events per unit time with corrections applied. One must specify any corrections to the detection rate, such as background or dark-count rates being subtracted, or rate-dependent corrections, such as those due to detector response nonlinearity.

Often corrections are applied to establish a rate of photons detected, yielding a “photon detection rate”.

For non-PNR detectors, detection events are synonymous with counts, so the raw detection rate is sometimes referred to as detector count rate.

N.B. Because a photon detection process is inherently probabilistic, the correct units are counts/s (not Hz) [21].

3.31. Detected count rate

See Raw detection rate.

3.32. Maximum count rate

The maximum count rate of a single-photon detector is a metric for the maximum rate at which a detection system can register detection events according to a chosen criterion. This criterion is a bound on some selected performance parameter (e.g., afterpulse probability, reduction in detection efficiency, etc.). In all cases, when stating a maximum count rate, the relevant detector operating conditions must be stated, e.g. gated, free-running, bias current, bias voltage, excess bias, pulsed excitation, CW excitation, etc. In the case of PNR detectors that can report multi-photon events, care must be taken to distinguish the detection-event rate from the photon-detection rate.

The importance of a performance-based metric rather than an operational one is highlighted by considering the minimum output-pulse-pair separation, a criterion historically used to define the maximum count rate in PMTs; the inverse of the minimum output-pulse-pair separation (or resolution) time can be used to define a maximum rate at which a detection system could, in principle, fire. This operational criterion ignores a variety of performance effects that can prohibit the useful operation of a detector at its minimum output-pulse-resolution rate, such as a marked degradation in the signal-to-noise ratio due to reduced system detection efficiency and/or increased noise, or in actively-quenched or gated SPADs, afterpulsing, or subtleties related to the twilight-detection process.

3.33. Single-photon-detector noise

Noise is defined relative to the signal of interest and thus will have different definitions depending on the experiment. Noise could include dark counts, background counts, crosstalk, afterpulses, shot noise, signal fluctuations in the single-photon-detector output that may impact assigning photon number, arrival time, etc. When the term “noise” is used, the context should be clearly described. This includes single-photon-detector output electrical noise defined herein.

3.34. Dark count

A dark count is a detection event in a single-photon or PNR detector that is uncorrelated with light at the input plane* of the detector. One common example is events thermally generated within the detector (either due to blackbody emission or thermal carrier generation).

Background counts, for example, due to irradiation involving stray light or blackbody radiation, may or may not be included in this definition, but this must be stated.

Dark counts are typically measured with input light blocked, though this approach can include detection events due to background photons emitted within the detector (e.g. thermal emission) or due thermal emission from the blocking shutter itself. Dark count detection events can induce afterpulses.

*The input plane must be carefully defined (see dictum). We note that “intrinsic detector dark count rate” should be used to refer to a dark count rate when the detector is operated with all input optics removed and the optical signal path blocked (for instance an SNSPD with its input fiber removed or maintained entirely at the detector’s base temperature), rather than with the device as actually operated. When characterized as actually operated, “system dark count rate” should be used. Note that for the intrinsic detector dark count rate, the detector input plane is moved to the detector’s active area.

3.35. Dark count rate

The dark count rate is the number of dark counts per unit time.

3.35.1. Intrinsic detector dark count rate

Intrinsic detector dark count rate refers to the dark count rate of the detector active region (including photons thermally generated there) without any input optics (see Fig. 4). This is in contrast to the system dark count rate, which refers to the total dark count rate of the device, including optics.

3.35.2. System dark count rate

System dark count rate refers to the dark count rate of the detector system with all input optics downstream of the input plane and thus this includes counts due to the thermal radiation of those optics.

3.36. Dark-count probability

Dark-count probability is the probability of a dark count occurring within a defined time, such as an experimental trial or temporal gate. For gated single-photon detectors (e.g. a gated SPAD), the dark-count behavior of the detection system is often quantified as the dark-count probability per gate.

3.37. Background count

A background count is a detection event in a single-photon detector caused by light other than the light of interest, for example, caused by stray light or thermal radiation from objects such as a room temperature input shutter. Background counts are distinguished from dark counts (see dark count).

3.38. Afterpulse

An afterpulse is a secondary detection event in a single-photon detector that is correlated with a prior detection event and is not due to a second photon incident at the detector's input. Afterpulsing is common to some types of single-photon detectors (e.g., SPADs, PMTs).

3.39. Afterpulse probability

Afterpulse probability is the probability of observing an afterpulse in a specified temporal window after a detection event.

3.40. Second-order model of a single-photon detector

Some single-photon detectors exhibit behavior that depends on their prior history of detection events. A second-order model of a detector is a theoretical model that describes the detector's behavior and transient effects dependent only on the photon arrival times and correlations up to the second order. This model can be used to characterize behaviors such as dead time and afterpulsing. The validity of a second-order model can be verified by making higher-order autocorrelation measurements.

N.B. The second-order model is a device-agnostic model and can be used to apply photon detection rate corrections to account for phenomena such as dead time and afterpulsing [47].

3.41. Backflash (or Breakdown flash)

The avalanche current in a single-photon avalanche diode can generate (probabilistically) photons that may escape the avalanche region, resulting in a backflash or breakdown flash. This flash can be detected as a later separate event. Backflash is sometimes also referred to as electroluminescence.

3.42. Detector crosstalk

Detector crosstalk is an interaction between independent single-photon detectors (usually near to each other in a network or array of detectors) whereby an event (optical input, dark count, output electrical signal, breakdown flash etc.) at one detector causes an output signal in another detector or detectors.

3.43. Detector nonlinearity

Detector nonlinearity is a change of a detector parameter (typically, detection efficiency) that deviates from the linear relationship between the input photon rate and the detector count rate. Blocking loss, dead time, and pulse pileup (all of which lead to saturation at high count rates) are common causes of detector nonlinearity.

3.44. Count-rate saturation

Count-rate saturation is the nonlinear phenomenon when the detector count rate no longer scales linearly with incident photon rate at high detection rates and may instead asymptote to a fixed value regardless of the input photon rate. Count-rate saturation can occur in both PNR and non-PNR single-photon detectors, and can depend on whether the light source is pulsed or CW.

3.45. Pulse pileup

Pulse pileup occurs when output signals are so closely spaced that they overlap. This may result in missed counts due to the readout system incorrectly discriminating events in such waveforms.

3.46. Detector paralysis

Detector paralysis occurs when the dead time is extended due to a second photon arriving during the recovery time of a previous detection event. For such a detection system, also known as a paralyzable detector, the output rate will tend toward zero at high input rates.

3.47. Detector latching

Detector latching is a phenomenon of SNSPDs. It occurs when the device switches from the superconducting state to the normal, non-superconducting state and does not return to the superconducting state. Typically, detector latching in SNSPDs is caused when the current during reset exceeds the critical current at the device's temperature, resulting in Joule heating that keeps the device from cooling down to its superconducting state.

3.48. Blocking loss

Blocking loss is the apparent reduction of detection efficiency with increasing input photon rate due to photons arriving during the recovery time. The apparent reduction in detection efficiency due to blocking loss can occur in both single- and multi-pixel (arrayed) detection systems, and in both cases is due to the non-zero recovery time of a pixel. Blocking loss is related to dead-time fraction.

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