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GROUP SPECIFICATION

Quantum Key Distribution (QKD); Component characterization: characterizing optical components for QKD systems

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This Group Specification (GS) has been produced by ETSI Industry Specification Group (ISG) Group Quantum Key Distribution (QKD).

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1 Scope

The present document gives specifications and procedures for the characterization of optical components for use in QKD systems. Examples of specific tests and procedures for performing such tests are given. Due to their importance in the security of a QKD system, particular attention is given to active optical components such as optical sources and single photon detectors.

2 References

2.1 Normative references

References are either specific (identified by date of publication and/or edition number or version number) or non-specific. For specific references, only the cited version applies. For non-specific references, the latest version of the reference document (including any amendments) applies.

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The following referenced documents are not necessary for the application of the present document but they assist the user with regard to a particular subject area.

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3 Definitions, symbols and abbreviations

3.1 Definitions

For the purposes of the present document, the following terms and definitions apply:

after-pulse probability: probability that a detector registers a false detection event in the absence of illumination, conditional on a detection event, due to incident photons of stated mean photon number, in a preceding detection gate

Alice: quantum information sender/transmitter

Bob: quantum information receiver

classical channel: communication channel used by two communicating parties for exchanging data encoded in a form which may be non-destructively read and fully reproduced

clock frequency: frequency of any electrical clock signal of interest

clock frequency variation: variation in the frequency of the electrical clock signal per unit time

dark count probability: probability that a detector registers a detection event within a stated duration time, in the absence of optical illumination

dead time: time interval after a detection event when the detector as a whole is unable to provide an output in response to incoming photons at the single photon level

detection efficiency: probability that a photon, of a specific energy (spectral frequency) or wavelength, incident at the optical input will be detected within a detection gate, and produce an output signal

detection efficiency linearity: minimum detection efficiency divided by the maximum detection efficiency over the specified range of powers

detection efficiency range due to polarization of input pulses: difference between the maximum DE for input polarized light, and the DE due to randomly polarized input light

detector gate efficiency profile: detection efficiency variation as a function of incident pulse arrival time

detector gate repetition rate: repetition rate of the time-intervals during which a detector has single-photon sensitivity

detector signal jitter: detection efficiency variation with respect to the arrival of a single photon at the input port of the DUT

Eve or eavesdropper: any adversary intending to intercept communication between Alice and Bob

intensity modulator: device that can rapidly alter its transmittance to optical signals

intrinsic dark count probability: probability that a detector registers a detection event within a stated duration time, in the absence of optical illumination, and excluding the probability of after-pulses generated from the intrinsic dark counts

mean spectral frequency: average frequency of spectral measurement

mean photon number: average number of photons per optical pulse

mean source power: absolute average power emitted by the source (transmitter) over the time period of a QKD session, or other stated time-interval

mean wavelength: average wavelength of spectral measurement

optical pulse repetition rate: repetition rate of the optical pulses emitted by the quantum signal source

partial recovery time (high): time duration after a photon detection event for the detection efficiency to return to 90 % (or some other specified fraction) of its steady-state value

partial recovery time (low): time duration after a photon detection event for the detection efficiency to return to 10 % (or some other specified fraction) of its steady-state value

phase modulator: device that can rapidly alter the phase of a photon that is transmitted by the modulator

power meter: device which measures incident optical power

QKD session: set of all raw bits which are subject to one particular round of sifting, error correction, and privacy amplification, to generate a particular secret key

quantum channel: communication channel for transmitting quantum signals

quantum photon source: optical source for carrying quantum information

qubit: unit of quantum information, described by a state vector in a two-level quantum mechanical system

recovery time: smallest time duration after which the detection efficiency is independent of previous photon detection history (i.e. its steady state value)

reset time: time between the end of the dead time and the recovery time

single-photon detector: device that transforms a single-photon into a detectable signal with finite probability

single-photon source: photon source that emits at most one photon at a time

short-term instability of output power of emitted pulses: variation in pulse-to-pulse intensity

source emission temporal profile: temporal distribution of photons within a single emitted pulse

source spectral frequency: spectral frequency of emitted photons

source linewidth: full width at half maximum of measured spectrum

source temporal profile: temporal intensity variation within a single optical pulse

source timing jitter: uncertainty in the emission time of an optical pulse at the optical output

source wavelength: wavelength of emitted photons

spectral responsivity: detection efficiency as a function of the wavelength of the incident photons

spectrometer: device for measuring the spectrum of optical radiation

stability of output power of emitted pulses: variation in source power over the time period of a QKD session, or other stated time-interval

weak laser pulse: optical pulses obtained through attenuating pulsed laser emission

3.2 Symbols

For the purposes of the present document, the following symbols apply:

A_{hi}	high-attenuation setting on attenuator
A_{low}	low-attenuation setting on attenuator
α	short-term instability of output power of emitted pulses (Grangier α parameter)
C_{dark}	number of dark counts
C_i	average number of detector counts in illuminated gates
C_{ni}	average number of detector counts in non-illuminated gates
C_X	number of detector counts in detector gate labelled X
dB	decibels (optical power)
$\eta(\lambda)$	detection efficiency (nm)
$\eta(\nu)$	detection efficiency (Hz)
$\eta(t)$	detector gate efficiency profile
$\eta(t,T)$	detector signal jitter, where T denotes photon arrival time, and η is measured over a range of t
Δ_1	time spacing between pulses within pair of pulses
Δ_2	time spacing between second pulse of a pair of pulses and first pulse of next pair of pulses
$\Delta\eta(\lambda)$	detection efficiency range (nm)
$\Delta\eta(\nu)$	detection efficiency range (Hz)
$\eta(\lambda)_{POLMAX}$	maximum detection efficiency (nm) resulting from varying polarization of input pulses
$\eta(\lambda)_{POLRAND}$	detection efficiency (nm) resulting from randomly-varying polarization of input pulses
$\eta(\nu)_{POLMAX}$	maximum detection efficiency (Hz) resulting from varying polarization of input pulses
$\eta(\nu)_{POLRAND}$	detection efficiency (Hz) resulting from randomly-varying polarization of input pulses
Δf_{clock}	clock frequency variation
Δi	current interval
$\Delta\lambda_{source}$	source linewidth (nm)
$\Delta\nu_{source}$	source linewidth (Hz)
$\Delta\nu_{stabilized}$	linewidth of a stabilized laser (Hz)
ΔT, Δt	time interval, defined in context
ΔT_D	time interval for fast photodiode
ΔT_{photon}	source emission temporal profile width
ΔT_{meas}	duration of a single measurement
ΔV	voltage interval
f_{clock}	clock frequency
f_{each}	frequency measured from a single histogram or trace
f_{gate}	detector gate repetition rate
F_L	detection efficiency linearity factor
$f_{overall}$	optical pulse repetition rate, measured over many pulses
f_{source}	optical pulse repetition rate of a simple emitter, such as an attenuated pulsed laser or LED
$f_{transmitter}$	optical pulse repetition rate of a complex emitter, e.g. a QKD optical transmitter comprising a pulsed source and other components, such as an unbalanced (asymmetric) Mach-Zehnder interferometer (AMZI)
$g^{(2)}(0)$	second-order Glauber autocorrelation function at time t=0
h	Planck's constant
J_{source}	source timing jitter
λ_m	mean wavelength (nm)
λ_{source}	source wavelength (nm)
μ	mean photon number of a simple emitter, such as an attenuated pulsed laser or LED
μ_{both}	mean photon number, summed over both split pulses produced by the AMZI in a QKD transmitter
N_{trig}	number of triggers
N_{after}	number of after-pulses
N_{click}	number of detector counts ('clicks')

N_{dark}	number of dark counts
N_{gates}	number of gates
N_{peaks}	number of peaks in a single histogram or trace
N_{true}	number of true photon detections
ν_m	mean (spectral) frequency (Hz)
ν_{source}	source (spectral) frequency (Hz)
P	optical power
PR	probability ratio
p	probability, defined in context
p_{after_av}	average after-pulse probability, defined in context
p_{after_total}	total after-pulse probability at stated gate repetition rate for gates of stated duration
$p_{after\_all}(N.\Delta T)$	total after-pulse probability at gate of stated duration occurring at time N.ΔT after previous detector 'click'
p_{after_all}	series of total after-pulse probabilities at gates of stated duration occurring at times ΔT, 2.ΔT, 3.ΔT, etc. after previous detector 'click'
$p_{after\_first}(N.\Delta T)$	first after-pulse probability at gate of stated duration occurring at time N.ΔT after previous detector 'click'
p_{after_first}	series of first after-pulse probabilities at gates of stated duration occurring at times ΔT, 2.ΔT, 3.ΔT, etc. after previous detector 'click'
p_{after_X}	after-pulse probability (defined in context) in detector gate labelled X
p_{click}	probability of a detector count ('click')
p_{click_i}	probability of a detector count ('click') in an illuminated gate
p_{click_ni}	probability of a detector count ('click') in a non-illuminated gate
p_{click_X}	probability of a detector count ('click') in detector gate labelled X
p_{coinc}	probability of a coincidence count
$p_{coincTrue}$	probability of a coincidence count due to photons emitted by source
p_{dark}	dark count probability
p_{idark}	intrinsic dark count probability
$P_{emission}(t)$	*source emission temporal profile*
P_{mean}	mean source power
P_{meas}	measured optical power (W)
p_{noise}	probability of a detector count ('click') due to dark counts, after-pulses, or stray light
p_{other}	probability of a detector count ('click') due to other processes, where other is defined in context
$p_{other}(N.\Delta T)$	probability of a detector count ('click') due to other processes, where other is defined in context, at time N.ΔT after earlier event, where the event is also defined in context
p_{other_X}	probability of a detector count ('click') due to other processes, in detector gate labelled X, where 'other' is defined in context
$P_{pulse}(t)$	source temporal profile
$P_{stability}$	stability of output power of emitted pulses
$p_{straylight}$	probability of a detector count ('click') due to stray light
p_{true}	probability of a detector count ('click') due to photons emitted by source
R	integer ratio of detector gates to optical pulses in measurement procedure
$S_{meas}(\lambda)$	measured spectral power density (spectrum) (W nm^{-1})
$S_{meas}(\nu)$	measured spectral power density (spectrum) (W Hz^{-1})
T	time unit, defined in context
Tj	time label, j defined in context
$t(\lambda)$	spectral transmittance as function of wavelength (nm)
$t(\nu)$	spectral transmittance as function of frequency (Hz)
T_{dead}	dead time
T_{each}	time-difference between pulses transmitted by separate arms of an AMZI, measured from single pulse-sequence
T_{gate}	gate duration
$T_{partial\_high}$	partial recovery time (high)
$T_{partial\_low}$	partial recovery time (low)
T_{period}	period of emitted pulse train
$T_{recovery}$	recovery time
T_{reset}	reset time
$T_{separation}$	averaged (over many measured pulse sequences) time-difference between pulses transmitted by separate arms of an AMZI
$U(x)$	uncertainty in x, where x is the measured value
$wbin\_\lambda_i$	wavelength bin-width of measurement at λ_i

$wbin\_\nu_i$	frequency bin-width of measurement at ν_i

3.3 Abbreviations

For the purposes of the present document, the abbreviations given in ETSI GS QKD 003 [i.1] and the following apply:

AMZI	Asymmetric Mach-Zehnder Interferometer
APC	Angled Physical Contact
APD	Avalanche PhotoDiode
BNC	Bayonet Neill-Concelman connector
BS	British Standard
CIE	International Commission on Illumination (Commission Internationale de l'Eclairage)
CML	Current Mode Logic
CW	Continuous Wave
DE	Detection Efficiency
DUT	Device Under Test
DVM	Digital VoltMeter
ECL	Emitter Coupled Logic
FC	Ferrule Connector or Fibre Channel
FSR	Free Spectral Range
FWHM	Full Width at Half Maximum
HBT	Hanbury Brown-Twiss
I/O	Inputs and Outputs
IR	Infrared
LED	Light-Emitting Diode
MCA	Multi-Channel Analyser
NA	Numerical Aperture
PC	Physical Contact
PIN	Positive Intrinsic Negative
PM	Polarization-Maintaining
QKD	Quantum Key Distribution
RP-SMA	Reverse Polarity Sub-Miniature version A connector
S/N	Signal-to-Noise ratio
SI	International System of Units (Système International d'Unités)
SM	Single Mode
SMA	Sub-Miniature version A connector
SMB	Sub-Miniature version B connector
SMK	Sub-Miniature version K connector
SNSPD	Superconducting Nanowire Single-Photon Detector
SPAD	Single-Photon Avalanche photoDiode
TAC	Time-to-Amplitude Converter
TCSPC	Time-Correlated Single-Photon Counting
TTL	Transistor-Transistor Logic

4 QKD Systems and Components

4.1 Overview

The present document focusses on optical components of Weak Laser Pulse QKD using the One-Way Mach-Zehnder Implementation over optical fibre [i.1].

Clause 4.2 presents a generic description of QKD systems.

Clause 4.3 describes weak laser pulse QKD.

Clause 4.4 describes the one-way Mach-Zehnder implementation of weak laser pulse QKD.

Clause 4.5 lists the relevant electrical properties common to both QKD transmitters and receivers for which measurement procedures are prescribed. A short description of appropriate methods is also given.

Clause 4.6 lists the relevant optical components properties of QKD transmitters for which measurement procedures are prescribed. A short description of appropriate methods is also given.

Clause 4.7 lists the relevant optical components properties of QKD receivers for which measurement procedures are prescribed. A short description of appropriate methods is also given.

Clause 5 describes the conditions under which measurements shall be reported.

Clauses 6 to 20 specify measurement procedures.

Annex A provides information about uncertainty evaluation

Annex B provides information about the requirements of, and uncertainties due to, common measurement instrumentation

Annex C lists authors and contributors to the present document

4.2 Generic Description

A QKD system comprises a number of internal components. The purpose of the present document is to identify the components which are common to many systems, and to define how these components are to be traceably characterized.

A survey of the literature reveals that many different types of QKD system have been proposed. Many of these have been implemented physically with different levels of sophistication. At the most basic level, these systems utilize the laws of quantum theory to make claims about the security levels of the shared key. Most commonly, they use signal encoding upon quantum light states using several different bases which are non-orthogonal to one another. Quantum theory dictates that it is impossible to gain full information of this encoding through measurement without prior information about the encoding bases or post-selection of the bases used. This property is used to ensure that the legitimate users of the system share more information than an eavesdropper can determine.

One convenient method of categorizing different types of QKD system is according to the photon source that they use. Examples include true single-photon sources, entangled-photon pair sources and weak laser pulses. Common methods for encoding the qubit information include controlling the phase or the polarization state of the transmitted photon. A QKD system consists of two units which are physically separated at opposite ends of a pair of communication channels, as illustrated by figure 4.1. The sending and receiving unit contain a source of randomness for use in the key generation protocol. The source of randomness can be intrinsic, as in the case of sending entangled photons, or it can be an active random number generator or a passive random selection component, such as a non-polarizing beam splitter. Here, the sending unit consists of a signal source and an encoder for the source, the receiving unit contains a component for signal demodulation, i.e. for selecting the measurement basis, as well as one or more signal detectors. Control electronics, with access to an independent random number generator, is necessary to generate the drive signals for these devices. The detected signals are used by the control electronics to form the initial (or raw) shared key, which is then post-processed (sifted, reconciled and privacy amplified) to achieve the final secure shared key.

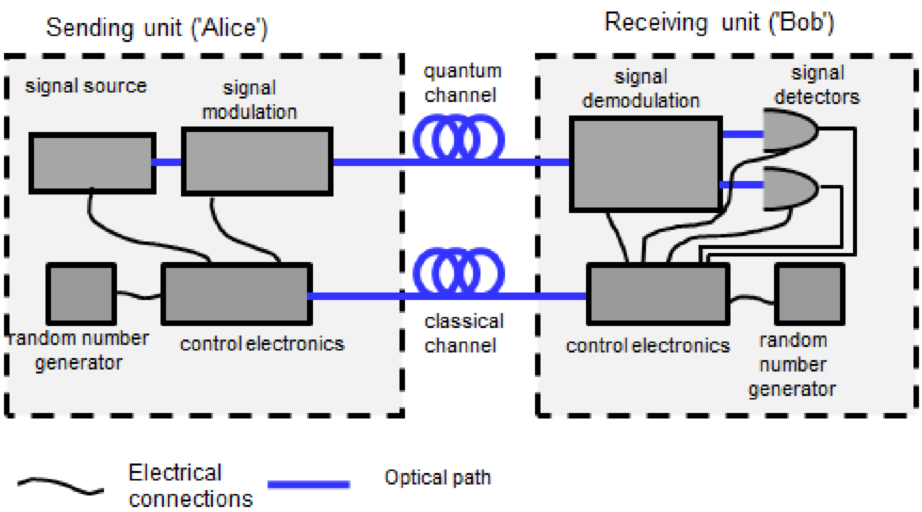


Figure 4.1: Schematic of a generic QKD system showing internal interfaces and connections

4.3 Weak Laser Pulse QKD

In weak laser pulse QKD systems, the qubit values shall be encoded upon laser pulses attenuated to the single-photon level. The sender (Alice) in a weak laser pulse QKD contains at least one weak laser source that is used as a quantum information carrier. In implementations involving more than one weak laser source, the sources shall be indistinguishable from one another in every measurable attribute except the degree of freedom the quantum information is encoded upon.

The sender shall contain a quantum encoder that encodes qubit information on each weak laser pulse. This encoder shall have a source of randomness that determines an encoding basis and an encoding bit value for each weak pulse. The source of randomness shall come from a random number generator.

The photon number splitting attack, and other such attacks, shall be accounted for in the privacy amplification process in a QKD session. To achieve this, the intensity and photon number statistics of each weak laser source shall be calibrated. The source stability shall also be calibrated. In the case that the source is unstable, the worst case scenario shall be considered in the privacy amplification process.

4.4 One-Way Mach-Zehnder Implementation

Figure 4.2 shows an example of a QKD system using weak laser pulses as the signal carriers and Asymmetric Mach-Zehnder Interferometers (AMZIs) to encode the quantum states, based on the paper by Dynes et al. [i.8]. The system uses the decoy pulse protocol to obtain higher secure bit rates than are otherwise possible using weak laser pulses with constant intensity. Intensity modulation is used to produce signal, decoy and vacuum pulses of differing intensities, as well as strong reference pulses to enable active stabilization. The vacuum pulses could also be produced by omitting trigger pulses to the signal laser. The signal, decoy and vacuum pulses are produced in a non-deterministic sequence and have pre-determined relative occurrence probabilities assigned to them. The signal and decoy pulses are attenuated to the single-photon level before entering the quantum channel implemented in standard single mode fibre.

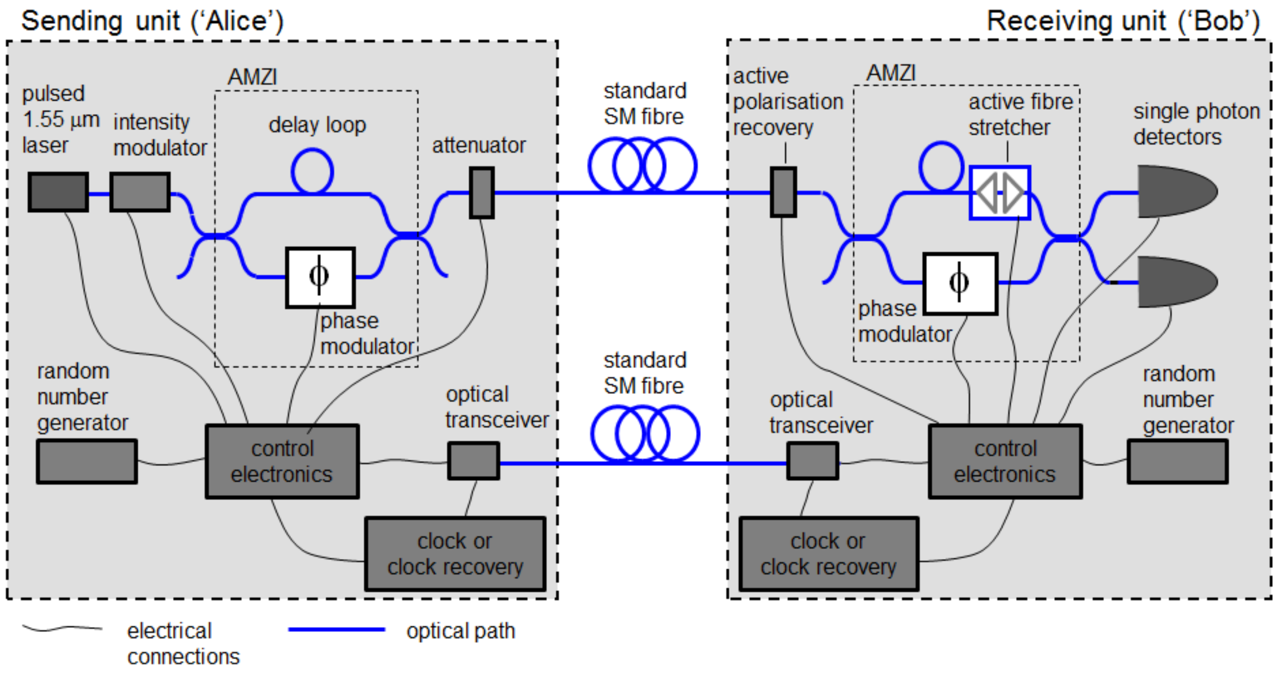


Figure 4.2: Schematic of a one-way, weak-laser-pulse QKD system

The receiver's single-photon detectors are two InGaAs avalanche photodiodes (APDs), operated in gated Geiger mode.

This system uses active stabilization to lock the path phase difference in the sending and receiving AMZI. The strong reference pulses are produced by the intensity modulator(s) at pre-determined times. These strong reference pulses are either unmodulated, or modulated with pre-determined phase values by the phase modulator in the sending AMZI. Detection rates of these reference pulses are used as a feedback to actively adjust a phase compensation component in Bob, here a fibre stretcher, to compensate for the path phase difference. A similar active stabilization technique is used to control the polarization state of photons entering Bob's AMZI.

In this implementation, the combination of the 1 550 nm laser diode, the intensity modulator and the attenuator forms the photon source. Because only one laser diode is used for encoding all qubits, the indistinguishability of the source is guaranteed. An intensity modulator is required to implement the decoy QKD protocol. Alice's AMZI is the encoder. Standard single mode fibre is used as the quantum channel. In the receiving unit, the combination of the active polarization recovery, active fibre stretcher and AMZI forms the decoder.

Each control electronics unit can contain optoelectronics components, such as optoelectronics-based random-number-generators used as the sources of randomness.

Optical transceivers at Alice and Bob are used to provide signals for clock synchronization/recovery and classical communications for sifting and data processing. These classical optical signals may either be transmitted through a separate standard fibre, as shown in figure 4.2, or be combined with the quantum signal through the same fibre using wavelength- or time-division multiplexing.

4.5 Common electrical properties for which measurement procedures are prescribed

Table 4.1 summarizes properties which may apply to both single-photon sources (or QKD transmitters) and single-photon detectors (or QKD receivers).

Table 4.1

Row number	Property	Symbol	Units	Description	Measurement method	Measurement clause
1	Clock frequency	f_{clock}	Hz	The frequency of the clock signal	Measure via standard traceable time and frequency calibration techniques - e.g. measuring the pulse train with a frequency counter or fast oscilloscope	6
2	Clock frequency variation	Δf_{clock}	Hz/ΔT, where ΔT is a second, minute, hour, day, etc.	The variation in the clock frequency over a stated time interval	Repeated measurements of clock frequency during the required total measurement time	6

4.6 Single photon source (QKD transmitter) properties for which measurement procedures are prescribed

Table 4.2

Row number	Property	Symbol	Units	Description	Measurement method	Measurement clause
1	Optical pulse repetition rate	f_{source}, or $f_{transmitter}$	Hz Hz	Repetition rate (frequency) of the emitted optical pulses (as opposed to the clock signal frequency f_{clock}).	Record the emitted optical pulse trains using a detector and recording device, and analyse these recordings. The preferred approach is to carry out these measurements before the pulses are attenuated to the single-photon level, so that every pulse is measured with approximately equal probability. Measurement at the single-photon level implies that every pulse cannot be detected, and only an averaged temporal output can be measured. Therefore, random features or temporal variations in the pulse emission sequence may not be detected.	7
2	Mean photon number	μ	Photons per pulse	Average number of photons per emitted pulse	i) Measure using traceably calibrated single photon detector; ii) Measure the average power with a traceably calibrated power meter, and calculate mean photon number using $P = nh\mu\nu$, where P is the measured power, n is the number of pulses per second, h is Planck's constant, μ is the mean photon number per pulse, and ν is the mean spectral frequency of the pulses. The measurement techniques rely on the detection model and the photon statistics of the source. Both assumptions should be checked. Method ii) is only suitable for a transmitter that is emitting photons with the same mean photon number, and at a sufficient pulse repetition rate to be measureable with a power meter.	8

Row number	Property	Symbol	Units	Description	Measurement method	Measurement clause
3	Source power	P_{mean}	W	The average power emitted by the laser over the time period of a QKD session	Direct measurement by using a calibrated power meter.	9
4	Long-term power stability		dB/hr	The variation in source intensity over the duration of a QKD session, or some other stated time-interval.	Stability measurement using calibrated power meter or single photon detector depending on the pulse repetition rate, and whether the measurement is performed before or after the signal is attenuated to the single photon level. Measurement for each power reading has a predetermined integration time, for example, 1 s.	10
5	Short term power stability		dB	The variation in pulse intensity over a set period, e.g. 1 minute	If the pulse energy of the laser is unstable, this will induce a super-Poissonian behaviour. This can be detected from the measurement of the parameter α (Grangier et al. [i.5]) using a Hanbury Brown-Twiss interferometer.	11
6	Source emission temporal profile	$P_{emission}(t)$		The distribution of photons within the emitted pulses as a function of temporal position.	Measurements can be carried out before pulses are attenuated to the single-photon level, or at the single photon level. The un-attenuated source can be detected by a fast, low jitter detector. By correlating many successive detection events with the clock signal triggering the source, a histogram of detection times will be observed. By deconvolving this signal from the instrumental lineshape of the measurement instrumentation (comprising the detector, amplifier, and recording device) the source emission temporal profile can be determined. The attenuated source, with its output at the single-photon level, can be detected by a superconducting nanowire single-photon detectors, since the jitter of such detectors is low (< 100 ps) in comparison to other detectors (Hadfield [i.7]). By correlating many successive detection events with the clock signal triggering the source, a histogram of detection times will be observed. By deconvolving this signal from the detector's inherent jitter, the source emission temporal profile can be determined. If measurements are carried out with a superconducting nanowire detector, a measurement uncertainty < 50 ps is feasible. In the case of measurement in the high power regime, the source timing jitter can be separated from the source temporal profile. This is because source timing jitter can be measured by selecting the photon flux level within the pulse at which measurements are made.	12

Row number	Property	Symbol	Units	Description	Measurement method	Measurement clause
7	Source timing jitter	J_{source}	s	The uncertainty in the emission time of a single pulse at the optical output.	Measurement of the optical output pulse from the source, is carried out prior to the attenuator that reduces the flux to the single-photon level. By performing this measurement on laser pulses containing many photons, it is then possible to detect them with a fast, low-jitter photodiode, rather than a photon-counting detector. The jitter is derived from the variation of the rising and falling edges of the detected signal. A measurement uncertainty < 10 ps is feasible.	12
8	Source temporal profile	$P_{pulse}(t)$		The intensity variation within a single pulse as a function of temporal position within the optical pulse.	Measurement of the optical output pulse from the source, is carried out prior to the attenuator that reduces the flux to the single-photon level. By performing this measurement on laser pulses containing many photons, it is then possible to detect them with a fast, low-jitter photodiode, rather than a photon-counting detector. The source temporal profile is derived from the measured source emission temporal profile by deconvolving the source timing jitter from it.	12
9	Source wavelength Source spectral frequency	λ_{source} ν_{source}	nm Hz	Wavelength of photons that are emitted.	Attenuated laser sources used in commercial quantum communication systems often operate in the 1 300 µm and 1 500 µm regions of the near-IR spectrum. The calibration of wavemeters and the wavelength scale of optical spectrum analysers is usually performed with using a tunable laser such as external-cavity or distributed feedback laser which gives a single wavelength output. The laser output is locked to molecular vibration-rotation transitions of gas-phase molecules, and, in the 1 500 nm region, CO and $^{13}C_2H_2$ transitions are employed (HC [i.6], Edwards et al. [i.4]). The accuracy with which a device can be calibrated depends on the spectral resolution and stability of the device under test, but for a high-quality wavemeter with resolution of 0,1 pm, or 1 pm, the achievable uncertainty can be as low as 0,15 pm, or 0,6 pm, respectively (k = 2). When the laser in the QKD source is driven to emit short optical pulses, typically < 100 ps in duration, the spectral width of the source is $\Delta\lambda_{source}$ ~ 0,1 nm, which corresponds to $\Delta\nu_{source}$ ~ 12 GHz. This will affect the accuracy with which the wavelength can be measured. A wavemeter suitable for use with pulsed sources can measure such a laser's centre wavelength, λ_{source}, with an uncertainty $\Delta\lambda_{source}$ of ~ 0,002 - 0,01 nm, depending on stability, spectral profile, and S/N.	13

Row number	Property	Symbol	Units	Description	Measurement method	Measurement clause
10	Spectral line width	$\Delta\nu$ $\Delta\lambda$	GHz nm	Bandwidth of the emitted photons.	A wavemeter, or optical spectrum analyser, can also be used to measure the spectral linewidth of an attenuated laser source. In addition, two other methods are available: i) By using the light emitted by the pulsed laser source, prior to the attenuator, and beating it against a tunable narrow-linewidth auxiliary laser, the spectral linewidth can be measured. The tunable narrow linewidth laser should be stabilized such that its linewidth $\Delta\nu_{stabilized} \leq 10$ MHz, i.e. much narrower than the attenuated source ($\Delta\nu_{source}$). The spectral linewidth of the pulsed laser source will be revealed by the beatnote, observable when the auxiliary laser is tuned near the source's optical frequency. Using this beat note method, a resolution of ~ 200 MHz, should be feasible. Note that this method is not suitable for optical pulses at the single-photon level. ii) The use of a stable, tunable Fabry-Perot resonator provides another route to measuring the source linewidth. The technique requires that the cavity free spectral range (FSR) is much greater than the source's pulsed laser linewidth, *i.e.* FSR >> $\Delta\nu_{source}$, yet have a linewidth $\Delta\nu_{cavity} << \Delta\nu_{source}$. When used in transmission mode, the Fabry-Perot cavity can be tuned to resonance with the pulsed laser source to record its spectral profile. When analysing the optical pulses prior to the attenuator, the signal should be measured using a PIN photodiode. The technique is also appropriate for measuring the attenuated laser pulses (containing on average one photon or less), by using a superconducting nanowire detector. For example, for a pulsed laser source operating at 80 MHz repetition rate, and using the nanowire detector, good signal to noise can be achieved with the cavity resolution stated above.	13

4.7 Single-photon detector (QKD receiver) properties for which measurement procedures are prescribed

Table 4.3

Row number	Property	Symbol	Units	Description	Measurement method	Measurement clause
1	Detector gate repetition rate	f_{gate}	Hz	The repetition rate of the time-intervals during which a detector has single-photon sensitivity. In the case of a SPAD, this should correspond to the times during which the reverse-biased p-n junction is biased above the breakdown voltage.	A CW source (at the single-photon level) is sent to the DUT. Analysis of the detection histogram (obtained from triggering the timer/counter every *R*th detector gate) yields the gate frequency.	14
2	Dark count probability	p_{dark}	gate^{-1} s^{-1}	For a gated detector this is the probability that a detector registers a detection event in a gate of stated duration, in the absence of optical illumination. For a free-running detector this is the probability that a detector registers a detection event in 1 s, or some other stated time-interval, in the absence of optical illumination.	i) The dark count probability can be measured by recording detection events per gate or per unit time in the absence of photon flux illuminating the detector's sensitive area. A counting device records the detector output signal. In order to count only detection events during gates, a time-correlated photon-counting device can be used to record the detector output signal. By correlating many dark count events with a clock signal triggering the detector gate, a time delay histogram can be observed in accordance to Yuan et al. [i.13]. To calculate the dark count probability of the detector, the detected count rate will be normalized to the total number of applied gates. This method cannot separate intrinsic dark counts from their after-pulses. The uncertainty will depend on the uncertainty of the trigger clock signal and the uncertainty of the counting device, both of which can be calibrated against a traceable frequency standard, as well as the count statistics. ii) Measurement of the time-intervals between events from a detector in the absence of illumination can be used to separate the intrinsic dark count and after-pulse probabilities [i.23]. The intrinsic dark count probability is described by an exponential decay in counts as a function of length of time-interval, and the after-pulse probability p_{after_first} is described by the additional function required to obtain a fit to the experimental data. Uncertainties will be introduced by the curve-fitting required to express the experimental data as the sum of the dark count and after-pulse behaviours. This uncertainty can be reduced by obtaining measurements for long time-intervals between events, where intrinsic dark counts will dominate, thereby enabling the intrinsic dark count exponential to be more reliably estimated. iii) The dark count probability can also be obtained from method (ii) of row 3 in this table.	15

Row number	Property	Symbol	Units	Description	Measurement method	Measurement clause
3	After-pulse probability	 $p_{after\_first}(\Delta T)$ $p_{after\_all}(\Delta T)$ p_{after_total}	Unitless	The probability that a detector registers a false detection event in the absence of illumination, conditional on a detection event in a preceding detection gate at a time ΔT earlier. $p_{after\_first}(\Delta T)$ represents the probability of first after-pulses only $p_{after\_all}(\Delta T)$ represents the sum of the probabilities of first and secondary after-pulses The sum of $p_{after\_all}(\Delta T)$ terms for all ΔT	After-pulsing introduces a secondary source of false counts, with a charge carrier production rate proportional to the trap levels. These levels have fairly long lifetimes and fairly high concentration in InGaAs/InP SPADs. As a result, the after-pulsing effect can limit the transmission rate of single photons in QKD systems. i) Method (ii) described in row 2 of this table can be employed to measure the after-pulse probability for intrinsic dark counts, i.e. pulses of mean photon number, μ, =0. ii) The after-pulse probability can be measured in accordance with the double-pulse technique described by Cova et al. [i.20], and adapted by Yuan et al. [i.13], which is also suitable for determining the photon detection probability. The DUT is illuminated by a pulsed laser source attenuated to the single-photon level. The laser pulse frequency is stepped down by an integer factor *R* compared to the detector gate repetition rate, in order to record detection events in the *(R-1)* non-illuminated gates between the gates corresponding to consecutive laser pulses. TCSPC is used to record a histogram of time delays between the laser trigger and the detector output. Counts in the non-illuminated gates are due to after-pulses (and dark counts). Normalizing the detected count rate to the total number of events in the illuminated gate, after correction for dark counts, enables the after-pulse probability to be calculated. If only first events subsequent to an event in the illuminated gates are recorded, p_{after_first} can be determined; if all events in non-illuminated gates are recorded, p_{after_all} can be determined. If *R* is sufficiently large such that the counts in gates corresponding to large values of *R* reach a constant level, this constant level can be taken to be due to dark counts alone (i.e. the after-pulse probability has decayed to being much less than the dark count probability), enabling the dark count probability to be obtained. The uncertainty will depend on the uncertainty of the clock frequency as well as the temporal resolution of the time-correlated photon counter, both of which can be calibrated against a traceable frequency standard, as well as the uncertainties due to p_{dark} and the count statistics. Uncertainties below the 1 % level are achievable if the system is stable.	15

4	Photon detection probability (Detection efficiency)	$\eta(\nu)$ or $\eta(\lambda)$	Unitless	The probability that a photon of a specific energy (wavelength) incident at the optical input will be detected within a detection gate.	Two measurement approaches can be identified: the first is based on the traditional substitution method, the second exploits a heralded single-photon source: i) The photon detection probability can be measured in accordance with the technique described by Yuan et al. [i.13] (see method (ii) in row 3). Counts in an illuminated gate are due to true detections, as well as after-pulses and dark counts. Knowledge of the combined dark count and after-pulse probability enables the probability of a true detection, p_{true}, to be calculated. The dark count probability and the after-pulse probability can be obtained from the same measurement, described as method (ii) in row 3 of this table. Knowledge of the mean photon number per pulse, μ, enables the photon detection probability, η, to be calculated as a function of μ. The mean photon number per pulse, μ, can be obtained by calibrating the attenuated laser source against a traceable detector standard. The latter is available for the infrared spectral region only recently; a superconducting nanowire single-photon detector was calibrated against a standard InGaAs diode using synchrotron radiation with uncertainties of approximately 2 %. A practical solution is to use a calibrated detector to measure the power for a given pulse repetition rate, and then use a calibrated attenuator to reduce the pulse photon number to the single-photon level. The overall uncertainty in calibrating the photon detection probability depends on the uncertainties due to p_{dark}, p_{after}, p_{true}, and the count statistics. For fibre coupled devices at 1 550 nm, best case uncertainties around 2 % (k = 2) are currently achievable. ii) An alternative technique to the traditional one based on radiometric substitution is based on the use of parametric down-conversion to produce a heralded single-photon source Chunnilall et al. [i.14]. Detection of one of the down-converted photons heralds the existence of its twin, which can be directed to the device under test (DUT). This approach still suffers from multiple photon events, and various experiments (Brida et al. [i.2], Polyakov et al. [i.12], Cheung et al. [i.3]) have been carried out to demonstrate the equivalence of the two methods at the photon counting level. However, optical scales remain based on cryogenic radiometry since the lowest uncertainty so far achieved with the heralded single-photon approach (0,18 %) (at single-photon level, in the visible spectral region) is over an order of magnitude less accurate than that based on cryogenic radiometry (0,005 %) (at the 100 μW level). This is mainly due to need to estimate the absorption in the path the heralded photon takes from the point of creation within the non-linear medium until it is incident on the detector, which may include geometrical or absorptive spectral filtering. The method also suffers from limited spectral tuneability at high accuracy. The importance of this technique lies in the fact that it establishes an absolute means of measuring detection efficiency, which is independent of cryogenic radiometry, and operates in the single/few photon regime. In respect of QKD receivers, the random occurrence of downconversion events means that the technique is not viable with detectors that cannot be asynchronously gated, such as SPAD detectors employing a d.c. bias just below the avalanche breakdown voltage, on top of which a high-speed periodic low amplitude bias is added (Namekata [i.11], Yuan [i.13]), unless a pulsed pump, synchronized with the detector gates, is employed.	15

Row number	Property	Symbol	Units	Description	Measurement method	Measurement clause
5	Linearity factor (for detection efficiency)	F_L	Unitless	Minimum detection efficiency divided by the maximum detection efficiency over the specified range of powers	The calibrated mean photon number of the attenuated laser pulses is varied (e.g. with a calibrated attenuator), and the detection efficiency is measured.	16
6	Detection efficiency range due to polarization variation of input pulses	$\Delta\eta$	Unitless	The difference between the maximum DE and the DE for randomly polarized light	The input polarization of the input pulses is varied over all pure states, and the minimum and maximum DE values obtained. Optimization strategies can be employed to avoid the need to carry out a full mapping of DE over the surface of the Poincaré sphere.	17
7	Dead time	t_{dead}	s	The time interval after a detection event when the detector as a whole is unable to provide an output in response to incoming photons at the single photon level.	The measurement method is based on that reported in [i.18], [i.9] and [i.19]. Optical pulse pairs of equal intensities at the single-photon level are used to illuminate the detector under test. The laser pulses are synchronized to the detector gates and the relative time delay between the laser pulses only needs to be varied in steps of one gating period. At a particular time separation, detector outputs should be recorded for several pairs of incident photon pairs, where the time separation between pairs significantly exceeds the expected recovery time. The dead time is the minimum time separation at which non-zero coincidences are recorded.	18
8	Recovery time	$t_{recovery}$	s	The smallest time duration after which the detection efficiency is independent of previous photon detection history.	The measurement method is based on that reported in [i.18], [i.9] and [i.19]. Optical pulse pairs of equal intensities at the single photon level are used to illuminate the detector under test. The laser pulses are synchronized to the detector gates and the relative time delay between the optical pulses only needs to be varied in steps of one gating period. At each time separation, detector outputs should be recorded for several pairs of incident photon pairs, where the time separation between pairs significantly exceeds the expected recovery time. Usually, the rate of coincidence (detection of both pulses within a pair) will increase (either monotonically, or possibly with some ringing) with the pulse separation, and saturate at large pulse separation. This time of saturation will be the recovery time, and is usually also the value of pulse separation for which the probability of measuring the second pulse is equal to the probability of measuring the first pulse.	18
9	Low and high partial recovery times	$t_{partial\_low}$ $t_{partial\_high}$	s	The time duration after a photon detection event for the detection efficiency to return to x % of its steady-state value. x = 5, 10 or some other stated value for $t_{partial\_low}$; x = 99, 90 or some other stated value for $t_{partial\_high}$	The measurement method is based on that reported in [i.18], [i.9] and [i.19]. Optical pulse pairs of equal intensities at the single photon level are used to illuminate the detector under test. The laser pulses are synchronized to the detector gates and the relative time delay between the optical pulses only needs to be varied in steps of one gating period. At each time separation, detector outputs should be recorded for several pairs of incident photon pairs, where the time separation between pairs significantly exceeds the expected recovery time. Usually, the rate of coincidence (detection of both pulses within a pair) will increase (either monotonically, or possibly with some ringing) with the pulse separation, and saturate at large pulse separation.	18

Row number	Property	Symbol	Units	Description	Measurement method	Measurement clause
10	Detector signal jitter	$\eta(t,T)$, where T denotes photon arrival time	s	Photon detection probability (detection efficiency) variation with respect to the arrival of a single photon at the input port of the DUT.	In order to ensure good timing resolution of a single photon detector, the time interval between the absorption of a photon and the generation of an output electrical signal should be short and stable, corresponding to a small timing jitter. A common technique to determine this parameter is to measure the detector's instrument response function. For that purpose the FWHM of the laser pulses illuminating the detector should be much narrower than the single photon detector's timing jitter. By correlating many detection events with the trigger signal of the laser, a time histogram can be observed by a time-correlated photon counter, from which the detector's response function (detection efficiency vs. time) can be calculated. Measurements should be carried out using pulses incident at different times with respect to the gate trigger (within, and outside, the detector gate) to see if the timing jitter varies as a function of pulse temporal position.	19
11	Photon detection probability (detection efficiency) profile	$\eta(t)$	Unitless	Photon detection probability (detection efficiency) variation as a function of incident pulse arrival time.	The detection efficiency profile is obtained by calculating the mean detection efficiency for each detector signal jitter curve (row 10 of this table) and plotting these values as a function of the respective pulse arrival time relative to the gate trigger.	19
12	Spectral Responsivity	$\eta(\nu)$ or $\eta(\lambda)$		The photon detection probability (detection efficiency) as a function of wavelength of the incident photons.	Single-photon detectors are sensitive only over a spectral range determined by its constituting material. Within this certain spectral range their detection efficiency is a function of the wavelength of the incident photons, which is described as the detector's spectral responsivity. Losses in optical fibres are lowest at a wavelength of 1 550 nm, which makes this wavelength favourable for use in fibre-based QKD systems. To measure the spectral responsivity of the detector, its detection efficiency can be measured as described in the photon detection probability section at different wavelengths. The laser operation wavelength can be characterized by a commercial, calibrated wavemeter (0,01 nm).	20

5 Measurement conditions

5.1 Overview

Measurements shall be traceable to the SI system. This can be achieved by ensuring that all measurement equipment is calibrated to national standards.

The following conditions under which the various measurements described in clauses 6 to 20 are carried out shall be reported as follows:

i) Environment (temperature, humidity) Mandatory

ii) Operational settings of the DUT Mandatory, where the user has the ability to adjust them.

iii) Measurement set-up settings Recommended; mandatory where multiple properties requiring separate measurement set-ups are reported

Examples of DUT settings which may be relevant are shown in tables 5.1 and 5.2. Additional settings may be important, depending on the manner in which the DUT is operated.

Relevant measurement settings are listed within each measurement procedure.

If a device is characterized over a range of values of a (or many) setting(s), and it is decided not to report each measured quantity of a property corresponding to each value of each setting, then for each stated setting range (or sub-range), the maximum and minimum values of the measured quantity shall be stated. A typical (modal) value may also be stated, estimated as if the setting space is evenly sampled.

Measurement data shall not be extrapolated to cover extended settings.

Where multiple properties of a device are reported, measurement data corresponding to a common set of operational and measurement settings shall be reported (or available from measurements over extended setting ranges) to enable the user to understand the relationship between these properties for a given set of operational settings. By way of illustration, measurement of receiver dark count probability may be carried out for photodiode temperatures between 200 K and 270 K, while measurement of after-pulse probability may only be carried out between 250 K and 270 K. This means that between 250 K and 270 K, there is a common setting range for comparing these properties.

Examples of measurements for which common DUT and measurement are required are shown in tables 5.3 and 5.4.

Table 5.1

Electrical settings	Clock frequency	Trigger setting	Intensity setting
Optical settings	Attenuator setting(s)	Polarization	
Environmental settings	Emitter temperature		

Table 5.2

Electrical settings	Bias voltage(s)	Gate frequency	Gate bias profile
Optical settings			
Environmental settings	Photodiode temperature		

Table 5.3

Attenuated pulsed laser (transmitter)		
Measurements	**DUT settings (see note)**	**Measurement settings**
Source emission temporal profile, source timing jitter, source temporal profile, source wavelength, spectral linewidth, power stability	Input trigger level, intensity setting, emitter temperature	Spectral and temporal bandwidth
NOTE: Where adjustable.		

Table 5.4

Single-photon avalanche photodiode (receiver)		
Measurements	**DUT settings (see note)**	**Measurement settings**
After-pulse probability, detection efficiency, dark counts, detector signal jitter, detection efficiency profile	Sensor temperature, gate bias settings, gate repetition rate, gate duration	Input probe pulse characteristics, pulse position relative to gate, output signal threshold used to trigger measurement instrumentation
Dead-time, recovery times, reset time	Sensor temperature, gate bias settings, gate repetition rate	Input probe pulse characteristics, output signal threshold used to trigger measurement instrumentation
NOTE: Where adjustable.		

5.2 Electrical and optical inputs/outputs

5.2.1 Standardization

It is desirable that physical connections are standardized, in order to reduce the cost of calibrations. Specifying these settings should take account of any recommendations for interoperability.

Electrical I/O - type of connector - BNC, SMA, RP-SMA, SMB, SMK, etc.

Electrical I/O - signal format - TTL, CML, ECL, etc. for clock o/p, and any other signals.

Optical I/O - optical fibre core size and NA, SM, fibre connectors - e.g. FC/PC or FC/APC, key/slot size, etc.

5.2.2 Diagrams in clauses 6 to 20

Unless otherwise stated, in the figures in clauses 6 to 20, blue arrows denote the direction of photon flux within optical fibres, and black arrows indicate electrical signal flow.

6 Measurement of clock frequency, and its variation

6.1 Definitions, symbols and units

Definitions, symbols and units relevant to this clause can be found in clause 3

NOTE 1: The clock frequency is stated in Hz.

EXAMPLE: The electrical clock signal of interest can serve as a time reference for triggering an optical component, such as a source, detector, or modulator.

NOTE 2: The clock frequency variation is stated in Hz T^{-1}, where T can be seconds, minutes, hours, days etc.

NOTE 3: The clock frequency variation is expressed using the symbols $\Delta f_{clock}\, T^{-1}$, where T can be expressed in seconds, minutes, hours, days etc.

6.2 Procedure scope

This procedure covers the measurement of the clock frequency (f_{clock}) used to control the DUT, and which may be the clock in a QKD transmitter or receiver.

Measurement of the variation Δf_{clock} in f_{clock} is also covered in this procedure.

6.3 Measurement set-up

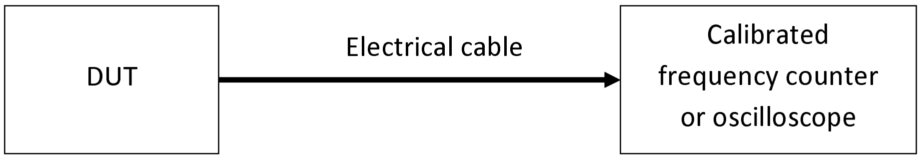


Figure 6.1: Measurement set-up

6.4 Applicable methods

6.4.1 Measurement of clock frequency

Measurement may be carried out with a frequency counter or a sampling or real-time oscilloscope.

6.4.2 Measurement of clock frequency variation

The methods described in clause 6.5 shall be used to measure f_{clock} and Δf_{clock} at intervals of time Δt, over some total time ΔT.

Each value of f_{clock} and Δf_{clock} , and the time of the measurement (and its uncertainty) relative to an arbitrary start time shall be recorded.

6.5 Measurement of clock frequency

6.5.1 Measurement with a frequency counter

6.5.1.1 Equipment required

A high-bandwidth frequency counter.

6.5.1.2 Equipment specifications

See Annex B for further details. Where no specifications are listed here, those listed in Annex B are sufficient.

DUT: The clock signal shall be externally available

Frequency counter.

6.5.1.3 Measurement process

6.5.1.3.1 Measurement position

The point at which measurements are made. This is normally the first point at which the signal from the DUT clock is accessible.

The set-up shown in figure 6.1 is used.

6.5.1.3.2 Signal

The measured frequency shall be displayed by the frequency counter.

6.5.1.4 Environment

The temperature and humidity of the environment during the measurement shall be recorded.

6.5.1.5 Operational settings

The control settings of the DUT shall be recorded.

Clause 5 provides guidance on the settings to be recorded.

6.5.1.6 Calculations

The mean frequency f_{clock} (Hz) and standard deviation of the emitted signal is recorded, using the in-built software of the frequency counter.

If the frequency counter does not have the functionality to calculate the standard deviation of the measured frequency, the measured values of the frequency are recorded, and the standard deviation calculated off-line.

6.5.1.7 Uncertainties

The measurement uncertainty $U(f_{clock})$ will be due to the calibration uncertainty of the frequency counter, appropriate for the measured frequency and signal waveform characteristics.

Further information relating to uncertainty evaluation can be found in Annexes A and B.

6.5.2 Measurement with an oscilloscope

6.5.2.1 Equipment required

A high-bandwidth, sampling or real-time, oscilloscope.

6.5.2.2 Equipment specifications

See Annex B for further details. Where no specifications are listed here, those listed in Annex B are sufficient.

DUT: The clock signal shall be externally available.

Oscilloscope: This instrument shall be capable of temporally resolving the signal expected from the DUT clock.

The linearity of the intensity axis is recommended, but is not mandatory.

The oscilloscope may be sampling or real-time.

6.5.2.3 Measurement process

6.5.2.3.1 Measurement position

The point at which measurements are made. This is normally the first point at which the signal from the DUT clock is accessible.

The set-up shown in figure 6.1 is used.

6.5.2.3.2 Signal

An output trace of the signal voltage is obtained.

A slower external trigger signal may also need to be supplied to the oscilloscope. If a sampling oscilloscope is used, this can be derived from the clock signal (e.g. by using a frequency divider as shown in figure 6.2).

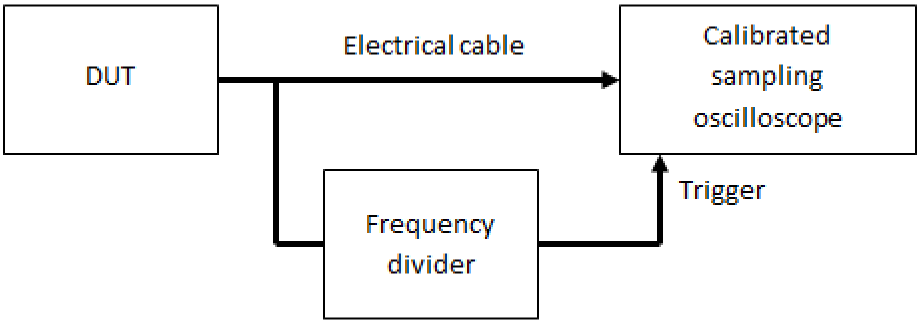


Figure 6.2: Measurement set-up for a sampling oscilloscope

6.5.2.4 Environment

The temperature and humidity of the environment during the measurement shall be recorded.

6.5.2.5 Operational settings

The control settings of the DUT shall be recorded.

Clause 5 provides guidance on the settings to be recorded

6.5.2.6 Calculations

The mean frequency f_{clock} (Hz) and standard deviation of the emitted signal is recorded, using the in-built software of the oscilloscope.

6.5.2.7 Uncertainties

The measurement uncertainty $U(f_{clock})$ will be due to the calibration uncertainty of the oscilloscope, appropriate for the measured frequency and signal waveform characteristics.

Further information relating to uncertainty evaluation can be found in Annexes A and B.

6.6 Measurement of clock frequency variation

6.6.1 Calculation

The methods described in clause 6.5.1 or 6.5.2 shall be used to measure f_{clock} and $U(f_{clock})$ at intervals of time ΔT, over some total time T.

Each value of f_{clock} and $U(f_{clock})$, and the time of the measurement (and its uncertainty) relative to an arbitrary start time shall be recorded.

6.6.2 Uncertainties

Information relating to uncertainty evaluation can be found in Annexes A and B.

6.7 Results

6.7.1 Reporting measurement on clock frequency

The following measurements on clock frequency shall be reported:

1) Unique identification number of DUT.
2) Measurement date(s).
3) Measurement duration.
4) Mean clock frequency and its uncertainty.
5) Measurement environment (temperature, humidity).
6) Measurement settings - see clause 5.
7) DUT operation settings - see clause 5.
8) Exceptions or deviations from procedure.
9) Measurement operator(s).

6.7.2 Measurement of clock frequency variation

The following measurements on clock frequency variation shall be reported:

1) Unique identification number of DUT.
2) Measurement date(s).
3) Measurement duration for individual measurements of $f_{clock.}$
4) Time spacing Δt of individual measurements of $f_{clock.}$
5) Total measurement time ΔT.
6) Each value of f_{clock} and $U(f_{clock})$, and the time of the measurement (and its uncertainty) relative to an arbitrary start time.
7) Any figures of merit extracted from the data, together with a description of how they were calculated.
8) Measurement environment (temperature, humidity).
9) Measurement settings - see clause 5.
10) DUT operation settings - see clause 5.
11) Exceptions or deviations from procedure.
12) Measurement operator(s).

6.7.3 Other information to be reported

The following information may be reported:

1) Measurement set-up.
2) Make and model number of key measurement equipment.
3) Measurement method.
4) Description of calculation.

5) Traceability to SI.

7 Measurement of output optical pulse repetition rate

7.1 Definitions, symbols and units

Definitions, symbols and units relevant to this clause can be found in clause 3.

NOTE: The optical pulse repetition rate is stated in Hz.

7.2 Procedure scope

This procedure covers the measurement of the repetition rate (frequency) of the optical pulses emitted by the DUT (as opposed to the clock signal frequency f_{clock}).

Where the DUT is a simple emitter, the repetition rate is represented by f_{source}.

Where the DUT is a more complex device such as a QKD transmitter, the repetition rate is represented by $f_{transmitter}$.

Measurement of the time-delay between the two pulse-trains created by an AMZI is also described, where the measurement allows it.

7.3 Measurement set-up

The measurement set-up is shown in figure 7.1.

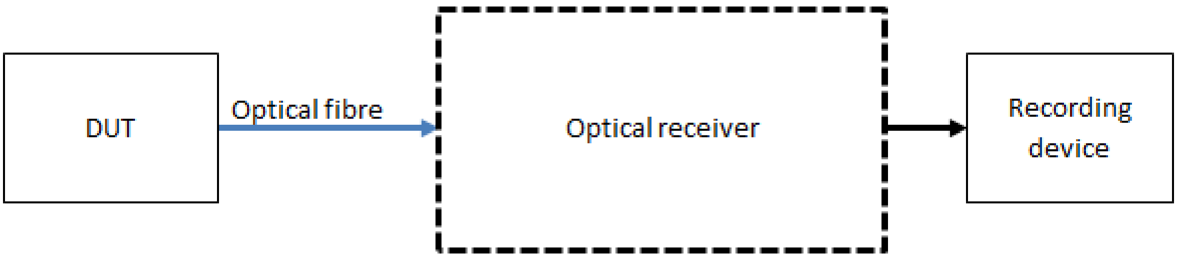


Figure 7.1: Measurement set-up

7.4 Applicable methods

7.4.1 Measurement before attenuation to the single-photon level

The pulse sequence produced by the emitted pulses is measured in the high-power regime, before attenuation to the single-photon level, in order to ensure that every pulse is measured with approximately equal probability. An analogue detector whose responsivity extends to a frequency which is greater than the expected optical pulse repetition rate, and which is ideally a least an order of magnitude greater, shall be used.

An example of such a device is a high-bandwidth photodiode, coupled to a high-bandwidth current-to-voltage amplifier, the output of which is connected to a recording device such as a high-bandwidth frequency counter or oscilloscope.

7.4.2 Measurement at the single-photon level

Using a single-photon counter to measure the pulse repetition rate at the single-photon level is not optimal, since the combination of $\eta_{detector} < 1$ and $\mu_{transmitter} < 1$ means that every pulse cannot be detected, and only an averaged temporal output can be measured. Therefore, random features or temporal variations in the pulse emission sequence may not be detected.

7.5 Measurement before attenuation to the single-photon level

7.5.1 Equipment required

1) A fibre-coupled, high-bandwidth analogue detector (e.g. a high-bandwidth photodetector coupled to a high-bandwidth current-to-voltage amplifier).

2) A means for recording the amplified detected signal as a function of time, such as a real-time oscilloscope or an event timer. A sampling oscilloscope, or a frequency counter may also be employed, although they will have limited ability to detect random or temporal variations in the pulse emission sequence.

7.5.2 Equipment specifications

See Annex B for further details. Where no specifications are listed here, those listed in Annex B are sufficient.

1) DUT:
   i) The optical signal shall be available, before attenuation to the single-photon level.
   ii) The clock signal will also be required if a sampling oscilloscope is used as the recording device.
2) High-bandwidth analogue detector and amplifier.
3) High-bandwidth oscilloscope:
   i) The linearity of the intensity axis should be calibrated, but is not mandatory
   ii) The oscilloscope should ideally be a real-time oscilloscope, capable of recording long signal trains.
   iii) A sampling oscilloscope may be used, although this will have limited ability to observe any non-periodic presence or absence of pulses.
4) Event timer.
5) Frequency counter:
   i) A frequency counter shall have limited ability to observe any non-periodic presence or absence of pulses.
   ii) A frequency counter shall not be able to measure the time-delay between the two pulse-train generated by an AMZI.

7.5.3 Measurement process

7.5.3.1 Measurement position

Arrangements shall be made to measure the optical pulses before they are attenuated to the single-photon level. This is necessary to ensure that every pulse is measured with approximately equal probability, and so check if pulses are missed, or extra pulses produced.

The measurement set-up is shown in figure 7.2.

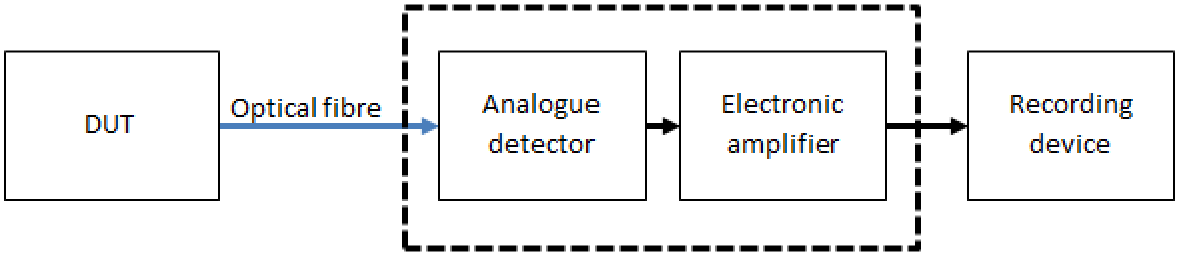


Figure 7.2: Measurement set-up

If the measurement is carried out after the AMZI in a QKD transmitter, then $f_{transmitter}$ is expected to be double the laser pulse repetition rate f_{source}.

7.5.3.2 Measurement signal

7.5.3.2.1 Measurement with a frequency counter

The threshold for registering an event on the frequency counter shall be set to record only one event per pulse, to ensure that there is no multiple triggering on a single pulse.

7.5.3.2.2 Measurement with a real-time oscilloscope

Multiple traces of the signal (pulse sequences) produced by the analogue detector shall be recorded, with the oscilloscope triggered by a signal that need not be derived from the DUT clock signal.

7.5.3.2.3 Measurement with an event timer

The threshold for registering an event on the timer/counter shall be set to record only one event per pulse, to ensure that there is no multiple triggering on a single pulse. Multiple event (pulse) sequences are recorded, with the counter/timer triggered by a signal that may not be derived from the DUT clock signal.

7.5.3.2.4 Measurement with a sampling oscilloscope

A trace (pulse sequence) is recorded. A slower external trigger signal, referenced to the DUT clock, may have to be supplied to the oscilloscope. This can be derived from the clock signal by using a frequency divider - see figure 7.3.

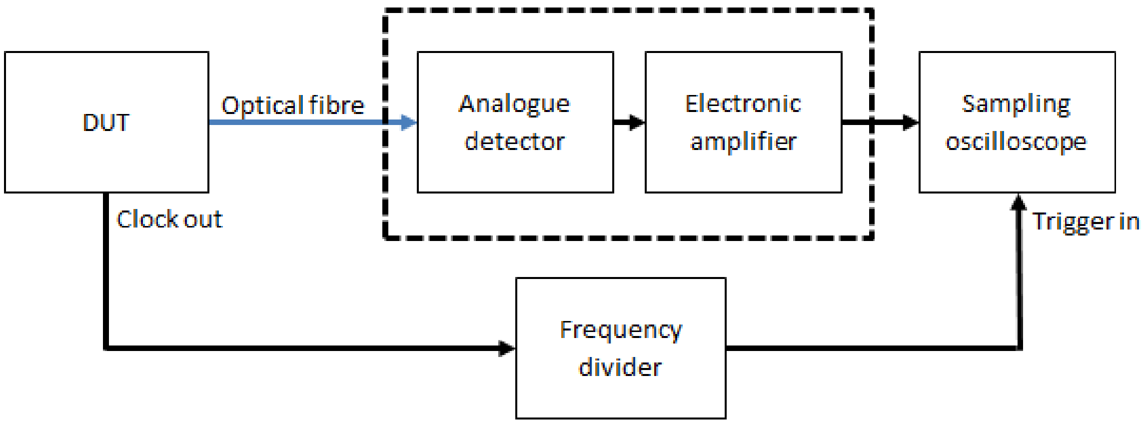


Figure 7.3: Measurement set-up for a sampling oscilloscope

7.5.3.2.5 Measurement, with an oscilloscope or event timer, of a transmitter incorporating an AMZI

Each measured trace (sequence) shall include at least three (ideally at least four) pulses if one wishes to measure the arrival time difference between the pulse trains emanating from the two separate arms of the AMZI (see clause 7.5.6.1.2.3). Note that it is likely that one pulse train will not be delayed by exactly half of its period with respect to the other pulse train.

A frequency counter cannot be used to measure the arrival time difference between the pulse trains emanating from the two separate arms of the AMZI.

7.5.4 Environment

The temperature and humidity of the environment during the measurement shall be recorded.

7.5.5 Operational settings

The control settings of the DUT shall be recorded.

Clause 5 provides guidance on the parameters to be recorded.

7.5.6 Calculations

7.5.6.1 Calculation of pulse frequency

7.5.6.1.1 Measurement with frequency counter

The mean frequency f_{each} (Hz) of producing a given number, n, of pulses is recorded.

An overall mean frequency, f_{source} (Hz) or $f_{transmitter}$ (Hz), is calculated:

$$f_{overall} = \frac{\sum_{1}^{k} f_{each_i}}{k} \tag{7.1}$$

where k pulse sequences were measured.

7.5.6.1.2 Measurement with a real-time oscilloscope or event timer

7.5.6.1.2.1 Detected pulse sequences

The detected pulse sequences are inspected for missing or aperiodic pulses.

7.5.6.1.2.2 Simple emitter

The mean frequency f_{each} (Hz) from each pulse sequence is calculated.

The calculation of f_{each} (Hz) may be carried out using the in-built analysis software of the recording device, or external analysis software.

Alternatively, f_{each} (Hz) may be calculated from a recorded pulse-train trace as follows:

The mean frequency f_{each} (Hz) from each pulse sequence is given by:

$$f_{each} = \frac{n-1}{|T_1 - T_n|} \tag{7.2}$$

where n pulses are counted within a particular pulse sequence, T_1 is the time of the peak of the first pulse, T_n is the time of the peak of the final pulse.

Standard curve-fitting calculations may be applied to determine T_1 and T_n.

The overall mean frequency, f_{source} (Hz), is calculated using equation (7.1), where $f_{source} = f_{overall}$, and k signal trains were measured.

If the calculations of f_{each} used differing numbers of pulses, equation (7.1) shall be weighted appropriately.

7.5.6.1.2.3 Transmitter incorporating an AMZI

The mean frequency f_{each} (Hz) from each pulse sequence is calculated as described in equation (7.2).

An odd number of pulses shall be counted in applying equation (7.2), so that pulses from the same arm of the AMZI are used to determine T_1 and T_n. A second calculation should also be performed where pulses from the other arm of the AMZI are used to determine T_1 and T_n. Hence two estimations f_{eachP} and f_{eachQ} of f_{each} are generated, where P and Q denote the different arms of the AMZI.

The overall mean frequency, $f_{transmitter}$ (Hz), is calculated similarly to (7.1):

$$f_{transmitter} = \frac{\sum_{1}^{k} f_{eachP_i} + \sum_{1}^{k} f_{eachQ_i}}{2k} \tag{7.3}$$

where k signal trains were measured.

7.5.6.1.3 Measurement with a sampling oscilloscope

7.5.6.1.3.1 Averaging

A sampling oscilloscope builds up its trace from many pulse sequences, and therefore incorporates averaging over many pulse sequences.

The overall mean frequency, f_{source} (Hz) or $f_{transmitter}$ (Hz), is calculated from the repeatedly sampled wavetrain. In the case of a simple emitter, this calculation may be carried out using the in-built analysis software of the recording device. Otherwise, the calculations described in clauses 7.5.1.3.2 and 7.5.1.3.3 shall be used.

7.5.6.1.3.2 Simple emitter

The overall mean frequency $f_{overall}$ (Hz) is calculated:

$$f_{overall} = \frac{n-1}{|T_1 - T_n|} \tag{7.4}$$

where n pulses were observed in the pulse train, T_1 is the time of the peak of the first pulse, T_n is the time of the peak of the final pulse.

Standard curve-fitting calculations may be applied to determine T_1 and T_n.

7.5.6.1.3.3 Transmitter incorporating an AMZI

An odd number of pulses shall be counted in applying equation (7.4), so that pulses from the same pulse-train are used to determine T_1 and T_n. A second calculation shall also be carried where pulses from the other pulse-train are used to determine T_1 and T_n. Hence two estimations $f_{overallP}$ and $f_{overallQ}$ of $f_{overall}$ are generated, where P and Q denote the different arms of the AMZI.

$$f_{transmitter} = \frac{f_{overallP} + f_{overallQ}}{2} \tag{7.5}$$

7.5.6.2 Calculation of arrival time difference between the pulse-trains produced by the two arms of the AMZI

7.5.6.2.1 Measurement with real-time oscilloscope or event timer

The positions of all, or a selected set of consecutive, pulses in the pulse sequence are calculated.

Standard curve-fitting calculations may be applied.

The mean pulse-train separations from each signal train are calculated:

$$T_{each\,1} = \frac{\sum_{1}^{p} \left| T_{2i} - T_{2i-1} \right|_i}{p} \quad \text{and} \quad T_{each\,2} = \frac{\sum_{1}^{q} \left| T_{2i+1} - T_{2i} \right|_i}{q} \qquad (7.6)$$

where:

- T_{each1} is the time-delay of the pulse-train represented by the (2nd, 4th, etc.) pulses in the pulse sequence with respect to the pulse-train due to the (1st, 3rd, etc.) pulses in the pulse sequence;
- T_{each2} is the time-delay of the pulse-train represented by the (3rd, 5th, etc.) pulses in the pulse sequence with respect to the pulse-train due to the (2nd, 4th, etc.) pulses in the pulse sequence;
- m is the number of consecutive pulses used in the calculation;
- $p=m/2$ [m even], $p=(m-1)/2$ [m odd];
- $q=(m-2)/2$ [m even], $q=(m-1)/2$ [m odd].

The user may choose to select 1 or more subsets of consecutive pulses from a particular measured pulse sequence for analysis.

The overall pulse-train separations are calculated:

$$T_{Separation\,1} = \frac{\sum_{1}^{k} T_{each1_i}}{k} \quad \text{and} \quad T_{Separation\,2} = \frac{\sum_{1}^{k} T_{each2_i}}{k} \qquad (7.7)$$

where k pulse sequences or sub-sequences are analysed.

Note that T_{each1} for one pulse sequence may correspond to T_{each2} of another pulse sequence, depending on which pulse-train provides the first pulse of the respective sequence.

7.5.6.2.2 Measurement with a sampling oscilloscope

The positions of all, or a selected set of consecutive, pulses in the pulse sequence are calculated.

Standard curve-fitting calculations may be applied.

The mean pulse-train separations from each signal train are calculated:

$$T_{separation\,1} = \frac{\sum_{1}^{p} \left| T_{2i} - T_{2i-1} \right|_i}{p} \quad \text{and} \quad T_{separation\,2} = \frac{\sum_{1}^{q} \left| T_{2i+1} - T_{2i} \right|_i}{q} \qquad (7.8)$$

where:

- $T_{separation1}$ is the time-delay of the pulse-train represented by the (2nd, 4th, etc.) pulses in the pulse sequence with respect to the pulse-train due to the (1st, 3rd, etc.) pulses in the pulse sequence;

- $T_{separation2}$ is the time-delay of the pulse-train represented by the (3rd, 5th, etc.) pulses in the pulse sequence with respect to the pulse-train due to the (2nd, 4th, etc.) pulses in the pulse sequence;
- m is the number of pulses in the pulse sequence;
- $p=m/2$ [m even], $p=(m-1)/2$ [m odd];
- $q=(m-2)/2$ [m even], $q=(m-1)/2$ [m odd];

The user may choose to select 1 or more subsets of consecutive pulses from the measured pulse sequence for analysis.

7.5.7 Uncertainties

7.5.7.1 Measurement equations

Equations (7.1) to (7.8) are the relevant measurement equations.

Equations (7.2), (7.4), (7.6), and (7.8) are based on the same general procedure:

i) A sequence of pulses is measured and selected for analysis.

ii) The number of pulses in the sequence is counted.

iii) The position of certain pulses is measured in the instrumental time-scale. A consistent measure is used for determining the pulse position, e.g. peak position, centre-of-gravity, etc.

iv) The separation in time between the pulses is calculated in the instrumental time-scale, and converted into 'true', i.e. SI-traceable time.

It may be assumed that no error, or uncertainty, is introduced in step ii). However, the user shall check that this is the case, and if not, estimate an appropriate uncertainty.

Averaging, and calculating the standard deviation over many pulses and wavetrains will take account of uncertainties due to jitter and noise.

7.5.7.2 Measurement of frequency

This is relevant to equations 7.2 and 7.4.

These equations involve measuring the pulse positions of a pulse sequence comprising approximately identical pulses This being the case, any distortion due to the analogue detector and amplifier which means that the recorded signal is not a faithful representation of the optical signal can be ignored, once the recorded pulses are individually resolved and do not overlap each other.

If some more sophisticated analysis is performed, for example by evaluating principal Fourier components, then one should estimate whether these factors cause any significant error.

Where an AMZI is incorporated, non-linearities in the photodiode and/or amplifier (see clause B.5) may mean that any difference in the pulse shapes in the two pulse-trains results in their being distorted to differing extents. In this situation, the method of extracting values for f_{each} from each pulse sequence should compensate for this effect (clause 7.5.6.1.2.3).

7.5.7.3 Measurement of arrival time difference between the pulse-trains produced by each arm of an AMZI

This is relevant to equations 7.6 and 7.8.

Where an AMZI is incorporated, two-interleaved pulse trains are measured; the pulses within each pulse-train will be approximately identical, while the pulses from different pulse-trains may differ slightly in intensity and shape. Non-linearities in the photodiode and/or amplifier (see clause B.7) may then lead to the pulses in the two pulse-trains being distorted to differing extents.

7.5.7.4 Uncertainty evaluation

Further information relating to uncertainty evaluation can be found in Annexes A and B.

7.6 Measurement at the single-photon level

7.6.1 Equipment required

1) Fibre-coupled gated non-photon-number-resolving photon counter.

2) Means for synchronizing the arrival of a photon at the detector within the duration of the detector gate.

3) Event timer with histogram capability.

7.6.2 Equipment specifications

See Annex B for further details. Where no specifications are listed here, those listed in Annex B are sufficient.

1) DUT: The optical signal shall be available:

   i) The clock signal shall be available.

2) Photon counter: The detector gates shall be externally triggerable.

3) Tunable delay: This is to synchronize the arrival of a photon at the detector within the duration of the detector gate.

4) Event timer.

7.6.3 Measurement process

7.6.3.1 Measurement position

The point at which measurements are made. This is normally the first point at which the signal from the DUT is accessible.

The measurement set-up shown in figure 7.4.

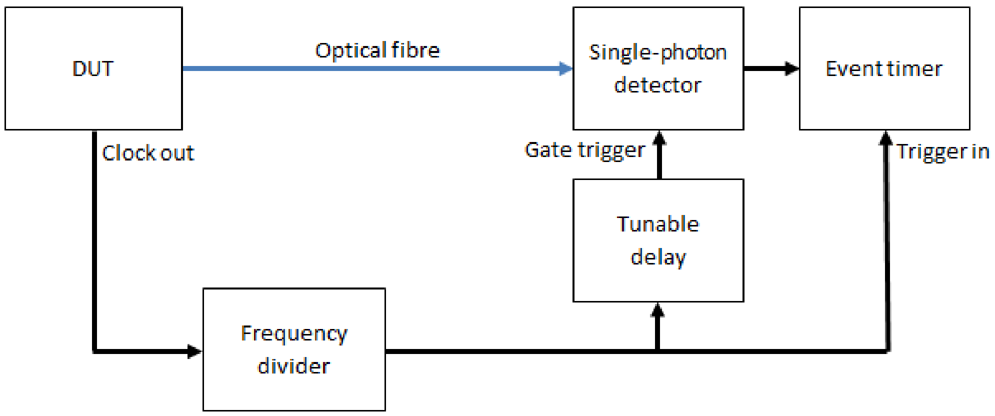


Figure 7.4: Measurement set-up for measurement at single-photon level

7.6.3.2 Measurement signal - a simple emitter

Individual measurements should be repeated a number of times to enable a mean and standard deviation to be calculated.

The following options are available:

i) A single-photon detector with a gate narrower than the shortest expected output pulse spacing is used as the optical measurement device. The detector shall be triggered at a frequency of (f_{clock}/n), where n is a positive integer ($n \geq 1$). A histogram of detections versus time-delay is collected, and a tunable delay is used to synchronize every nth pulse from the pulse-train with the detector gate. The tunable delay is then incrementally changed by steps << 1/ f_{clock} until the pulses from the pulse-train are again synchronized within the detector gate. A consistent criterion shall be used to determine when the pulses are synchronized. A suitable criterion may be when the number of detections is maximized.

The above principle may be applied to measure the time between k consecutive synchronizations.

From the detection histogram, the time between consecutive synchronizations will yield the pulse spacing, from which the repetition rate of the photon source f_{source}, shall be calculated.

It is expected that the detector gate will be wider than the optical pulse. Even if this is not the case, the above still applies.

Note that this method shall only be able to confirm if there are emitted pulses at (and/or multiples/sub-multiples of) the trigger frequency.

ii) The detector gate can be set wide enough so that n consecutive pulses can be measured within a single detector gate, where n is a positive integer (n ≥ 1). The jitter from the detection system shall not prevent adjacent output pulses from being resolved.

A histogram of detections versus time is collected, and the pulse spacing obtained. The histogram counter and detector shall be triggered at intervals corresponding to (n + int) clock triggers, where n and int are positive integers {n ≥ 1, (int ≥ 0)}.

It may be observed that there are more counts towards the start of the detector gate, since the detector may only be able to record one event within a gate.

iii) A free-running detector, such as an SNSPD or a free-running SPAD, can be used as the optical measurement device. The detector should not need to be repeatedly triggered.

The jitter from the detection system shall not prevent adjacent output pulses from being resolved.

A histogram of detections versus time is collected, and the pulse spacing obtained. The histogram counter shall be triggered at intervals corresponding to (n + int) clock triggers, where n and int are positive integers (n ≥ 1, int ≥ 0).

7.6.3.3 Measurement signal - a QKD transmitter incorporating an AMZI

i) Measurements are carried out as described in clause 7.6.3.2 i). In this case the shortest expected output pulse spacing can be less than half that of the simple device without an AMZI. The tunable delay is used to synchronize every nth pulse from one of the pulse-trains (corresponding arbitrarily to either the long or short arm of the AMZI) with the detector gate. The tunable delay is then incrementally changed by steps << 1/(2 f_{clock}) until every nth pulse from the adjacent pulse-train is synchronized within the detector gate. The tunable delay is then further varied until pulses from the first pulse-train are again synchronized. The tunable delay is then further varied until pulses from the second pulse-train are again synchronized, etc. From the detection histogram, the time between pulses from the same pulse-train will yield the pulse repetition rate of the photon source f_{source}, and the spacing between the separate pulse-trains will give the arrival time difference between the pulse trains ~ 1/(2. f_{source}).

ii) Measurements are carried out as described in clause 7.6.3.2 ii). The detector gate is set wide enough so that at least 3 (ideally ≥ 4) consecutive pulses shall be measured within a single detector gate.

A histogram of detections versus time is collected. The time between next-nearest neighbouring pulses shall yield the pulse repetition rate of the photon source f_{source}, and the time between nearest neighbouring pulses will give the arrival time difference between the two pulse trains ~ 1/(2. f_{source}).

iii) Measurements are carried out as described in clause 7.6.3.2 iii). At least 3 (ideally ≥ 4) consecutive pulses shall be measured.

A histogram of detections versus time is collected. The time between next-nearest neighbouring pulses shall yield the pulse repetition rate of the photon source f_{source}, and the time between nearest neighbouring pulses shall give the arrival time difference between the two pulse trains ~ 1/(2. f_{source}).

7.6.4 Environment

The temperature and humidity of the environment during the measurement shall be recorded.

7.6.5 Operational settings

The control settings of the DUT shall be recorded.

Clause 5 provides guidance on the settings to be recorded.

7.6.6 Calculations

7.6.6.1 Method described in clauses 7.6.3.2 i) and 7.6.3.3 i)

The positions of the first synchronization, T_1, and the mth synchronization, T_m, are calculated from the measured histograms. Standard curve-fitting calculations may be applied.

The mean pulse period T_{period} (s) is given by:

$$T_{period} = \frac{\sum_{1}^{k} \left| T_1 - T_m \right|_i}{k(m-1)} \tag{7.9}$$

where k measurements of $\left| T_1 - T_m \right|$ were carried out.

The global mean frequency f_{source} (Hz) is given by:

$$f_{source} = \frac{1}{T_{period}} \tag{7.10}$$

Where the pulses are transmitted through an AMZI equation 7.11 shall be used, and m shall be an odd number, so that pulses from the same pulse-train are used to determine T_1 and T_m, e.g. the first and third synchronizations. A second calculation shall also be carried out where pulses from the other pulse-train are used to determine T_1 and T_m, e.g. the second and fourth synchronizations. Hence two estimations $T_{periodP}$ and $T_{periodQ}$ of T_{period} are generated, where P and Q denote the different arms of the AMZI.

$$t_{period} = \frac{\sum_{1}^{k} \left| t_1 - t_m \right|_i}{k(m-1)/2} \tag{7.11}$$

$$f_{transmitter} = \frac{4}{T_{periodP} + T_{periodQ}} \tag{7.12}$$

Standard curve-fitting calculations may be applied to determine T_1 and T_m.

The mean pulse-train separations from each synchronization sequence are calculated:

$$T_{separation\_1} = \frac{\sum_{1}^{p} \left| T_{2i} - T_{2i-1} \right|_i}{p} \quad \text{and} \quad T_{separation\_2} = \frac{\sum_{1}^{q} \left| T_{2i+1} - T_{2i} \right|_i}{q} \tag{7.13}$$

where:

- $T_{separation\_1}$ is the time-delay of the pulse-train represented by the (2nd, 4th, etc.) synchronizations in the synchronization sequence with respect to the pulse-train due to the (1st, 3rd, etc.) synchronizations in the synchronization sequence;
- $T_{separation\_2}$ is the time-delay of the pulse-train represented by the (3rd, 5th, etc.) synchronization in the synchronization sequence with respect to the pulse-train due to the (2nd, 4th, etc.) synchronization in the synchronization sequence;
- m is the number of synchronizations in the synchronization sequence;
- $p=m/2$ [m even], $p=(m-1)/2$ [m odd];
- $q=(m-2)/2$ [m even], $q=(m-1)/2$ [m odd];

The overall pulse-train separations are calculated:

$$T_{separation\_1} = \frac{\sum_{1}^{k} T_{each1_i}}{k} \quad \text{and} \quad T_{separation\_2} = \frac{\sum_{1}^{k} T_{each2_i}}{k} \qquad (7.14)$$

where k synchronization sequences or sub-sequences are analysed.

Note that T_{each1} for one synchronization sequence may correspond to T_{each2} of another synchronization sequence, depending on which pulse-train provides the first synchronization of the respective sequence.

7.6.6.2 Methods described in 7.6.3.2 ii) and 7.6.3.3 ii)

Let there be k measured pulse sequences.

Let each measured pulse-train contain m pulses, yielding $(m-1)$ separations.

The calculations described for synchronization sequences in clause 7.6.6.1 shall be applied to the measured pulse sequences.

Note that the entire measured pulse sequence need not be analysed; the user may choose to select 1 or more subsets of consecutive pulses from a particular measured pulse sequence for analysis.

7.6.6.3 Methods described in 7.6.3.2 iii) and 7.6.3.3.iii)

Let there be k measured pulse sequences.

Let each measured pulse-train contain m pulses, yielding $(m-1)$ separations.

The calculations described for synchronization sequences in clause 7.6.6.1 shall be applied to the measured pulse sequences.

Note that the entire measured pulse sequence need not be analysed; the user may choose to select 1 or more subsets of consecutive pulses from a particular measured pulse sequence for analysis.

7.6.7 Uncertainties

7.6.7.1 Measurement equations

Equations 7.9 to 7.14 are the relevant measurement equations.

i) A sequence of pulses is measured and selected for analysis.

ii) The number of pulses in the sequence is counted.

iii) The position of certain pulses is measured in the instrumental time-scale. A consistent measure is used for determining the pulse position, e.g. peak position, centre-of-gravity, etc.

iv) The separation in time between the pulses is calculated in the instrumental time-scale and converted into 'true', i.e. SI-traceable time.

It may be assumed that no error, or uncertainty, is introduced in step ii). However, the user shall check that this is the case, and if not, estimate an appropriate uncertainty.

Averaging, and calculating the standard deviation over many pulses and wavetrains shall take account of uncertainties due to jitter and noise.

7.6.7.2 Measurement of frequency

This is relevant to equations 7.10 to 7.12.

Detector saturation may lead to incorrect measuring of pulse position. If no saturation data is available for the single-photon detectors, saturation can be investigated by using an attenuator which is spectrally neutral in the wavelength range of the pulses.

Where an AMZI is incorporated, there may be a difference in the pulse shapes from the two pulse trains. In this situation, the method of extracting two values for T_{period} from each pulse sequence should compensate for this.

7.6.7.3 Measurement of arrival time difference between the pulse-trains produced by each arm of an AMZI

This is relevant to equations 7.13 and 7.14.

Detector saturation can lead to incorrect measuring of pulse position. If no saturation data is available for the single-photon detectors, saturation may be investigated by using an attenuator which is spectrally neutral in the wavelength range of the pulses.

7.6.7.4 Uncertainty evaluation

Further information relating to uncertainty evaluation can be found in Annexes A and B.

7.7 Results

7.7.1 Reporting measurement on output optical pulse repetition rate:

The following measurements on output optical pulse repetition rate shall be reported:

1) Unique identification number of DUT.
2) Measurement date(s).
3) Measurement duration.
4) Mean repetition rate and its uncertainty.
5) Measurement environment (temperature, humidity).
6) DUT operation settings - see clause 5.
7) Exceptions or deviations from procedure.
8) Measurement operator(s).

7.7.2 Other information to be reported:

The following information may be reported:

1) Measurement set-up.
2) Make and model number of key measurement equipment.
3) Measurement method.
4) Description of calculation.
5) Traceability to SI.

8 Measurement of mean photon number

8.1 Definitions, symbols and units

Definitions, symbols and units relevant to this clause can be found in clause 3.

NOTE: The mean photon number is stated in photons pulse^{-1}.

8.2 Procedure scope

This procedure covers the measurement of the mean photon number(s) (μ) of the pulses emitted by a fibre-coupled Device Under Test (DUT).

The DUT may be a simple emitter, such as an attenuated pulsed laser, or a more complex device such as a QKD transmitter.

The DUT may operate in the following modes:

a) The DUT emits pulses with the same μ.
b) The DUT emits pulses whose μ changes according to a fixed, repetitive pattern.
c) The DUT emits pulses whose μ changes randomly from pulse to pulse.

For pulses with a particular μ, the probability of there being N photons in a pulse is assumed to follow the Poissonnian distribution, i.e.

$$p(N,\mu) = \frac{\mu^N}{N!} e^{-\mu} \tag{8.1}$$

where μ is the mean number of photons in a pulse (mean photon number), and $p(N, \mu)$ is the probability of there being N photons in a particular pulse when the mean photon number is μ.

The procedure is only applicable where the emission is confined to a single, continuous spectral region.

In the case where the DUT is a QKD transmitter, it is assumed that the DUT incorporates an asymmetric Mach-Zehnder interferometer (AMZI) which splits the pulse train emitted by the photon emitter inside the DUT into a pair of pulse trains, where one train is delayed relative to the other. It is possible that this delay will not be exactly $1/(2.\ f_{source})$.

In the case where the DUT is a QKD transmitter, signals for quantum and classical communications may be multiplexed into the same optical fibre. Where the performance of an internal source module is being reported based on measurements on such a complete QKD transmitter, the classical communication laser(s) shall be turned off for the duration of the measurements, or appropriate filtering applied to remove the classical signals to an acceptable level.

Where an output from a complete QKD transmitter is being reported, measurements with the classical communications laser turned off may still be relevant (e.g. for certain security analyses on QKD transmitters in which emissions from the classical communications laser(s) are introduced into the fibre(s) carrying the quantum channel after all the components that are involved in encoding information on the quantum channel) and shall be reported. In other cases, measurements on emissions within the quantum channel after filtering (classical communications laser(s) on), as may be applied in a QKD receiver may be relevant (e.g. for certain performance analyses) and shall be reported.

Where classical communications are emitted by the DUT the measurement conditions shall be reported with the result. These shall include whether the classical communications laser(s) were turned on or off, what classical traffic was being sent if turned on and what filtering was applied to the output of the DUT before the measuring apparatus.

8.3 Measurement set-up

The measurement set-up is shown in figure 8.1.

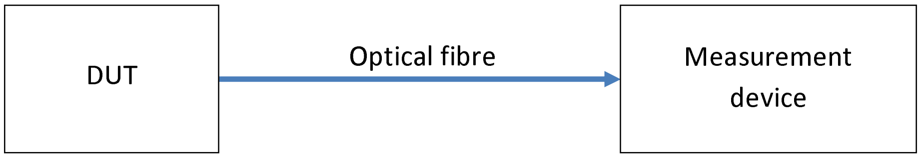


Figure 8.1 Measurement set-up

8.4 Applicable methods

8.4.1 Measurement with a power meter

This method is only applicable for clause 8.2 a), and where the emitted power from the DUT is large enough to be measureable with a power meter.

8.4.2 Measurement with a gated photon counter

8.4.2.1 Method 1: Every detector gate is illuminated

8.4.2.2 Method 2: Every *R*th detector gate is illuminated

Both methods are applicable for clause 8.2 a) and b). Only method 1 is applicable for clause 8.2 c)

8.5 Measurement with a power meter

8.5.1 Applicability

This method is only applicable for clause 8.2 a).

a) The emitted power at the output port of the DUT is high enough to be directly measurable with a power meter.

b) The sensitivity of the power meter is such that the power cannot be measured at the single-photon output of the DUT. In this case, arrangements shall be made to measure the optical pulses before they are attenuated to the single-photon level. In this case the spectral transmittance $t(\nu)$ from the point of measurement to the exit of the DUT shall also be measured.

c) In the case where the DUT is a QKD transmitter, this method only allows the mean photon number μ_{both}, summed over both split pulses produced by the AMZI in the DUT, to be measured.

8.5.2 Equipment required

1) Fibre-coupled power meter.

2) Measurement of pulse repetition rate - see clause 7.

3) Measurement of spectral frequency of photons - see clause 13.

8.5.3 Equipment specifications

See Annex B for further details. Where no specifications are listed here, those listed in Annex B are sufficient.

1) DUT: The optical signal shall be available:

   i) Access to the optical signal before attenuation to the single-photon level (if required).

   ii) The clock signal shall be available.

2) Power meter: The optical power responsivity shall be traceably calibrated to the SI at the repetition rate of the DUT pulses, and in the spectral region of interest.

8.5.4 Measurement process

8.5.4.1 Measurement position

The point at which measurements are made. This is normally the first point at which light from the DUT is externally accessible.

The set-up shown in figure 8.1 is used.

8.5.4.2 Spectrum

The spectrometer (the measurement device in figure 8.1) is connected to the DUT.

The spectral power density as a function of frequency (or wavelength), $S_{meas}(\nu)$, in units of W Hz^{-1} of the emitted pulses is measured (see clause 13).

If the sensitivity of the spectrometer is such that the spectrum cannot be measured at the single-photon output of the DUT, arrangements shall be made to measure the optical pulses before they are attenuated to the single-photon level. In this case, any spectral variation in the transmittance path from the point of measurement to the exit of the DUT shall be measured - see methods B and C in [6].

8.5.4.3 Power

The power meter (the measurement device in figure 8.1) is connected to the DUT.

The emitted power P_{meas} (W), in units of W, is measured using the power meter, and corrected for any signal offset in the absence of radiation.

If the sensitivity of the power meter is such that the spectrum cannot be measured at the single-photon output of the DUT, arrangements shall be made to measure the optical pulses before they are attenuated to the single-photon level. In this case, the spectral transmittance of the path from the point of measurement to the exit of the DUT shall be measured - see methods B and C in [6].

8.5.4.4 Pulse repetition rate

The emitted optical pulse repetition rate, f_{source} for a simple component, $f_{transmitter}$ for a complex device, as opposed to the laser trigger frequency f_{clock}, shall be confirmed by measurement (see clause 7).

For a QKD transmitter $f_{transmitter}$ is expected to be double the laser trigger frequency f_{clock} because of the embedded AMZI.

8.5.5 Environment

The temperature and humidity of the environment during the measurement shall be recorded.

8.5.6 Operational settings

The control settings of the DUT shall be recorded.

Clause 5 provides guidance on the settings to be recorded.

8.5.7 Calculations

The mean spectral frequency ν_m (Hz) of the emitted spectrum is calculated from $S_{meas}(\nu)$ (see clause 13).

If the spectrum was measured at a point before the desired measurement position, the measured spectrum $S_{meas}(\nu)$ shall be corrected for the spectral transmittance $t(\lambda)$ or $t(\nu)$ of the path from the actual measurement position to the desired measurement position before calculating mean spectral frequency ν_m (Hz) at the desired measurement position. See methods B and C in [6].

If the power was measured at a point before the desired measurement position, the measured power P_{meas} shall be corrected for the spectral transmittance $t(\lambda)$ or $t(\nu)$ of the path from the actual measurement position to the desired measurement position to obtain the power P at the desired measurement position. See methods B and C in [6].

There are five possible cases:

i) The spectrum and power are measured at the single-photon output point.

ii) The spectrum and power are measured at the same point before the single-photon output point.

iii) The spectrum and power are measured at different points before the single-photon output point.

iv) The spectrum is measured before the single-photon output point, while the power is measured at the single-photon output point.

v) The spectrum is measured at the single-photon output point, while the power is measured before the single-photon output point.

Case iii) is unlikely in practice. In the remaining cases, the spectral transmittance $t(\nu)$ of the path from the point of measurement before the single-photon output to the single-photon output is measured.

Case i):

$$S_{meas}(\nu) \to \nu_m \; ; P = P_{meas} \tag{8.2a}$$

Case ii):

$$S_{meas}(\nu)t(\nu) \to \nu_m \; ; P = P_{meas}\frac{\int S_{meas}(\nu)t(\nu)}{\int S_{meas}(\nu)} \tag{8.2b}$$

Case iv):

$$S_{meas}(\nu)t(\nu) \to \nu_m \; ; P = P_{meas} \tag{8.2c}$$

Case v):

$$S_{meas}(\nu) \to \nu_m \; ; P = P_{meas}\frac{\int S_{meas}(\nu)}{\int \left[S_{meas}(\nu)/t(\nu) \right]} \tag{8.2d}$$

The response of the power meter is assumed to be spectrally flat over the spectral extent of the pulse ($\Delta\lambda \lessapprox 1$ nm). If this is not the case, equations (8.2a) to (8.2d) will need to be modified accordingly.

For a simple component:

$$\mu = \frac{P}{f_{source} h\nu_m} \tag{8.3a}$$

For a QKD transmitter which includes an AMZI:

$$\mu_{both} = \frac{2P}{f_{transmitter}\, h\nu_m} \tag{8.3b}$$

where h is Planck's constant.

8.5.8 Uncertainties

Equations 8.3 are the measurement equations. Equations 8.2 are the measurement equations for P, and clauses 7 and 13 cover the evaluation of f_{source} or $f_{transmitter}$ and ν_m.

Further information concerning uncertainty evaluation can be found in Annexes A and B.

8.5.9 Results

8.5.9.1 Reporting measurement on mean photon number

The following measurements on mean photon number shall be reported:

1) Unique identification number of DUT.
2) Measurement date(s).
3) Measurement duration.
4) Pulse repetition rate and its uncertainty.
5) Mean spectral frequency and its uncertainty.
6) Mean photon number and its uncertainty.
7) Any steps taken to exclude classical communication signals co-existing on the same fibre (see clause 8.2).
8) Measurement environment (temperature, humidity).
9) DUT operational settings - see clause 5.
10) Exceptions or deviations from procedure.
11) Measurement operator(s).

8.5.9.2 Other information to be reported

The following information may be reported:

1) Measurement set-up.
2) Make and model number of key measurement equipment.
3) Measurement method.
4) Description of calculation.
5) Traceability to SI.

8.6 Measurement with a gated photon counter

8.6.1 Applicability

This method is applicable for clause 8.2 a), b) and c).

8.6.2 Equipment required

1) Fibre-coupled gated non-photon-number-resolving single-photon detector.
2) Means for synchronizing the arrival of a photon at the detector within the duration of the detector gate.
3) Means for separating the two pulse trains produced by the AMZI within a QKD transmitter (where relevant).
4) Measurement of pulse repetition rate - see clause 7.
5) Measurement of spectral frequency of photons - see clause 13.

8.6.3 Equipment specifications

See Annex B for further details. Where no specifications are listed here, those listed in Annex B are sufficient.

1) DUT:
   i) The single-photon output signal shall be available.
   ii) Access to optical signal before attenuation to single-photon level (if required).
   iii) The clock signal shall be available.
2) Photon counter:
   iv) The temporal width of the detector gate shall be longer than the temporal width of the transmitter pulses.
   v) See clause 8.6.4.5.4.
   vi) Refer to clauses 3 and 15.1 for definitions and discussion of the after-pulse probabilities p_{after_first}, p_{after_all}, p_{after_total}.
3) Synchronization: Means (such as a tunable delay) for synchronizing the arrival of a photon at the detector within the duration of the detector gate, such that any jitter imparted by the synchronization equipment maintains the arrival of a photon at the detector within the detector gate.

8.6.4 Measurement process

8.6.4.1 Measurement position

The point at which measurements are made. This is normally the first point at which light from the DUT is accessible.

The set-up shown in figure 8.2, or variants thereof, shall be used.

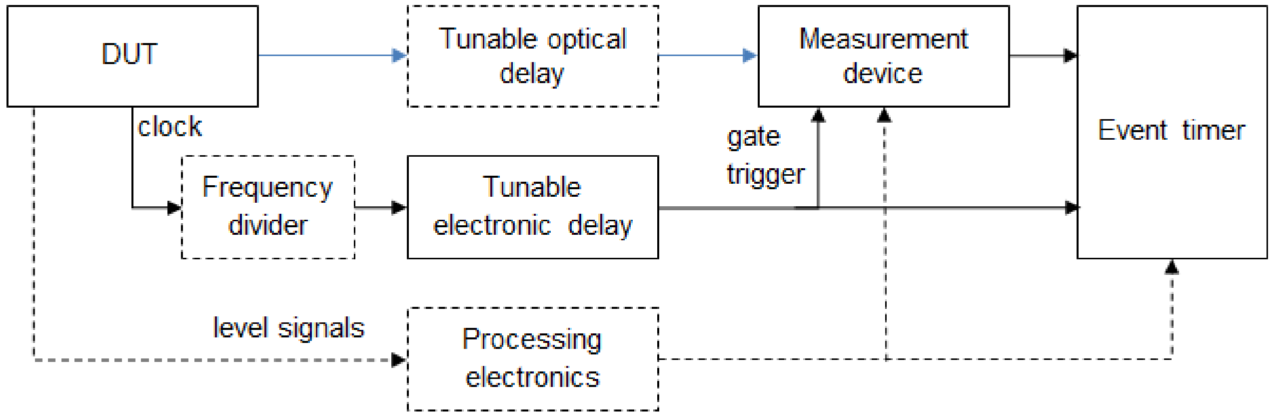


Figure 8.2: Experimental set-up.

Blue arrows indicate optical signals, black arrows electrical signals, dotted lines indicate optional equipment.

8.6.4.2 Pulse-pair considerations

In the case where the DUT is a QKD transmitter, it is assumed that the DUT incorporates an asymmetric Mach-Zehnder interferometer (AMZI) which splits the pulse train emitted by the photon emitter inside the DUT into a pair of pulse trains, where one train is delayed relative to the other. It is possible that this delay will not be exactly 1/(2. f_{source}).

Each pulse train is measured separately.

This requires that one, and only one, pulse from each of the emitted pulse trains shall be positioned within a detector gate.

This can be implemented if the detector gate is narrow enough to achieve this, while remaining broader than the optical pulse.

If this is not the case, but the detector gate is narrow enough to achieve this when one of the pulse trains is excluded from the emitted pulse stream, measurements can be carried out by excluding one pulse train, and then the other. In the case of systems which use polarization to encode pulses from the separate arms of the AMZI, this shall be done by inserting a polarization controller and beamsplitter/polarizer at the output of the QKD transmitter. The measurements will need to correct for the spectral transmittance losses $t(\lambda)$ or $t(\nu)$ introduced by these extra components.

[In order to measure both pulse trains at the same time, a detector whose gate width spanned only two pulses, one from each pulse train, is required. The detector recovery time is required to be shorter than the time separation between the pulses, i.e. shorter than the detector gate. This method may be implemented with a continuously gated detector of suitably short recovery time, together with some means of producing an optical or electronic gate to define the number of pulse-pairs measured. This is outside the scope of the present document].

8.6.4.3 Spectrum

The spectrometer (the measurement device in figure 8.2) is connected to the DUT.

The spectral power density as a function of wavelength, $S_{meas}(\nu)$, in units of W Hz^{-1} of the emitted pulses is measured (see clause 13).

If the sensitivity of the spectrometer is such that the spectrum cannot be measured at the single-photon output of the DUT, arrangements shall be made to measure the pulses before they are attenuated to the single-photon level. In the latter case, the measured spectrum $S_{meas}(\nu)$ shall be corrected for the spectral transmittance $t(\lambda)$ or $t(\nu)$ of the path from the actual measurement position to the desired measurement position before calculating mean spectral frequency ν_m (Hz) at the desired measurement position. See methods B and C in [6].

8.6.4.4 Pulse repetition rate

The emitted optical pulse repetition rate, $f_{transmitter}$, (as opposed to the laser trigger signal frequency f_{clock}) shall be confirmed by measurement (see clause 7).

For a QKD transmitter $f_{transmitter}$ is expected to be double the laser optical output rate f_{clock} because of the embedded AMZI.

8.6.4.5 Mean photon number

8.6.4.5.1 General considerations

The single-photon detector (the measurement device in figure 8.2) is connected to the DUT.

If the normal operation of the DUT is that another device (e.g. the QKD receiver) provides the master clock, then the set-up shown in figure 8.2 may be adapted, with the other device providing the master clock to the DUT, frequency divider or tunable electronic delay, and single-photon detector, as required.

Using a tunable electronic or optical delay, or both, the arrival of the optical pulses is set within the optical gate of the detector.

If an optical delay is used, the measured mean photon number shall be corrected for the spectral transmittance $t(\lambda)$ or $t(\nu)$ of the optical delay and connectors. See methods B and C in [6]. If the optical delay is built into the DUT, it can be treated as part of the DUT, and no corrections are required, assuming that there is no delay-dependent change in attenuation.

The time between successive detector gates shall exceed the detector dead-time and, ideally, the detector recovery time.

In the situation where clause 8.2 c) applies, additional signals (level signals) may need to be processed to identify the random changes in mean photon number settings.

8.6.4.5.2 Method 1: Every detector gate is illuminated

The detector gate frequency is either the same as the source trigger frequency, or an integer division of the source trigger frequency. In the latter case, a frequency divider can be included in the electronic delay circuit.

It is recommended that the detector gate frequency is set, if possible, to be some integer sub-multiple of the DUT clock frequency, so that the detection after-pulse probability is at least two orders of magnitude less than the detection efficiency. An optical shutter may be employed to block any pulses reaching the detector when it is not gated. The transmission loss $t(\nu)$introduced by this of extra component shall be accounted for in equation (8.6).

The intrinsic dark count probability per gate of the detector, p_{idark}, shall be calibrated as described in clause 15.6.6.3;

The series of first after-pulse probabilities, Σp_{after_first} shall be calibrated as described in clause 15.6.6.3 for the same gate repetition rate and gate-width, over the range(s) of incident mean photon number expected.

For incident photons corresponding a specific mean photon number setting of the DUT, the number of illuminated detector gates, N_{gates}, and the corresponding number of detections, N_{click}, is recorded.

8.6.4.5.3 Method 2: Every *R*th detector gate is illuminated

The detector gate frequency is an integer multiple R of the source trigger frequency. In this case, the detector or a device other than the DUT will provide the master clock, and a frequency divider can be used to divide the master clock frequency down to the desired DUT clock frequency.

In this case, only every Rth detector gate will be illuminated, as illustrated in figure 8.3.

The detection efficiency of the detector shall be calibrated as described in clause 15.6.6.4 with the same detector gate frequency, integer ratio R of detector gates to source pulses, at the spectral frequency of interest, ν_m, over the ranges of incident mean photon number expected.

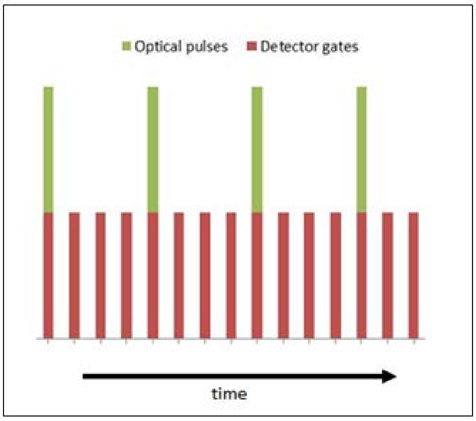


Figure 8.3: Illustration of only every *R*th gate being illuminated

Green columns indicate optical pulses, red columns indicate detector gates. In the illustration, $R = 4$, and a scan lasts for approximately 3.5 laser pulse periods.

Counts in illuminated gates are due to true detections, after-pulses and dark counts, whereas counts in non-illuminated gates are due to after-pulses and dark counts.

A cycle of gates refers to the R detector gates of a laser pulse period, where the first gate in the cycle is illuminated.

For incident photons of a specific mean photon number setting, the number of illuminated detector gates, N_{gates}, and the number of detections in each gate, C_X, are recorded.

NOTE: This method cannot be applied for clause 8.2 c).

8.6.4.5.4 Detector constraints

i) General

In order that $0 \le p_{true} \le 1$ in equations (8.8) and (8.10) below, the following constraints apply (refer to clauses 3, 8.6.7 and 15.1 for definitions and additional description of terms):

Method 1:	Method 2:
$0 \le p_{click} \le 1$	$0 \le p_{click\_i} \le 1$
$0 \le p_{idark} < 1$	$0 \le p_{dark} < 1$
$0 \le \Sigma p_{after\_first} < 1$	$0 \le p_{after\_R} < 1$

NOTE: p_{after_R} is the after-pulse probability in the gate immediately preceding an illuminated gate.

ii) p_{dark}

$p_{dark} > p_{idark}$, hence upper bounds applied to p_{dark} are valid for p_{idark}.

In order to reduce the number of darks to at most the same order of magnitude as the number of true counts (in order to ensure that the uncertainty in p_{dark} does not dominate the calculation of μ), the following more stringent constraints are recommended:

p_{dark} should be such that $N_{dark} < N_{true}$, i.e. $p_{dark} < 1 - e^{-\eta\mu}$

A simple method for checking this is to compare counts obtained with the source off (darks + dark after-pulses) to counts with the source on (trues + darks + (true+dark) after-pulses).

For known values of η, p_{dark} , this gives an estimate of the equivalent value of μ:

$$\mu > -\frac{1}{\eta}\ln\left(1 - p_{dark}\right) \tag{8.4}$$

A value of $p_{dark} < 0,01$ is generally achievable with telecom SPADs. Therefore it is recommended that $p_{dark} < 0,01$

iii) After-pulses

In order to ensure that the number of after-pulses is at most an order of magnitude less than the number of true counts (to ensure that the uncertainty in p_{after} does not dominate the calculation of μ), the following more stringent constraints are recommended:

Method 1: A value of $\Sigma p_{after\_first} < 0,1$ is generally achievable with telecom SPADs. Therefore it is recommended that $\Sigma p_{after\_first} < 0,1$.

For clause 8.2 c), it is required that $p_{after\_first}(1.\Delta T) \leq 0,001$, where $p_{after\_first}(1.\Delta T)$ is the first after-pulse probability after 1 gate, and ΔT is the gate repetition period. A value of $p_{after\_total} \leq 0,001$ is also satisfactory.

Method 2: A value of $p_{after\_R} \leq 0,1$ is generally achievable with telecom SPADs. Therefore it is recommended that $p_{after\_R} \leq 0,1$.

Methods 1 and 2: The total after-pulse probability p_{after_total} will exceed both Σp_{after_first} and p_{after_R}. Therefore, a value of $p_{after\_total} \leq 0,1$ is also satisfactory.

8.6.5 Environment

The temperature and humidity of the environment during the measurement shall be recorded.

8.6.6 Operational settings

The control settings of the DUT shall be recorded.

Clause 5 provides guidance on the settings to be recorded.

8.6.7 Calculations

8.6.7.1 General

The mean spectral frequency ν_m (Hz) of the emitted spectrum is calculated from $S_{meas}(\nu)$ (see clauses 13 and 8.6.4.3).

For pulses from an attenuated laser operating above threshold with a mean number of photons per pulse, μ, the probability of there being N photons in a pulse is assumed to follow the Poisson distribution, and the probability of a true detection, i.e. one due to the detection of a photon, and not a dark count or after-pulse, from a non-photon-number-resolving detector, is given by:

$$p_{true} = 1 - \exp\left(-\mu\eta\right) \tag{8.5}$$

where μ is the mean photon number to be measured, and η is the DE of the single-photon detector, calibrated at ν_m.

Therefore:

$$\mu = -\frac{1}{\eta\, t\left(\nu_m\right)}\ln\left(1 - p_{true}\right) \tag{8.6}$$

where $t(\nu_m)$ is the transmittance at ν_m of any additional optical elements inserted between the DUT and the single-photon detector.

8.6.7.2 Method 1: Every detector gate is illuminated

The probability of a detector count, p_{click} , for pulses of a specific mean photon level setting is recorded:

$$p_{click} = \frac{N_{\text{click}}}{N_{gates}} \tag{8.7}$$

N_{click} is due to a combination of true counts, dark counts, and after-pulses.

The probability of a true count is given by [i.22]:

$$p_{true} = 1 - \frac{(1 - p_{click})}{(1 - p_{idark})(1 - p_{click} \sum p_{after\_first})} \tag{8.8}$$

where:

p_{idark} is the intrinsic dark count probability per gate;

Σp_{after_first} is the series of all first after-pulse probabilities, measured for the same gate repetition rate, gate-width, and approximate incident mean photon number.

Hence μ can be calculated from equation 8.6.

8.6.7.3 Method 2: Every *R*th detector gate is illuminated

The click probability in the illuminated gate, p_{click_i}, is obtained by dividing the number of clicks in the illuminated gate C_i by the number of source triggers, N_{trig};

p_{click_i} is the combination of the true detection probability, p_{true}, and the probability of 'other' clicks, $p_{other}(R.\Delta T)$, due to dark counts and after-pulses of 'true' counts in the preceding illuminated gates:

$$p_{click\_i} = \frac{C_i}{N_{trig}} = 1 - (1 - p_{true})(1 - p_{other}(R.\Delta T)) \tag{8.9}$$

p_{true} may be estimated by approximating $p_{other}(R.\Delta T)$ with $p_{other}([R-1].\Delta T) = C_R/N_{trig}$, where C_R is the number of counts in gate R (non-illuminated). This may slightly overestimate $p_{other}(R.\Delta T)$:

$$p_{true} = 1 - \frac{1 - C_i / N_{trig}}{1 - C_R / N_{trig}} \tag{8.10}$$

Alternatively, the value of $p_{other}(R.\Delta T)$ may be estimated by extrapolation, based on knowledge of C_2 *to* C_R.

8.6.8 Uncertainties

Equation 8.6 is the measurement equation.

The uncertainty due to any variation or difference in maintaining the DUT output pulses at the same point within the single-photon detector gate at which the single-photon detector was calibrated shall be evaluated.

The value of η used in equation 8.6 may need to be adjusted if:

i) The spectrum of the emitted pulses is different to the wavelength at which the detector was calibrated. In this case an estimate of the detection efficiency of the photon counter at the emitted wavelength shall be made.

ii) The temporal extent of the emitted pulses are different to that used to calibrate the photon counter.

Additional corrections may be needed to take account of detector recovery times (clause 18).

Use of $\Sigma p_{after\_all} = p_{after\_total}$ instead of Σp_{after_first} will introduce a small error in evaluating equation 8.8. A small value of p_{after_total} reduces the size of this error. A correction shall be made for this error, and the estimated uncertainty included when evaluating the overall uncertainty of the measurement.

Further information relating to uncertainty evaluation can be found in Annexes A and B.

8.6.9 Results

8.6.9.1 Reporting measurement on mean photon number

The following measurements on mean photon number shall be reported:

1) Unique identification number of DUT.
2) Measurement date(s).
3) Measurement duration.
4) Pulse repetition rate and its uncertainty.
5) Mean spectral frequency and its uncertainty.
6) Mean photon number(s) and their uncertainties.
7) Measurement environment (temperature, humidity).
8) DUT operational settings (see clause 5) and mode of operation (see clauses 8.2 a) to 8.2 c)).
9) Any steps taken to exclude classical communication signals co-existing on the same fibre (see clause 8.2).
10) Exceptions or deviations from procedure.
11) Measurement operator(s).

8.6.9.2 Other information to be reported

The following information may be reported:

1) Measurement set-up.
2) Make and model number of key measurement equipment.
3) Measurement method.
4) Synchronization data - detector gate profile, electronic synchronization jitter, synchronization curve (detector counts as a function of tunable delay).
5) For modes 8.4 b) and 8.4 c), evidence that the correct pulses corresponding to a specific mean photon number setting were measured.
6) Description of calculation.
7) Traceability to SI.

9 Measurement of mean source power

9.1 Definitions, symbols and units

Definitions, symbols and units relevant to this clause can be found in clause 3.

NOTE: The mean source power is stated in W.

9.2 Procedure scope

This procedure covers the measurement of the mean optical power, averaged over all pulses emitted by a fibre-coupled DUT, over some stated time-interval.

The DUT may be a simple emitter, such as an attenuated pulsed laser, or a more complex device such as a QKD transmitter.

The stated time-interval may be the time of a QKD session, or some other stated time-interval.

The DUT may operate in the following modes:

i) the DUT emits pulses with the same μ;

ii) the DUT emits pulses whose μ changes according to a fixed, repetitive pattern;

iii) the DUT emits pulses whose μ changes randomly from pulse to pulse.

9.3 Measurement set-up

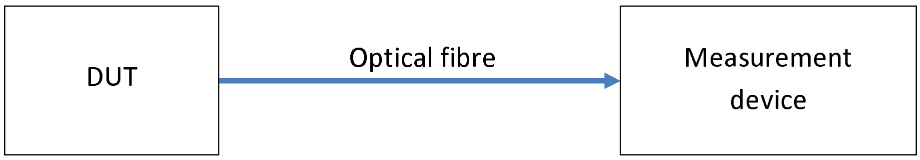


Figure 9.1 Measurement set-up

9.4 Applicable methods

9.4.1 Measurement with a power meter

The power at the output of the DUT is continuously measured using the methods described in clause 8.5.

9.4.2 Calculation from measurement of mean photon number(s)

The mean photon numbers (and their relative frequencies in cases 9.2 ii) and 9.2 iii)) are continuously measured, using the procedures described in clause 8.6. From these measured values, the mean power is calculated.

9.5 Measurement with a power meter

The emitted power is measured using the power meter, and corrected for any signal offset in the absence of radiation.

If measurements are carried out at a point before attenuation to the single-photon level, the transmittance of the optical path from the measurement point to the single-photon output port of the DUT shall be measured. See methods B and C of IEC EN 60793-1-40 [6].

9.6 Environment

The temperature and humidity of the environment during the measurement shall be recorded.

9.7 Operational settings

The control settings of the DUT shall be recorded.

Clause 5 provides guidance on the settings to be recorded.

9.8 Calculations

9.8.1 Measurement with a power meter

The mean power is given by:

$$P_{mean} = \langle P \rangle \tag{9.1}$$

where P are a series of measurements measured over the specified time-interval, and corrected for any losses in the path between the point of measurement and the required measurement position (see clause 8.5).

9.8.2 Measurement of mean photon number(s)

The mean photon numbers are continuously measured during the key session or other time-interval, using the methods described in clause 8.6.

$$P_{mean} = \left\langle \left(\sum_{1}^{2n} \mu_j p_j \right) \right\rangle \frac{f_{transmitte}}{2} h\nu_m \tag{9.2}$$

where:

- n is the number of different pulse intensity states
- μ_j are the measured mean photon numbers (one for each arm of the AMZI per pulse intensity state)
- p_j are the relative fraction of the total number of pulses emitted for each pulse intensity state j
- $f_{transmitter}$ is the total pulse output rate (Hz)
- h is the Planck constant (Js)
- ν_m is the mean spectral frequency of the pulses (assumed to be identical) (Hz)

9.8.3 Uncertainties

Equations 9.1 and 9.2 are the relevant measurement equations.

Further information relating to uncertainty evaluation can be found in Annexes A and B.

9.9 Results

9.9.1 Reporting measurement on mean source power

The following measurements on source power shall be reported:

1) Unique identification number of DUT.
2) Measurement dates.
3) Measurement duration.
4) Mean power and its uncertainty.
5) Measurement environment (temperature, humidity).
6) DUT operational settings - see clause 5.
7) Exceptions or deviations from procedure.

8) Measurement operator(s).

9.9.2 Other information to be recorded

The following information may be reported:

1) Measurement set-up.

2) Make and model number of key measurement equipment.

3) Measurement method.

4) Description of calculation.

5) Traceability to SI.

10 Measurement of stability of mean optical power of emitted pulses

10.1 Definitions, symbols and units

Definitions, symbols and units relevant to this clause can be found in clause 3.

NOTE: The stability of the output power of emitted pulses is stated in dB/<X>, where <X> may be seconds, minutes, hours, days.

10.2 Procedure scope

This procedure covers the measurement of the stability of the mean optical power of the pulses emitted by a fibre-coupled DUT, over some stated time-interval.

The DUT may be a simple emitter, such as an attenuated pulsed laser, or a more complex device such as a QKD transmitter.

The stated time-interval may be the time of a QKD session, or some other stated time-interval.

The DUT may operate in the following modes:

i) The DUT emits pulses with the same μ;

ii) The DUT emits pulses whose μ changes according to a fixed, repetitive pattern;

iii) The DUT emits pulses whose μ changes randomly from pulse to pulse.

10.3 Applicable methods

Measurements can be carried out as described in clause 9, where the time of each measurement period is suitably short so that the variation of the output power can be recorded, and the stability determined.

Where a power meter is employed, the shortest measurement time for a single measurement shall be determined by the response time and S/N ratio of the power meter. Similarly, when a photon counter is employed, the shortest measurement time for a single measurement shall be determined by the S/N ratio.

The overall time over which measurements are carried out shall be determined by the requirements for the measurement. Short-term (of the order of 1 s), medium-term (the duration of a QKD key session), and long-term (of the order of days and weeks) stability values may all be required.

10.4 Calculation

The FWHM and span of the frequency histogram of the output power measurements are calculated.

The span shall be the central range of power values which encompass a stated fraction of all recorded values. The remaining values shall be split equally on either side of the central range. Values for the stated fraction may be 0,90, 0,95, 0,99, or any other stated value.

10.5 Uncertainties

Information relating to uncertainty evaluation can be found in Annexes A and B.

10.6 Environment

The temperature and humidity of the environment during the measurement shall be recorded.

10.7 Results

10.7.1 Reporting measurement on stability of mean optical power of emitted pulses

The following measurements on stability of mean optical power of emitted pulses shall be reported:

1) Unique identification number of DUT.
2) Measurement date(s).
3) Total measurement duration, and duration of individual measurements.
4) Mean power stability (FWHM and span) and its uncertainty.
5) Measurement environment (temperature, humidity).
6) DUT operational settings - see clause 5.
7) Exceptions or deviations from procedure.
8) Measurement operator(s).

10.7.2 Other information to be reported

The following information may be reported:

1) Measurement set-up.
2) Make and model number of key measurement equipment.
3) Measurement method.
4) Description of calculation.
5) Traceability to SI.

11 Confirmation of Poissonian nature of emitted pulses

11.1 Definitions, symbols and units

Definitions, symbols and units relevant to this clause can be found in clause 3.

11.2 Procedure scope

This procedure covers the measurement of the short-term, i.e. pulse-to-pulse, energy/power instability from a fibre-coupled (pseudo-) single-photon source (the device under test, DUT), such as an attenuated pulsed laser.

The short-term instability of output power of emitted pulses is estimated by means of the Grangier α parameter [i.5]

NOTE 1: The Grangier α parameter [i.5] is dimensionless.

The procedure is only applicable where the emission is confined to a single, continuous spectral region.

The DUT may be a simple emitter, or a more complex device such as a QKD transmitter.

If the mean pulse energy of the laser is unstable, this shall induce a super-Poissonian behaviour of the, in principle, Poissonian behaviour of the pulsed coherent source, that can be detected from the measurement of the α parameter (Grangier et al. [i.5])

The pulse instability can be represented by a probability density function of the mean number of photons per pulse $f(\mu)$, thus the probability of having n photons per pulse can be expressed as:

$$p(n) = \int \mathrm{d}\mu\, f(\mu)\ \mathrm{Poi}(\mathrm{n}|\mu) \tag{11.1}$$

with $\mathrm{Poi}(\mathrm{N}|\mu) = \mu^N \exp(-\mu^N)/N!$. In the case of a stable Poissonian source of μ_0 mean number of photon per pulse, the probability density function reduces to a Dirac delta function, i.e. $f(\mu) = \delta(\mu - \mu_0)$.

In general, defining $\mu_0 = \int \mathrm{d}\mu\, \mu\, f(\mu)$, and $Var[\mu] = \int \mathrm{d}\mu\, (\mu - \mu_0)^2\, f(\mu)$, it can be shown that:

$$\langle N \rangle = \mu_0,$$

$$\langle N^2 \rangle - \langle N \rangle^2 = \mu_0 + Var[\mu], \tag{11.2}$$

where the super-Poissonian behaviour is represented by the term $Var[\mu]$. This has a direct implication on the value of $g^{(2)}(0)$ (for which α represents a good approximation), since:

$$g^{(2)}(0) = \frac{\left(\langle N^2 \rangle - \langle N \rangle\right)^2}{\langle N \rangle} = 1 + \frac{Var[\mu]}{{\mu_0}^2}. \tag{11.3}$$

Thus, observing $\alpha > 1$ corresponds to the presence of some super-Poissonian, i.e. non-stable, behaviour of the source. The value of α provides some information regarding the magnitude of these fluctuations, i.e. the variance.

Full reconstruction of the probability density function $f(\mu)$ requires that all the moments of the distribution should be measured, i.e. all the higher-order g-functions.

In the case where the DUT is a QKD transmitter, it is assumed that the DUT incorporates an asymmetric Mach-Zehnder interferometer (AMZI) which splits the pulse train emitted by the photon emitter inside the DUT into a pair of pulse trains, where one train is delayed relative to the other. It is possible that this delay will not be exactly $1/(2.\ f_{source})$.

This procedure can be adapted to a Device Under Test (DUT) operating in the following modes:

a) the DUT emits pulses with the same μ;

b) the DUT emits pulses whose μ changes according to a fixed, repetitive pattern;

c) the DUT emits pulses whose μ changes randomly from pulse to pulse;

by using time-tagging techniques.

11.3 Measurement set-up

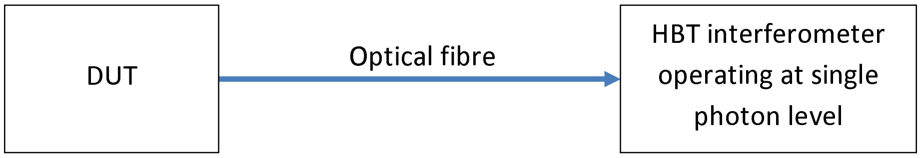


Figure 11.1: Measurement set-up

11.4 Applicable methods

11.4.1 Measurement with an HBT interferometer operating at the single-photon level

This method is applicable to a pulsed pseudo-single-photon-source that induces counts on the (click/noclick) single-photon detectors operating far below their saturation level. The measurement apparatus consists of a Hanbury Brown-Twiss (HBT) interferometer comprising a beamsplitter and two click/noclick detectors. As these detectors will have finite dead-times, it is necessary to reduce the repetition rate of the DUT in order to not lose counts because of these dead-times (i.e. the period of the repetition rate should be longer than the deadtime). If this is not possible, appropriate corrections should be performed.

11.5 Measurement with an HBT interferometer operating at the single-photon level

11.5.1 Equipment required

1) Two fibre-coupled gated non-photon-number-resolving single-photon detectors.

2) Pigtailed 50:50 (non-polarizing) beam splitter.

3) Means for synchronizing the arrival of photons at the detectors within the duration of their detector gates.

4) Electronics to perform time-correlated single photon counting (TCSPC), in particular coincidence measurements (such as e.g. TAC, MCA or time-tagging systems).

11.5.2 Equipment specifications

See Annex B for further details. Where no specifications are listed here, those listed in Annex B are sufficient:

1) DUT: Access to the optical single-photon output shall be available.

2) Single-photon detectors:

   i) The detection efficiency shall be approximately known in the spectral region of interest.

   ii) The temporal width of the detector gate shall be longer than the temporal width of the transmitter pulses.

   iii) The presence of unexpected non-linear behaviour by the detectors should be investigated.

3) 50:50 beam-splitter: The pigtailed beam-splitter is part of the HBT interferometer. The splitting behaviour and its independence from the polarization of the input pulses shall be confirmed.

4) Synchronization: Means (such as a tunable delay) for synchronizing the arrival of a photon at the detector within the duration of the detector gate, such that any jitter imparted by the synchronization equipment maintains the arrival of a photon at the detector during the detector gate.

5) TCSPC electronics: The TCSPC electronics (e.g. an event timer) shall be tested and characterized in order to ensure that their temporal answers are the correct ones and no over- or under-estimation of the coincident events occur.

11.5.3 Measurement process

11.5.3.1 Pulse-pair considerations

In the case where the DUT is a QKD transmitter, it is assumed that the DUT incorporates an Asymmetric Mach-Zehnder Interferometer (AMZI) which splits the pulse train emitted by the photon emitter inside the DUT into a pair of pulse trains, where one train is delayed relative to the other. It is possible that this delay will not be exactly $1/(2. f_{source})$.

Each pulse train is measured separately.

This requires that one, and only one, pulse from each of the emitted pulse trains can be positioned within the detector gate.

This shall be implemented if the detector gate is narrow enough to achieve this, while remaining broader than the optical pulse.

If this is not the case, but the detector gate is narrow enough to achieve this when one of the pulse trains is excluded from the emitted pulse stream, measurements can be carried out by excluding one pulse train, and then the other. In the case of systems which use polarization to encode pulses from the separate arms of the AMZI, this shall be done by inserting a polarization controlled and beamsplitter/polarizer at the output of the QKD transmitter. The measurements will need to correct for losses introduced by these extra components.

11.5.3.2 Measurement position

The point at which measurements are made. This is normally the first point at which light from the DUT is accessible.

11.5.3.3 Pulse repetition rate

The emitted optical pulse repetition rate, $f_{transmiter}$, (as opposed to the laser trigger signal frequency f_{clock}) shall be confirmed by measurement (clause 7).

For a QKD transmitter $f_{transmitter}$ is expected to be double the laser optical output rate f_{clock} because of the embedded AMZI.

11.5.3.4 Measurement of emitted pulses

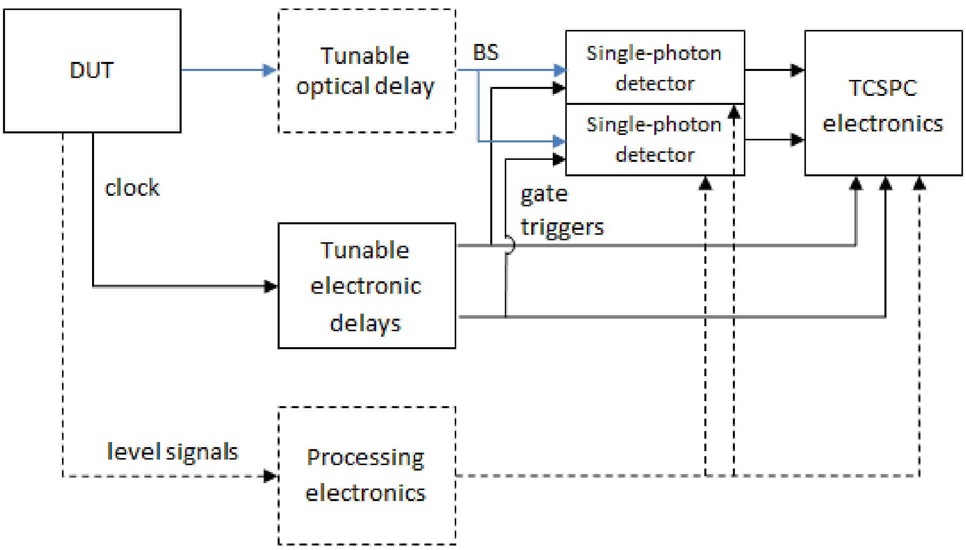


Figure 11.2: The set-up used to measure the Grangier α parameter

In figure 11.2, blue arrows indicate optical signals, black arrows electrical signals. BS stands for fibre-coupled beamsplitter. Dashed lines indicate optional equipment.

If the normal operation of the DUT is that another device (e.g. the QKD receiver) provides the master clock, then the system as shown in figure 11.2 shall be adapted, where the Clock signal from the DUT to the Tunable electronic delays is replaced by connecting the Clock signal from this other device to the DUT and Tunable electronic delays.

Using tunable electronic or optical delays, or both, the arrival of photons is set within the optical gates of the two detectors.

The detector gate frequency is either the same as the clock frequency, or an integer sub-multiple of the clock frequency. In the latter case, a frequency divider may be included after the clock output.

Sub-multiples of the clock frequency may be used to investigate instabilities at different time scales. This will reveal if correlated or anti-correlated behaviour is present for different time-intervals.

The time between successive detector gates shall exceed the detector dead-time, and ideally, the detector recovery time.

In the situation described in clause 11.2 c), additional signals (level signals) may need to be processed to identify the random changes in mean photon number settings.

11.6 Environment

The temperature and humidity of the environment during the measurement shall be stable and recorded.

11.7 Operational settings

The control settings of the DUT shall be recorded.

Clause 5 provides guidance on the settings to be recorded.

11.8 Calculations

The single-photon emission is measured by means of the parameter α (Grangier et al. [i.5]). In the situation described, α is equivalent to the Glauber second-order autocorrelation function at time $T = 0$ (i.e. $g^{(2)}(T = 0)$). For this reason the measurement of the parameter α with the experimental apparatus described above is often referred to as the measurement of $g^{(2)}$.

The parameter α is estimated as the ratio between the probability of a coincidence count induced by the light emitted by the source ($p_{\text{coincTrue}}$) and the product of the probability of a "click" by each detector induced by the photons of the source ($p_{\text{true,A}}\, p_{\text{true,B}}$), i.e.

$$\alpha = \frac{p_{coincTrue}}{p_{\text{true},A}\, p_{\text{true,B}}} \tag{11.4}$$

The detection probability of having a click from a photon of the source $p_{\text{true,i}}$ (with $i=A,B$) is estimated from the probability of having a click $p_{\text{click,i}}$:

$$p_{\text{click,i}} = p_{true,i} + p_{noise,i} - p_{true,i}\, p_{noise,i} \tag{11.5}$$

where $p_{noise,i}$ is due to either dark counts, after-pulses or stray light. Note that the last term accounts for the fact that both the detection of a "true" photon and a "noise" count may occur within the same gate.

$p_{\text{true,I}}$ is obtained by inverting the above formula as:

$$p_{true,i} = \frac{p_{\text{click,i}} - p_{noise,i}}{1 - p_{noise,i}} \tag{11.6}$$

The probability of a coincidence count $p_{coincTrue}$ is similarly obtained from p_{coinc}:

$$p_{\text{coinc}} = p_{coincTrue} + p_{trueA}\, p_{noiseB} + p_{trueB}\, p_{noiseA} + p_{noiseA}\, p_{noise,B} \tag{11.7}$$

where the last three terms are essentially the probability of having an accidental coincidence count.

The probabilities $p_{\text{coinc}}, p_{\text{click,i}}$, are estimated from the measured numbers of counts:

$$p_{click,i} = \frac{N_{\text{click,i}}}{N_{\text{gates}}} \tag{11.8}$$

where $N_{\text{click,i}}$ is the number of clicks produced by the detector *i* in N_{gates} (number of illuminated gates).

$$p_{coinc} = \frac{N_{\text{coinc}}}{N_{\text{gates}}} \tag{11.9}$$

where p_{coinc} is the number of clicks produced by the detector *i* in N_{gates} (number of illuminated gates).

$p_{noise,i}$ is given by:

$$Pp_{noise} = p_{dark} + p_{after_{total}} + p_{straylight} - p_{dark}p_{after_{total}} - p_{dark}p_{straylight} - p_{after\_total}p_{straylight} + p_{dark}p_{after\_total}p_{straylight} \tag{11.10}$$

which sums up the contributions due to stray light, after-pulses and dark counts. The probabilities of having a dark count per gate (p_{dark}) and an after-pulse per gate (p_{after_all}) are calculated according to clause 15. The probability of having stray light in a pigtailed system is usually negligible, but this shall be confirmed; otherwise it shall be estimated, by not illuminating the HBT system.

11.9 Uncertainties

Equation (11.4) is the measurement equation.

In order to avoid saturation effects in the estimation of α by the HBT system it is necessary to maintain a value of $p_{click,i} \ll 1$.

The splitting ratio of the 50:50 beamsplitter, and the detection efficiency shall be approximately known, although an accurate calibration is not strictly necessary, since the quantum efficiency of the two detectors cancels out (this is because in the limit of $p_{True,i} \ll 1$, $p_{coincTrue}$ and ($p_{True,A}\ p_{True,B}$) have approximately the same dependence on inefficiencies and losses in general, and on the splitting ratio and detection efficiency in particular).

Additional corrections may be needed to take account of possible detector recovery efficiency (clause 18).

Further information relating to uncertainty evaluation can be found in Annexes A and B.

11.10 Results

11.10.1 Reporting on Poissonian nature of emitted pulses

The following measurements on the Poissoninan nature of emitted pulses shall be reported:

1) Unique identification number of device under test.

2) Measurement date(s).

3) Pulse repetition rate.

4) Mean spectral frequency.

5) Measurement environment (temperature, humidity).

6) Transmitter operation settings - see clause 5.

7) Measured probabilities of observing a click, a dark count, an after-pulse per gate for each of the two detectors of the HBT interferometer.

8) Measured probabilities of observing coincident clicks.

9) Measured value of α and the associated uncertainty.

10) Exceptions or deviations from procedure.

11.10.2 Other information to be recorded

The following information may be reported:

1) Measurement set-up.
2) Make and model number of key measurement equipment.
3) Measurement method.
4) Description of calculation.
5) Traceability to SI.

12 Measurement of source emission temporal profile, source temporal profile, and source timing jitter

12.1 Definitions, symbols and units

Definitions, symbols and units relevant to this clause can be found in clause 3.

NOTE: The source timing jitter is stated in s.

12.2 Procedure scope

12.2.1 Measurement of source emission temporal profile of an optical pulse

$$\text{Source emission temporal profile} = \text{source temporal profile} * \text{source timing jitter} \quad (12.1)$$

where $*$ denotes convolution.

The measured source emission temporal profile is given by:

$$\text{Measured source emission temporal profile} = \text{source temporal profile} * \text{source timing jitter} \, [* \, \text{inst}_j]_{(j=1:n)} \quad (12.2)$$

where:

inst_j = instrumental lineshape function of each of n devices in measurement chain.

12.2.2 Measurement at high flux level - enables source temporal profile and source timing jitter to be measured.

In an intense pulse, many photons will be temporally distributed within it.

The detector (e.g. a fast photodiode) can respond to a high number of photons incident upon it within a time interval ΔT_D that is small compared to the source temporal profile width ΔT_{photon}.

Therefore, if the flux level is high enough, the source emission temporal profile shall be measured at intervals $\Delta T_D << \Delta T_{photon}$.

If the measurement of the source emission is repeated many times, a record shall be kept of the time distribution of detection events corresponding to a particular power/photon flux level, i.e. measured photocurrent range Δi (or voltage ΔV after V/I amplifier). This provides a measurement of the combined effect of the second and subsequent terms of the right-hand side of equation (12.2) - source timing jitter $[* \, \text{inst}_j]^n$.

If these measurements are carried out where δi/δt (the rate of change of signal with respect to time) is highest, i.e. where δt/δi is lowest, then the measurement range Δi will contribute the lowest amount of intrinsic (due to source temporal profile) variation to ΔT. Suitable values are the points of steepest gradient on the rising and falling edges of the measured source emission temporal profile (for which the half-height position is a good approximation).

As a consequence:

i) The source temporal profile shall be calculated from the measured source emission temporal profile (in principle - depends of S/N etc.).

ii) Assuming that the $[* \text{inst}_j]^n$ terms in equation (12.2) are known, the source timing jitter shall also be calculated (in principle - depends of S/N etc.).

12.2.3 Measurement at single-photon level - only source emission temporal profile can be measured

In the case of a single-photon pulse, a single photon (on average) will be distributed anywhere within the overall pulse duration, with positional probability proportional to the pulse-shape at high-flux level.

Where the detection gate is wider than the source emission temporal profile, repeated measurements yield the measured source emission temporal profile described by equation (12.2), from which the source temporal profile shall be calculated if the $[* \text{inst}_j]$ terms in equation (12.2) are known.

Where the detection gate is narrower than the source emission temporal profile, repeated measurements yield the measured source emission temporal profile described by equation (12.3), where slice denotes a temporal segment of the source emission temporal profile carved out from the overall source emission profile.

$$\text{Measured source emission temporal profile} = [\text{source temporal profile} * \text{source timing jitter}]_{\text{slice}}\ [* \text{inst}_j]_{(j=1:n)} \quad (12.3)$$

The source emission temporal profile slice shall be calculated if the $[* \text{inst}_j]$ terms in equation (12.3) are known, and the overall source emission temporal profile assembled by sweeping the detector gate through the source emission temporal profile by using a tunable delay.

In neither of the above two cases can the jitter be separated from the pulse profile. This is because the analogous measurement to the high power case cannot be made, i.e. select the photon flux level within the pulse at which measurements are made.

12.3 Applicable methods

12.3.1 Measurement before attenuation to the single-photon level

Measurement prior to the attenuator that reduces the flux to the single-photon level shall be carried out with a fast photodiode and amplifier, which has a higher bandwidth and significantly less jitter than a single-photon detector.

Measurement shall also be made of any jitter introduced by the path from the point to the source measurement to the single-photon output port. Jitter can be caused by optical elements (such as filters and attenuators) which lead to multiple optical paths. The measurement is the same as described in clause 11.5, where a high-power laser is characterized before and after transmittance through the extra optical path.

12.3.2 Measurement at the single-photon level

Superconducting nanowire single-photon detectors (SNSPDs) exhibit the lowest jitter (< 100 ps) of single-photon detectors, and are commercially available. These are currently the detectors of choice if measurements are to be performed at the single-photon level.

12.4 Measurement before attenuation to the single-photon level

12.4.1 Measurement set-up

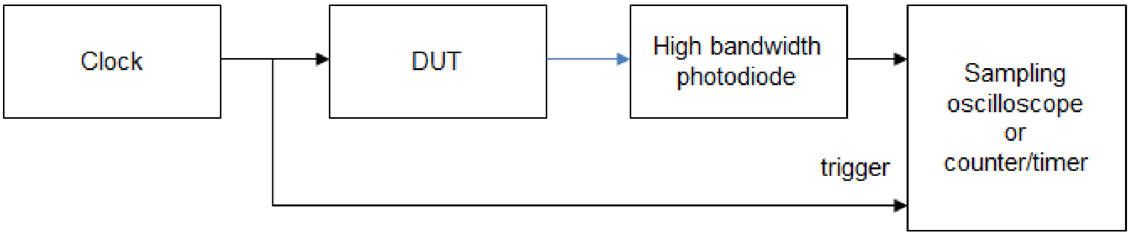


Figure 12.1: Measurement set-up

12.4.2 Equipment

12.4.2.1 Equipment required

1) Master clock
2) High-bandwidth photodiode and amplifier
3) High bandwidth sampling oscilloscope, or event timer

12.4.2.2 Equipment specifications

See Annex B for further details. Where no specifications are listed here, those listed in Annex B are sufficient:

1) DUT: The optical signal shall be available, before attenuation to the single-photon level.
2) Master clock: This may be an external device, or an internal clock within the DUT which is used to drive the laser, and which is also accessible to trigger the counter/timer.
3) High-bandwidth photodiode and amplifier.
4) High-bandwidth sampling oscilloscope: A sampling oscilloscope may be used, although this will have limited ability to observe any non-periodic presence or absence of pulses.
5) Event timer.

12.4.3 Measurement of jitter

12.4.3.1 Measurement

12.4.3.1.1 Measurement position

The point at which measurements are made. This is at a point before attenuation to the single-photon level.

The set-up shown in figure 12.1 is used.

12.4.3.1.2 Signal measurement with an oscilloscope

The oscilloscope is set to a mode such that a history of sampled points from the trace produced by the photodiode, as a function of time relative to the trigger, is accumulated.

12.4.3.1.3 Signal measurement with an event timer

A histogram of detection times shall be observed by correlating many successive detection events with the clock signal triggering the source. The maximum of the photodiode signal shall be established by increasing the threshold setting for the signal from the photodiode to the point at which counts begin to fall off. The threshold is then set to half this level for a rising edge, and a histogram of the number of points (as a function of time) is obtained. The threshold is then set at the same level for a falling edge, and a histogram of the number of points (as a function of time) is obtained. These histograms are due to the source timing jitter, the detector signal jitter, and jitter due to the event timer.

12.4.3.2 Environment

The temperature and humidity of the environment during the measurement shall be recorded.

12.4.3.3 Operational settings

The control settings of the DUT shall be recorded.

Clause 5 provides guidance on the settings to be recorded.

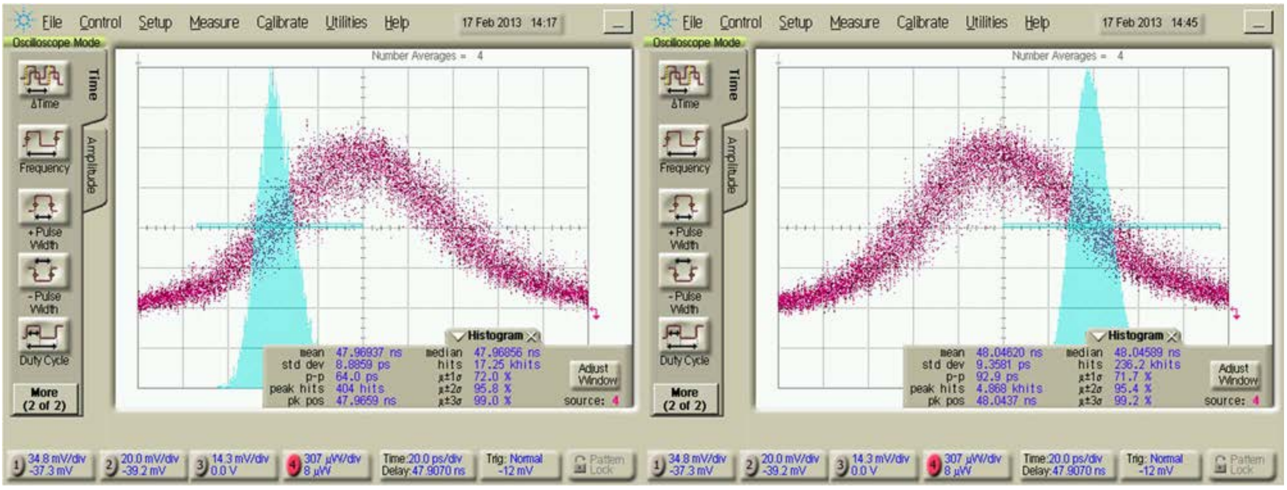
12.4.3.4 Calculation

12.4.3.4.1 Measurement with an oscilloscope

The baseline and maximum of the observed data is estimated.

A histogram of the number of points (as a function of time) on the rising edge of the measured trace at the half-height value is calculated. This histogram is due to the source timing jitter, detector signal jitter and scope jitter. In practice, the detector and scope jitter are likely to be negligible. The span and standard deviation of this histogram gives the peak-to-peak and standard deviation jitter for the rising edge of the pulse.

A histogram of the number of points (as a function of time) on the falling edge of the measured trace at the half-height value is calculated. This histogram due to the source timing jitter, detector signal jitter and scope jitter. In practice, the detector and scope jitter are likely to be negligible. The span and standard deviation of this histogram gives the peak-to-peak and standard deviation jitter for the falling edge of the pulse.



NOTE: The blue rectangles denote the region over which the histograms are calculated. The jitter of the rising edge (8,9 ps) is less than that of the falling edge (9,4 ps).

Figure 12.2: Examples of analysis of rising and falling edge of measured pulse

12.4.3.4.2 Measurement with an event timer

In practice, the jitter due to the detector and counter/timer is likely to be negligible.

The span and standard deviation of the rising edge histogram give the peak-to-peak and standard deviation jitter for the rising edge of the pulse.

The span and standard deviation of the falling edge histogram give the peak-to-peak and standard deviation jitter for the falling edge of the pulse.

12.4.4. Measurement of temporal profile

12.4.4.1 Measurement

12.4.4.1.1 Measurement position

The point at which measurements are made. This shall be at a point before attenuation to the single-photon level.

The set-up shown in figure 12.1 is used.

12.4.4.1.2 Signal measurement with an oscilloscope

The oscilloscope is set to a mode such that a history of sampled points from the trace produced by the photodiode, as a function of time relative to the trigger, is accumulated.

The mean signal level for each time-delay is then calculated to obtain the resulting response curve.

12.4.4.1.3 Signal measurement with an event timer

A histogram of detection times shall be observed by correlating many successive detection events with the clock signal triggering the source. Data shall be collected as the event timer threshold level is varied from ground up to the maximum value of the photodiode signal (rising edge trigger) and then as the threshold level is reduced back down to ground (falling edge trigger).

If the amplifier is an inverting amplifier, data shall be collected as the event timer threshold level is varied from ground down to the minimum value of the photodiode signal (falling edge trigger) and then as the threshold level is increased back up to ground (rising edge trigger).

The mean time for each threshold level is calculated, and the resulting data plotted as signal level versus time delay from the trigger. This will produce an inverted version of the source emission temporal profile, which is then re-inverted about its half-height value.

12.4.4.2 Environment

The temperature and humidity of the environment during the measurement shall be recorded.

12.4.4.3 Operational settings

The control settings of the DUT shall be recorded.

Refer to clause 5 for guidance on the parameters which should be recorded.

12.4.4.4 Calculation

The obtained response curve is due to the source emission temporal profile, as well as detector and oscilloscope or counter/timer jitter. The detector, oscilloscope and counter/timer jitters are likely to be negligible, and the response curve can be taken to represent the source emission temporal profile.

If the FWHM of the response curve is less than five times broader than the FWHM of the source jitter (see clause 12.4.3), one may wish to consider deconvolving the source jitter from the response curve.

Where both profiles are symmetric, and similar to Gaussian profiles, the following calculation may be applied:

$$FWHM_{source}{}^{2} = FWHM_{response}{}^{2} - FWHM_{jitter}{}^{2} \tag{12.4}$$

Otherwise, the source temporal profile can be taken to be the same as the source emission temporal profile.

If the FWHM of the response curve is less than five times broader than the FWHM of the detector jitter (see clause 19), one may also wish to consider deconvolving the detector jitter from the response curve.

12.4.5 Uncertainties

Information relating to uncertainty evaluation can be found in Annexes A and B.

If the FWHM of the response curve is at least five times broader than the FWHM of the source jitter, which itself is an approximately symmetric single-peaked function, and no deconvolution was performed, the error introduced should be less than 2 %.

If the FWHM of the response curve is at least five times broader than the FWHM of the detector jitter, which itself is an approximately symmetric single-peaked function, and no deconvolution was performed, the error introduced should be less than 2 %.

12.5 Measurement at the single-photon level

12.5.1 Measurement approach

The methods described in clause 8.6 shall be applied. As described in clause 12.2.3, only the source emission temporal profile can be measured at the single-photon level.

12.5.2 Measurement considerations - detection gate is wider than the source emission temporal profile

A detection histogram is obtained, and the mean photon number at each point in the measured source emission temporal profile calculated from the corresponding detections in the histogram. Clause 8.6.7 describes how these calculations may be performed.

The distribution of after-pulses at any point in the histogram shall be assumed to be uniform, with the numerical value calculated from the total number of detections within the histogram.

If detections are time-stamped, suitable corrections for after-pulsing may be carried out on each detection event.

It is recommended that the detector gate frequency is set, if necessary, to be some integer sub-multiple of the DUT clock frequency, so that the detection after-pulse probability is at least two orders of magnitude less than the detection efficiency.

12.5.3 Measurement considerations - detection gate is narrower than the source emission temporal profile

For each set of measurement data corresponding to a measurement slice, the same considerations stated in clause 12.5.2 shall be applied.

12.5.4 Calculations

The source emission temporal profile shall be calculated from the measured source emission temporal profile, as described in clause 12.2.3, if the [$*$ $inst_j$] terms in equations 12.2 and 12.3 are known. One of these terms will be the single-photon detector signal jitter (see clause 19).

12.5.5 Uncertainties

Information relating to uncertainty evaluation can be found in Annexes A and B.

12.6 Results

12.6.1 Reporting measurement on source emission profile, source temporal profile, and source timing jitter

The following measurements on source emission profile, source temporal profile, and source timing jitter shall be reported:

1) Unique identification number of DUT.

2) Measurement date(s).

3) Total measurement duration, and duration of individual measurements.

4) The following properties (where they have been measured):

   a) Source timing jitter and its uncertainty. Separate values may be quoted for the rising and falling edges if measured.

   b) Source temporal profile - a table or plot of the data, together with their uncertainties.

   c) Source emission temporal profile and its uncertainty - a table or plot of the data, together with their uncertainties.

5) Measurement environment (temperature, humidity).

6) DUT operational settings - see clause 5.

7) Exceptions or deviations from procedure.

8) Measurement operator(s).

12.6.2 Other information to be reported

The following information may be reported:

1) Measurement set-up.

2) Make and model number of key measurement equipment.

3) Measurement method.

4) Description of calculation.

5) Traceability to SI.

13 Measurement of source wavelength (source frequency) and source linewidth

13.1 Definitions, symbols and units

Definitions, symbols and units relevant to this clause can be found in clause 3.

NOTE 1: The source wavelength is stated in nm (wavelength).

NOTE 2: The source frequency is stated in Hz (spectral frequency).

NOTE 3: The source linewidth is stated in Hz (spectral frequency) or nm (wavelength).

13.2 Procedure scope

This procedure covers the measurement of the spectrum of the emitted photons, and calculation of the mean or peak wavelength (frequency).

13.3 Measurement set-up

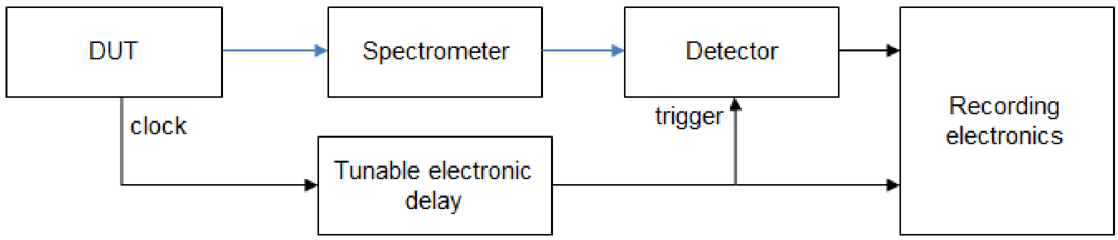


Figure 13.1: The measurement set-up

The tunable delay, detector and recording electronics may be separate or integral to the spectrometer.

13.4 Applicable methods

Measurements shall be carried out by a fibre-coupled spectrometer, ideally at the single-photon level.

If the spectrometer cannot perform measurements at the single-photon level, measurements shall be carried out before attenuation to the single-photon level. In the latter case, the spectral transmittance of the optical path from the measurement point to the single-photon output port of the DUT shall be measured - see methods B and C in [6].

13.5 Equipment

13.5.1 Equipment required

1) Fibre-coupled spectrometer

2) (Tunable delay)

3) Recording electronics, such as an event timer, or DVM

13.5.2 Equipment specifications

See Annex B for further details. Where no specifications are listed here, those listed in Annex B are sufficient.

1) DUT: Access to single-photon signal output of device.
    i) Access to optical signal before attenuation to single-photon level (if required).
    ii) Access to clock signal.
2) Fibre-coupled spectrometer:
    i) This encompasses all devices capable of measuring the spectrum of the emitted pulses, and includes wavemeters, optical spectrum analysers, etc.
    ii) The spectral range of sensitivity shall cover the entire spectral region over which emission occurs. When the laser in the QKD source is driven to emit short optical pulses, typically < 100 ps in duration, the spectral width of the source, $\Delta\nu_{source}$, will be greater than 10 GHz (0.08 nm), but is more likely to be of the order of 120 GHz (1 nm).
3) Synchronization: If the spectrometer uses a gated detector, a means (such as a tunable delay) is required for synchronizing the arrival of a pulse or photon at the detector within the detection window or detector gate.
4) Recording electronics:
    i) A means for recording the detector signal as a function of wavelength or optical path interval.
    ii) If a single-photon detector is used, an event counter is required.
    iii) If the detector is an analogue detector, a digital voltmeter is required.

13.6 Measurement

13.6.1 Measurement position

The point at which measurements are made. This is normally the first point at which the QKD optical signal from the DUT is accessible.

If the spectrometer is not sensitive at the single-photon level, arrangements shall be made to measure the signal at a point before attenuation to the single-photon level.

13.6.2 Signal

Where a gated detector is used, the electronic delay is used to ensure that the emission from the DUT is synchronized to the detector measurement window.

If the spectrometer is able to provide a point-by-point spectral measurement, the signal shall be measured spectral point by spectral point.

It is assumed that the spectrum is measured spectral point by spectral point.

The spectrum of the emitted pulses is recorded. If the spectrometer operates in the spectral domain, this will be $S_{meas}(\lambda)$ W nm^{-1}. If the spectrometer operates in the frequency domain, this will be $S_{meas}(\nu)$ W Hz^{-1}.

13.7 Environment

The temperature and humidity of the environment during the measurement shall be recorded.

13.8 Operational settings

The control settings of the DUT shall be recorded.

Clause 5 provides guidance on the settings to be recorded.

13.9 Calculations

13.9.1 Wavelength / frequency

The source wavelength λ_{source} or spectral frequency ν_{source} may be taken as either the wavelength or frequency of peak emission, or the mean wavelength or frequency of the emission.

If the spectrum was measured at a point before the desired measurement position, the spectrum shall first be multiplied by the spectral transmittance $t(\lambda)$ or $t(\nu)$ of the path from the actual measurement position to the desired measurement position, before calculating its mean value.

The mean wavelength is calculated using:

$$\lambda_m = \frac{\sum_1^n wbin\_\lambda_i \times \mathrm{S}_{\mathrm{meas}}(\lambda_i) \times \lambda_i}{\sum_1^n wbin\_\lambda_i \times \mathrm{S}_{\mathrm{meas}}(\lambda_i)} \tag{13.1}$$

where n spectral measurements were obtained, i denotes the ith measurement, λ_i is the measurement wavelength, $S_{meas}(\lambda_i)$ is the measured power, and $wbin\_\lambda_i$ is the wavelength bin-width.

The mean frequency is calculated using:

$$\nu_m = \frac{\sum_1^n wbin\_\nu_i \times S_{meas}(\nu_i) \times \lambda_i}{\sum_1^n wbin\_\nu_i \times S_{meas}(\nu_i)} \tag{13.2}$$

where n spectral measurements were obtained, i denotes the ith measurement, ν_i is the measurement frequency, $S_{meas}(\nu_i)$ is the measured power, and $wbin\_\nu_i$ is the frequency bin-width.

If the result is required in the wavelength domain, and measurements were obtained in the frequency domain, the frequencies and limits of each measurement bin are converted into wavelength units using equation 13.3:

$$\lambda = \frac{c}{n\,\nu} \tag{13.3}$$

where c is the speed of light in vacuum. If measurements are required in air wavelengths, n is the refractive index of air, whereas for vacuum wavelengths, n=1.

If the result is required in the frequency domain, and measurements were obtained in the wavelength domain, the wavelengths and limits of each measurement bin are converted into frequency units using equation 13.4:

$$\nu = \frac{c}{n\,\lambda} \tag{13.4}$$

If the spectrometer was calibrated in air wavelengths, n is the refractive index of air, whereas if the spectrometer was calibrated in vacuum wavelengths, n=1.

13.9.2 Linewidth

The linewidth is normally defined as the full width at half-maximum (FWHM) of the measured spectral profile.

If the spectrum was measured at a point before the desired measurement position, the spectrum shall first be multiplied by the spectral transmittance $t(\lambda)$ or $t(\nu)$ of the path from the actual measurement position to the desired measurement position, before calculating its linewidth. See methods B and C in [6].

Equations 13.3 or 13.4 are applied to the measured data if necessary, and the FWHM of the spectrum is calculated.

13.10 Uncertainties

Information relating to uncertainty evaluation can be found in Annexes A and B.

13.11 Results

13.11.1 Reporting measurement on source wavelength (source frequency) and source linewidth

The following measurements on source wavelength (source frequency) and source linewidth shall be reported:

1) Unique identification number of DUT.
2) Measurement date(s).
3) Measurement duration.
4) The following derived quantities (where they have been measured):
    a) Wavelength or spectral frequency (mean value, or peak value), and its uncertainty.
    b) Spectral linewidth, and its uncertainty.
5) Measurement environment (temperature, humidity).
6) DUT operation settings - see clause 5.
7) Exceptions or deviations from procedure.
8) Measurement operator(s).

13.11.2 Other information to be reported

The following information may be reported:

1) Measurement set-up.
2) Make and model number of key measurement equipment.
3) Measurement method.
4) Description of calculation.
5) Traceability to SI.

14 Measurement of detector gate repetition rate

14.1 Definitions, symbols and units

Definitions, symbols and units relevant to this clause can be found in clause 3.

NOTE: The detector gate repetition rate is stated in Hz.

14.2 Procedure scope

This procedure covers the measurement of the detector gate repetition rate (f_{gate}).

The detector may be a single-photon detector, or more complex device such as a QKD receiver.

Since a QKD receiver may have more than one single-photon detector, it is understood that the operator has the ability to control and take readings from the detector of their choosing.

The actual gate repetition rate, f_{gate}, (as opposed to the clock trigger signal frequency f_{clock}) shall be confirmed by measurement.

14.3 Measurement set-up

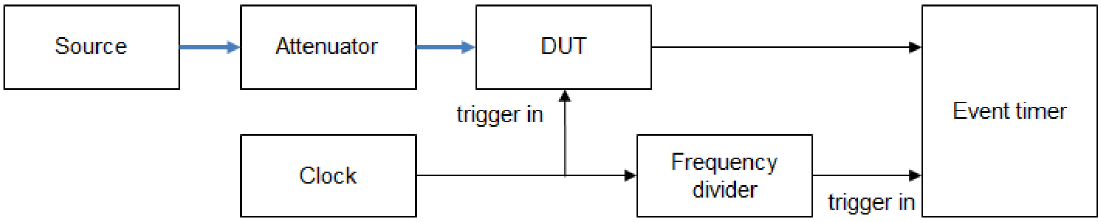


Figure 14.1: Measurement set-up.

Optical fibre links are shown in blue, electrical connections in black. The clock may be integral to the DUT, in which case the clock signal shall be externally available.

14.4 Applicable methods

Use a CW light source.

The measurement is based on the fact that photons from a CW laser are created at random points in time, and over many events yield a uniform time distribution.

The timer/counter is triggered every Rth gate, where R is an integer (≥ 1), and a histogram of detections versus time after the trigger is accumulated. The set of histogram peaks will yield the gate frequency.

This method cannot determine if a detector gate is randomly absent. If a gate is periodically absent, and $R = nP$, where n is a positive integer, and P is the period (in gates) of the missing gates, then the missing gates should lead to missing peaks in the detection histogram. If $nR = P$, then some peaks in the histogram should be reduced in intensity with regard to the other gates. However, if R/P or P/R are not integer values, the missing gates shall not be observable.

This method cannot determine if the detector circuitry is set up to deliberately defeat the measurement process. An example is where the input (or internal) trigger signal is divided down in frequency by an integer factor D before being sent to the detector bias circuit, and the detector circuitry randomly inserts time-delays to this divided-down trigger which are multiples $1, 2, \ldots, (D-1)$ of the D sub-multiple of its gate period. The effect of this would be to give an apparent gate frequency that is the input trigger frequency, but which is D times greater than its true gate frequency.

Measurement of the relative temporal profile of the detector gate detection efficiency is not addressed in this procedure, but it is noted that the shape of each histogram peak shall be indicative of this. It may differ from the true profile because of detector dead-time. This can be minimized by lowering the source output power so that photons are separated (on average) by more than the longer of the observed gate period or the detector dead-time. Clause 19 describes how the detection efficiency temporal profile shall be measured.

14.5 Measurement

14.5.1 Equipment required

1) A fibre-coupled CW light source
2) A fibre-couple attenuator
3) An event timer, or equivalent
4) A clock may be required to trigger the DUT, if it does not provide its own externally available trigger signal

14.5.2 Equipment specifications

See Annex B for further details. Where no specifications are listed here, those listed in Annex B are sufficient.

1) CW light source: The light source should emit radiation at the wavelength of interest.
2) DUT:
    i) The DUT can be triggered either internally, or externally.
    ii) The gate trigger output signal shall be available when internal triggering is employed.
    iii) The gate trigger input signal shall be available for external triggering.
    iv) The DUT detection signal shall be available.
3) Attenuator: The attenuation of the attenuator need not be calibrated.
4) Event timer.

14.5.3 Measurement process

14.5.3.1 Measurement position

The point at which measurements are referenced to. This is normally the first point at which a single-photon signal can be input into the QKD receiver.

The set-up shown in figure 14.1 is used.

14.5.3.2 Signal

The clock (internal or external) used to trigger the detector gates is set to a frequency f_{clock}.

The signal from the clock is also sent to a frequency divider, and divided by an integer factor N.

The divided signal is set to trigger the event timer.

The signal output from the DUT is connected to a stop input on the event timer.

A histogram of stop events for many triggers is recorded.

Additional histograms may be recorded.

14.6 Environment

The temperature and humidity of the environment during the measurement shall be recorded.

14.7 Operational settings

The control settings of the DUT shall be recorded.

Clause 5 provides guidance on the parameters to be recorded.

14.8 Calculations

The mean frequency f_{each} (Hz) from each histogram is calculated:

$$f_{each} = \frac{n_{peaks} - 1}{\left| T_1 - T_n \right|} \qquad (14.1)$$

where n_{peaks} peaks are counted within a particular histogram, each peak corresponding to a detector gate; T_1 is the time of the first peak, T_n is the time of the final peak.

Standard curve-fitting calculations may be applied to determine T_1 and T_n.

The overall (mean) repetition rate, f_{gate} (Hz) is calculated:

$$f_{gate} = \frac{\sum_{1}^{k} f_{each_i}}{k} \qquad (14.2)$$

where k histograms were recorded.

If the histograms were of different length, therefore containing different numbers of peaks, calculation 14.2 should be weighted appropriately.

14.9 Uncertainties

A long histogram should be collected to make n_{peaks} as large as possible, and therefore minimize the sensitivity of f_{each} to errors in T_1 and T_n (equation 14.1).

Information relating to uncertainty evaluation can be found in Annexes A and B.

14.10 Results

14.10.1 Reporting measurement on detector gate repetition rate

The following measurements on detector gate repetition rate on shall be reported:

1) Unique identification number of DUT.

2) Measurement dates.

3) Measurement duration.

4) Gate repetition rate, and its uncertainty.

5) Measurement environment (temperature, humidity).

6) DUT operation settings - see clause 5.

7) Exceptions or deviations from procedure.

8) Measurement operator(s).

14.10.2 Other information to be reported

The following information may be reported:

1) Measurement set-up.

2) Make and model number of key measurement equipment.

3) Measurement method.

4) Description of calculation.

5) Traceability to SI.

15 Measurement of dark count probability, after-pulse probability and detection efficiency

15.1 Definitions, symbols and units

Definitions, symbols and units relevant to this clause can be found in clause 3.

NOTE 1: Dark count probability, p_{dark}, can be described in terms of its constituent intrinsic dark count probability, p_{idark} , and the probability of generating after-pulses from the intrinsic dark counts.

NOTE 2: For a gated detector, it is appropriate to state the dark count probability in gate $^{-1}$, with the duration of the gate time also provided.

NOTE 3: After-pulse probabilities are expressed in three different ways:

i) the probability of the first after-pulse occurring at a time ΔT subsequent to a detection event;

ii) the combined probability of first and secondary after-pulses occurring at a time ΔT subsequent to a detection event;

iii) the total probability of after-pulses occurring subsequent to a detection event.

NOTE 4: Secondary after-pulses are the after-pulses generated by preceding after-pulses.

NOTE 5: After-pulse probabilities can be expressed as a function of the mean photon number of the incident photons.

NOTE 6: The first after-pulse probability, $p_{after\_first}(\Delta T)$, is the probability of a first after-pulse in a single gate of stated duration at a specified time ΔT after a detection event (relevant to a gated detector).

NOTE 7: The after-pulse probability, $p_{after\_all}(\Delta T)$, is the probability of first and secondary after-pulses in a single gate of stated duration at a specified time ΔT after a detection event (relevant to a gated detector).

NOTE 8: The total after-pulse probability, p_{after_total}, is the total probability of an after-pulse in gates of stated duration when the detector is gated at a stated repetition rate (relevant to a gated detector).

NOTE 9: p_{after_first} refers to the series containing terms for all values of ΔT.

NOTE 10: p_{after_all} refers to the series containing terms for all values of ΔT.

NOTE 11: From notes 7 and 10, it follows that for a gated detector, $p_{after\_total} = \Sigma p_{after\_all}$ where the ΔT correspond to the times of detector gates.

NOTE 12: The detection efficiency is stated at a given spectral frequency (Hz) or wavelength (nm).

NOTE 13: Measured detection efficiency values are reported as the maximum DE achievable using polarized light, or that obtained with randomly polarized light. Clause 17 provides relevant information.

15.2 Procedure scope

This procedure covers the measurement of the dark count probability (p_{dark}), the intrinsic dark count probability (p_{idark}), the after-pulse probabilities (p_{after_first}, p_{after_all}, p_{after_total}) and detection efficiency, $\eta(\nu)$ or $\eta(\lambda)$, of a gated single-photon detector.

The detector may be a single-photon detector, or a more complex device such as a QKD receiver.

Since a QKD receiver may have more than one single-photon detector, it is understood that the operator has the ability to control and take readings from the detector of their choosing.

15.3 Applicable methods

15.3.1 Method 1: Measure counts from the non-illuminated detector in a known number of detector gates

This method has no sub-variants.

15.3.2 Method 2: Analyse time-intervals between counts from the detector:

a) Measure times of counts from the non-illuminated detector.

b) Illuminate every *R*th detector gate; record the elapsed time between a 'click' in the illuminated gate and the first subsequent 'click' in a non-illuminated gate.

15.3.3 Method 3: Illuminate every *R*th detector gate; record 'clicks' in the illuminated gate, and the elapsed time between a 'click' in the illuminated gate and the first subsequent 'click' in a non-illuminated gate

This method has no sub-variants.

15.3.4 Method 4: Illuminate every *R*th detector gate; record all detector 'clicks' with an event timer

a) The counts in the final non-illuminated gates do not reach a constant level.

b) The counts in the final non-illuminated gates reach a constant level, which is taken to be the dark count level.

c) The counts in the final non-illuminated gates are at constant level for non-illuminated gate numbers ranging over at least an order of magnitude; the extrapolated fitted after-pulse level is two orders of magnitude below the dark count level at the final non-illuminated gate.

15.3.5 Comparison of applicable methods

The parameters that can be measured using the different methods are summarized in table 15.1. Table 15.2 provides general comments on some of the methods.

The symbol '(Y)' indicates that these terms are not obtained from the primary analysis of the experimental data, but may be estimated from the results of the primary analysis.

Table 15.1

Method	p_{dark}	p_{idark}	p_{after_total}	p_{after_all}	p_{after_first}	p_{true} (from which η can be calculated)	Comments
1	Y						After-pulses generated by dark counts are included within the measured dark count probability p_{dark}, i.e. p_{dark} cannot be separated into p_{idark} and p_{after_total}.
2a, 2b	(Y)	Y	(Y)	(Y)	Y		Method 2a measures the after-pulse probabilities for a mean photon number, μ, = 0 (i.e. dark counts); Method 2b measures the after-pulse probabilities for a mean photon number ≠ 0. In principle, if p_{after_first} was measured with method 2a for μ = 0, the after-pulse behaviour could be fitted to two series of p_{after_first} , one corresponding to that measured for μ = 0, and the other to the illuminating μ. However, the S/N of the data may not permit this; Dark counts are assumed to follow a Poissonian process (i.e. an exponential decay in the number of first counts as a function of increasing time-interval); Method 2a will require long measurement times because of the low probability of dark counts and after-pulses p_{dark}, p_{after_all} and p_{after_total} may be estimated from the measured values of p_{idark} and p_{after_first}.
3	(Y)	Y	(Y)	(Y)	Y	Y	Dark counts are assumed to follow a Poissonian process (i.e. an exponential decay in the number of first counts as a function of increasing time-interval); In principle, if p_{after_first} was measured with method 2a for μ = 0, the after-pulse behaviour could be fitted to two series of p_{after_first}, one corresponding to that measured for μ = 0, and the other to the illuminating μ. However, the S/N of the data may not permit this. p_{dark}, p_{after_all} and p_{after_total} may be estimated from the measured values of p_{idark} and p_{after_first}.
4a	Y		Y			Y	p_{dark} is evaluated by turning the source off, which then becomes method 1. This method does not allow the terms in p_{after_all} to be measured.

Method	p_{dark}	p_{idark}	p_{after_total}	p_{after_all}	p_{after_first}	p_{true} (from which η can be calculated)	Comments
4b	Y		Y	Y		Y	This method allows all 4 parameters identified on the left to be measured or derived from a single measurement process; A reasonable approximation to the terms in p_{after_all} is obtained from this measurement.
4c	Y		Y	Y		Y	This method allows all 4 parameters identified on the left to be measured or derived from a single measurement process; This method gives greater confidence in measuring the terms in p_{after_all} .

Table 15.2

Method	Comments
4a, 4b, 4c	Dark counts are assumed to follow a Poissonian process (i.e. a constant probability as a function of time)
3	The measured after-pulse probability is due to intrinsic dark counts as well as the illuminating pulses
4a, 4b, 4c	p_{after_total} excludes after-pulses from darks, since they are included in p_{dark}. The measured after-pulse probability is due to illuminating pulses of intensity μ
3, 4a, 4b, 4c	Knowledge of μ enables the photon detection probability (detection efficiency), η, to be calculated from p_{true}

Method 1 uses the simplest measurement set-up, where the number of detector gates and the 'clicks' from the non-illuminated detector are recorded for a specified number of gates.

Method 2a requires time-tagging of the 'clicks' from the non-illuminated detector. This method enables the dark count probability to be separated into its intrinsic dark count and after-pulse probabilities.

Methods 2b, 3 and 4 can be implemented with a similar set-up. The source frequency f_{source} is stepped down by an integer factor R compared to the detector gate repetition rate, e.g. by using a frequency divider. Therefore, only every Rth detector gate will be illuminated. Counts in the non-illuminated gates are solely due to dark counts and after-pulses, while counts in the illuminated gates will be due to true detections, dark counts, and after-pulses.

Methods 2b and 3 allow the dark count probability to be separated into the intrinsic dark counts and their afterpulses, and method 3 enables measurement of detection efficiency.

Method 4 enables p_{dark}, p_{after_total} and η to be measured.

Method 4a is the simplest variant, while methods 4b and 4c may be employed to obtain a more detailed analysis of the after-pulsing behaviour.

Method 4a provides a direct method of measuring p_{after_total} without requiring R to be large enough such that the after-pulse probability in the Rth detector gate is below p_{dark}. This enables measurements to be performed in a shorter time, and requires simpler calculations than the other methods.

It is possible to perform methods 3 and 4 in the same measurement process, by time-tagging all events to enable analysis of first 'click' after-pulses as required by method 3.

15.4 Method 1: Measure counts from the non-illuminated detector in a known number of detector gates

15.4.1 Measurement set-up

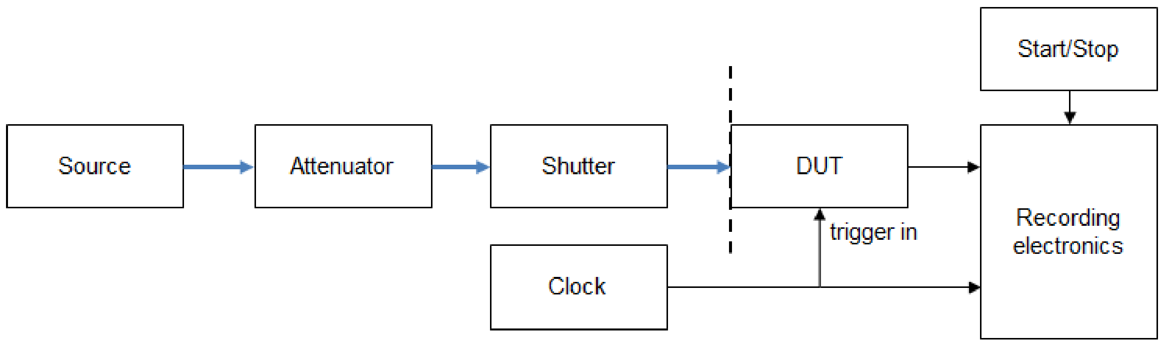


Figure 15.1: Measurement set-up

Items to the left of the dashed line are optional and can be replaced by an opaque end-cap. Blue arrows denote optical fibres, black arrows denote electrical connections.

15.4.2 Equipment required

1) Recording electronics comprising either:
   i) a two-channel frequency counter; or
   ii) two single-channel frequency counters; or
   iii) a two-channel event timer.
2) A clock may be required to trigger the DUT, if the DUT does not provide its own externally available trigger signal.
3) An opaque end-cap for blocking light to the input port.
4) The following items may also be used:
   i) a fibre-coupled source;
   ii) a fibre-coupled attenuator;
   iii) a fibre-coupled shutter.

15.4.3 Equipment specifications

See Annex B for further details. Where no specifications are listed here, those listed in Annex B are sufficient.

1) DUT:
   i) The DUT can be triggered either internally, or externally.
   ii) The gate trigger output signal shall be available when internal triggering is employed.
   iii) The gate trigger input signal shall be available for external triggering.
   iv) The DUT detection signal shall be available.
2) Pulse counter(s).
3) Event timer: At least two channels.
4) Clock.
5) End-cap: Opaque to all radiation for which the DUT is sensitive.
6) Light source: The light source shall emit radiation at the wavelength of interest.
7) Attenuator: The attenuation of the attenuator need not be calibrated.
8) Shutter: Opaque to all radiation for which the DUT is sensitive.

15.4.4 Measurement

15.4.4.1 Measurement position

The point to which measurements are referenced. This is normally the first point at which a single-photon signal can be input into the QKD receiver.

The basic measurement set-up shown in figure 15.1 (or variants thereof) shall be used.

The use of an end-cap instead of the devices to the left of the dashed line provides the minimal set-up required for measurement of dark count probability.

Where dark count probability is one of multiple properties being measured, the devices to the left of the dashed line are likely to be part of the measurement set-up.

The operator may wish to compare measurements made with an end-cap to those used with a fibre-coupled shutter, in order to investigate light leakage through the endcap, shutter, or fibre connecting the shutter and the DUT.

15.4.4.2 Signal

The gate trigger signal to or from the DUT is connected to a frequency counter, or event timer.

The signal output from the DUT is connected to a frequency counter, or event timer

The detector is set to gate at a set frequency f_{gate}, with gate duration T_{gate}. See clause 14.

The optical input to the DUT is blocked:

1) The number of counts per second, N, from the DUT is measured.

   The number of gates per second, M, from the trigger signal is measured.

2) The total number of counts N from the DUT in a fixed time-interval is measured.

   The total number of gates M from the trigger signal in the same time interval is measured.

15.4.5 Environment

The temperature and humidity of the environment during the measurement shall be recorded.

15.4.6 Operational settings

The control settings of the DUT shall be recorded, where possible.

Clause 5 provides guidance on the settings to be recorded.

15.4.7 Calculations

The dark count probability per gate of duration t_{gate}, p_{dark}, is given by

$$p_{dark} = \frac{N}{M} \tag{15.1}$$

15.4.8 Uncertainties

Equation 15.1 is the measurement equation.

Note that p_{dark} as calculated by Equation 15.1 also includes after-pulses from the dark counts

Information relating to uncertainty evaluation can be found in Annexes A and B.

15.4.9 Results

15.4.9.1 Reporting measurement on dark count probability

The following measurements on dark count probability shall be reported:

1) Unique identification number of DUT.
2) Measurement date(s).
3) Measurement duration.
4) Dark count probability, and its uncertainty.
5) Measurement environment (temperature, humidity).

6) DUT operation settings - see clause 5.

7) Exceptions or deviations from procedure.

8) Measurement operator(s).

15.4.9.2 Other information to be reported

The following information may be reported:

1) Measurement set-up.

2) Make and model number of key measurement equipment.

3) Measurement method.

4) Description of calculation.

5) Traceability to SI.

15.5 Method 2a: Analyse time-intervals between counts from the detector - measure timing of counts from the non-illuminated detector

15.5.1 Measurement set-up

The measurement set-up shown in figure 15.1 may be used. In this case, the recording electronics shall be able to time-stamp the arrival of signal pulses ('clicks') from the DUT

15.5.2 Equipment required

Item 1, or items 2 and 3, are required:

1) A two-channel event timer.

2) A single-channel event timer.

3) A frequency counter.

15.5.3 Equipment specifications

The specifications described in clause 15.4.3 are applicable, except that the event timer shall time-tag the arrival of event 'clicks' from the DUT.

15.5.4 Measurement

15.5.4.1 Measurement position

The conditions stated in clause 15.4.4.1 apply.

15.5.4.2 Signal

The signal output from the DUT is connected to an event timer, which time-tags the arrival of detector 'clicks'.

The gate trigger signal to or from the DUT may also be connected to another channel of an event timer, which time-stamps the triggers. This is not essential to the measurement. If not implemented, the gate repetition rate can be measured with a frequency counter.

The detector is set to gate at a set frequency f_{gate}, with gate duration T_{gate}. See clause 14.

The optical input to the DUT is blocked.

The event timer (and the frequency counter, if used) is started.

The event timer is stopped after N gates (if the gate trigger signal is sent to the event timer), or after a time ΔT_{meas} has elapsed. In the latter case, N is given by the rounded-down integer value of $(1 + \Delta T_{meas} / f_{gate})$.

Measurements shall be obtained by recording data for a sufficiently long time, in order to record counts at long-time intervals where dark counts dominate. This will need to be established by trial and error.

15.5.5 Environment

The temperature and humidity of the environment during the measurement shall be recorded.

15.5.6 Operational settings

The control settings of the DUT shall be recorded, where possible.

Clause 5 provides guidance on the settings to be recorded.

15.5.7 Calculations

i) The following calculations assume that the dead-time of the detector is less than the time-interval ΔT between consecutive gates, and that the detector has fully recovered its steady-state value (see clause 18) in less than ΔT seconds. The analysis below will need to be modified if these conditions are not satisfied.

ii) Calculate the elapsed time (as multiples of ΔT) between consecutive detector 'clicks'. If the gate trigger signal was also sent to the DUT, ΔT can be extracted from the trigger signals. Otherwise, the frequency counter can be used to determine ΔT.

iii) Create a histogram of the number of counts in time-bins of elapsed time.

iv) Convert counts into a probability by dividing each count value in the histogram by the total number of 'clicks', N_{total}.

v) Analyse the logarithm of the probability of a count versus linear time-bins of elapsed time.

vi) After-pulses are expected to be significant only at shorter elapsed times; the longer elapsed time region may be used to provide an initial estimate of the behaviour of the dark count probability.

vii) Model the intrinsic dark count probability by a straight line with negative slope on log(probability of a count) vs linear(elapsed time) axes.

The intrinsic dark count behaviour to be modelled is obtained by multiplying the probabilities calculated in paragraph iv by N_{total}/N, where N is the total number of gates.

The equation for dark-count probability is given by:

$$p_{idark}(N.\Delta T) = (1 - p_{idark})^{N-1} p_{idark} \tag{15.2}$$

where:

$p_{idark}(N.\Delta T)$ is the probability of an intrinsic dark count in the Nth gate at time $N.\Delta T$ following the previous click;

$p_{idark} = p_{idark}(1.\Delta T)$ is the probability of an intrinsic dark count in a detector gate;

N runs from 1 to R ($R \to \infty$ in the ideal case);

Hence:

$$\log[p_{idark}(N.\Delta T)] = (N-1)\log[(1 - p_{idark})] + \log[p_{idark}] \tag{15.3}$$

which is a straight line with negative slope log[(1-p_{idark})], and intercept log[p_{idark}] for N=1 when plotted on log[($p_{idark}(N)$)] vs ΔT axes. Hence, any chosen value of p_{idark} specifies both the N=1 value, and the slope.

The measured data at long time-intervals may be used to obtain an initial estimate for p_{idark}.

viii) Additional probabilities are assumed to be due to after-pulses.

ix) Fit the probability data to an analytic function (darks and after-pulses), or a mixture of analytic (darks) and numeric (after-pulses) functions, accounting for the possibility of darks and after-pulses coinciding within the same gate.

The combination of darks and after-pulses can be analysed as follows [i.22].

The probability of a click in the first time bin is given by:

$$p_{click}(\Delta T) = 1 - (1 - p_{idark})(1 - p_{after\_first}(1.\Delta T)) \tag{15.4a}$$

and the probability of a click in the Nth ($N > 1$) time bin is given by:

$$\begin{aligned} p_{click}(N.\Delta T) = (1 - p_{idark})^{N-1} \left[\prod_{j=1}^{N-1} (1 - p_{after\_first}(j.\Delta T)) \right] \times \\ \left[1 - (1 - p_{idark})(1 - p_{after\_first}(N.\Delta T)) \right] \end{aligned} \tag{15.4b}$$

where $p_{after\_first}(N.\Delta T)$ may be represented by an analytic function of the operator's choosing, or by numerical values;

x) The intrinsic dark count probability per gate, p_{idark}, is obtained from the function for the intrinsic dark count probability behaviour as a function of elapsed time obtained from steps i) to ix).

xi) The total after-pulse probability p_{after_total} is the sum of all p_{after_all} terms, which in turn can be derived from p_{after_first} terms.

The total after-pulse probability in gate N can be estimated by:

$$\begin{aligned} p_{after\_all}(N.\Delta T) = {} & p_{after\_first}(N.\Delta T) \\ & + p_{after\_first}(1.\Delta T) p_{after\_first}([N-1].\Delta T) + \ldots + p_{after\_first}([N-1].\Delta T) p_{after\_first}(1.\Delta T) \\ & + p_{after\_first}(1.\Delta T) p_{after\_first}(1.\Delta T) p_{after\_first}([N-2].\Delta T) + \ldots \\ & + etc \end{aligned} \tag{15.5}$$

The series may be truncated when the terms become insignificant.

The total after-pulse probability is then given by:

$$p_{after\_total} = p_{after\_all}(1.\Delta T) + p_{after\_all}(2.\Delta T) + \ldots \tag{15.6}$$

15.5.8 Uncertainties

The process described in clause 15.5.7 ix) and equations 15.3 and 15.4 define the measurement equations for p_{idark} and p_{after_first}.

Equation (15.6) defines the measurement equation for p_{after_total}.

Information relating to uncertainty evaluation can be found in Annexes A and B.

15.5.9 Results

15.5.9.1 Reporting measurement on dark count and after-pulse probability

The following measurements on dark count and after-pulse probability shall be reported:

1) Unique identification number of DUT.
2) Measurement date(s).
3) Measurement duration.
4) The following derived properties (where they have been measured or derived):
    a) Intrinsic dark count probability, and its uncertainty.
    b) First after-pulse probabilities, and their uncertainty. The incident mean photon number (= 0).
    c) Total after-pulse probability, and its uncertainty. The incident mean photon number (= 0).
5) Measurement environment (temperature, humidity).
6) DUT operation settings - see clause 5.
7) Exceptions or deviations from procedure.
8) Measurement operator(s).

15.5.9.2 Other information to be reported

The following information may be reported:

1) Measurement set-up.
2) Make and model number of key measurement equipment.
3) Measurement method.
4) Description of calculation.
5) Traceability to SI.

15.6 Methods 2b, 3 and 4: Every *R*th gate is illuminated

15.6.1 Relevant methods

Method 2b: Analyse time-intervals between counts from the detector - illuminate every *R*th detector gate; record the elapsed time between a 'click' in the illuminated gate and the first 'click' afterwards in a non-illuminated gate.

Method 3: Illuminate every *R*th detector gate; record 'clicks' in the illuminated gate, and the elapsed time between a 'click' in the illuminated gate and the first 'click' afterwards in a non-illuminated gate.

Method 4: Illuminate every *R*th detector gate; record all detector 'clicks' with an event timer.

The same experimental set-up can be used for these different measurement methods.

ΔT is the period of the DUT gates, and R shall be such that the $R.\Delta T$ exceeds the detector dead-time and recovery time.

15.6.2 Equipment required

1) Master clock.
2) Pulsed laser.
3) Frequency divider.
4) Two-channel waveform or function generator.
5) Tunable delay.
6) Calibrated optical attenuator.
7) Second optical attenuator (does not need to be calibrated).
8) Calibrated optical power meter.
9) Counter/timer.
10) Measurement of spectral frequency of probe pulses - see clause 13.
11) Measurement of pulse repetition rate - see clause 7.

15.6.3 Equipment specifications

See Annex B for further details. Where no specifications are listed here, those listed in Annex B are sufficient.

1) DUT:
   i) Access to the single-photon detector optical input shall be available.
   ii) The DUT can be triggered internally and/or externally.
   iii) The gate trigger signal input shall be available.
   iv) The gate trigger signal output shall be available if the detector is used as the master clock.
   v) The DUT detection signal shall be available.
2) Master clock: This is required to trigger the detector gates and the pulsed laser. If the detector generates its own gate trigger signal and this can be accessed externally, this item may not be required. A low-jitter master clock may be preferred to a higher-jitter detector-generated trigger. In what follows below, it is assumed that the gate trigger signal is either derived from the DUT or an external master clock.
3) Frequency divider: The frequency divider is used to reduce the frequency of the detector gate trigger signal by an integer factor R. This signal is then used to drive the pulsed laser.
4) Two-channel waveform or function generator:

   An alternative to using a frequency divider is to replace the pulse generator and frequency divider by a two-channel waveform or function generator capable of providing two synchronized signals to trigger the detector gates and the laser. This functionality is required for measuring dead time and recovery time (clause 18)
5) Tunable delay: This is required for synchronizing the arrival of a pulse or photon at the detector within the detector gate.
6) Calibrated optical attenuator: Either this, or the second optical attenuator, shall be capable of completely blocking the light transmitted through it.
7) Second optical attenuator (does not need to be calibrated):

   This attenuator is required to attenuate the pulses output from the laser to a value that:
   a) can be measured with the power meter;

b) is sufficiently low so that the calibrated attenuator can then attenuate the resulting optical pulses to the single-photon level

This item is not required if the calibrated optical attenuator (item 6) has sufficient dynamic range to implement a) and b).

Either this, or the calibrated optical attenuator, shall be capable of completely blocking the light transmitted through it.

8) Calibrated optical power meter (see note):

The optical power responsivity shall be traceably calibrated to the SI at the repetition rate of the DUT pulses, and in the spectral region of interest.

NOTE: The mean photon number of the probe pulses shall be reported for after-pulse probability measurements and detection efficiency measurements.

9) Event timer.

15.6.4 Measurement set-up

The set-up shown in figure 15.2 (or variants thereof) shall be used to measure dark count probability, after-pulse probability and detection efficiency.

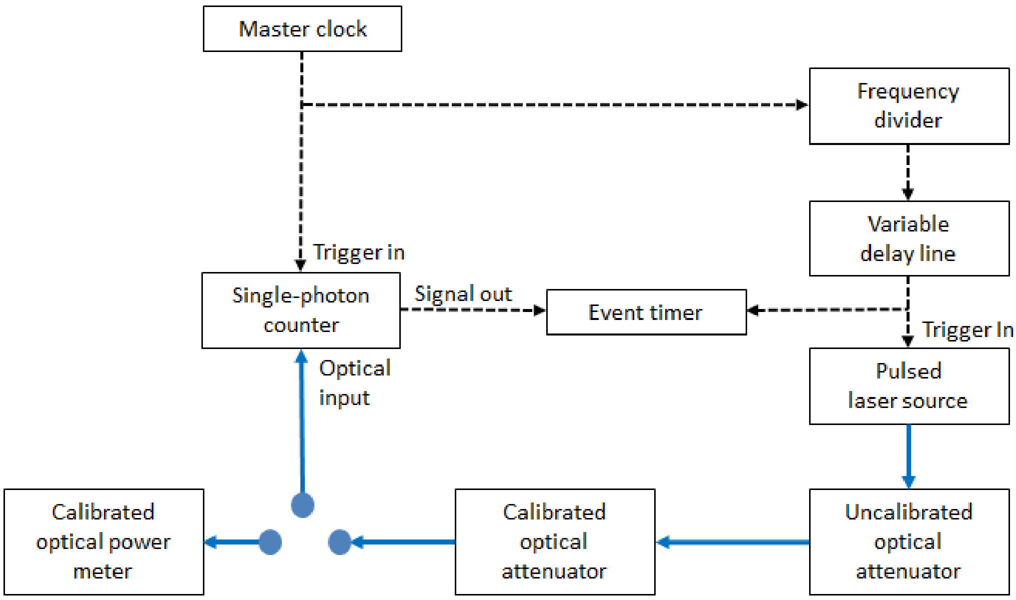


Figure 15.2: Set-up for calibration of QKD photon counter(s).

Electronic connections are shown in black arrows, fibre-optic connections in blue arrows.

NOTE: The output of the calibrated optical attenuator shall be connected to either the calibrated power meter or the QKD receiver/photon counter.

15.6.5 Measurement position

The point at which measurements are referenced to. This is taken to be the input port of the single-photon detector.

15.6.6 Measurement process

15.6.6.1 Processes required for methods 2b, 3 and 4

15.6.6.1.1 Synchronization of source and detector, measurement of mean photon number

The mean spectral frequency ν_m (Hz) of the pulses emitted by the laser is obtained as described in clause 13, and corrected for any spectral variation in the transmittance of the subsequent attenuators and optical fibre [6].

The laser pulse frequency f_{source} is stepped down by an integer factor R compared to the detector gate rate f_{gate} using a frequency divider. Therefore, only every *R*th detector gate will be illuminated, as illustrated in figure 15.3. The output of the pulsed laser is transmitted through an (uncalibrated) attenuator and a calibrated attenuator and measured with the calibrated optical power meter. The calibrated attenuator is set to its lowest attenuation setting, A_{low} (dB), that encompasses its insertion loss, and the uncalibrated attenuator is used to reduce the optical power from the laser to a value that:

i) can be measured with the power meter;

ii) is sufficiently low so that the calibrated attenuator can then attenuate the resulting optical pulses to the single-photon level.

The power P_{meas} is measured with the power meter. The attenuation of the calibrated attenuator is then increased to A_{hi} (dB) so that the output pulses are reduced to the single-photon level, and sent to the DUT.

The arrival of the laser pulses at the detector is synchronized to occur within the detector gates using the low-jitter delay line. The shape of the detector gate efficiency profile (clause 19) can be used to determine when the pulse is within the gate, but synchronization is usually set where the maximum number of counts is recorded, and may not correspond to the centre of the gate. A consistent criterion shall be used for determining the delay used for synchronization, and if this is not set where the maximum number of counts is recorded, the position of the pulse within the gate shall be measured and noted - see clauses 5 and 19.

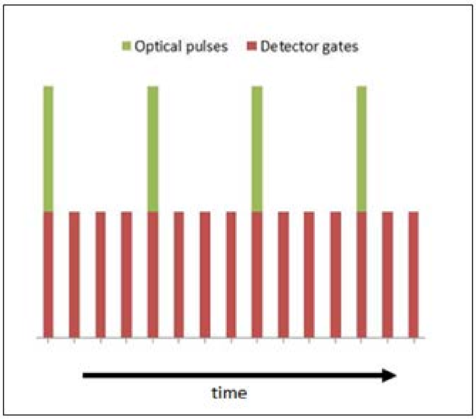


Figure 15.3: Illustration of only every *R*th gate being illuminated

Green columns indicate optical pulses, red columns indicate detector gates. In the illustration, $R = 4$, and a scan lasts for approximately 3,5 laser pulse periods.

Counts in illuminated gates are due to true detections, after-pulses and dark counts, whereas counts in non-illuminated gates are due to after-pulses and dark counts.

A cycle of gates refers to the R gates of a laser pulse period, where the first gate in the cycle is illuminated.

15.6.6.1.1 Calculation of incident mean photon number

The incident mean photon number is given by:

$$\mu = \frac{P_{meas} 10^{-(A_{hi} - A_{lo})/10}}{f_{source} h \nu_m} \tag{15.7}$$

where:

A_{lo} = attenuator attenuation (in dB) when P_{meas} is measured

A_{hi} = attenuator attenuation for single-photon emission

P_{meas} = measured power for A_{lo} setting

ν_m = mean spectral frequency of optical pulse (see clause 13)

15.6.6.2 Processes specific to method 2b

15.6.6.2.1 Measurement

An event timer, with dead time less than the time between consecutive detector gates, is used to record the first 'clicks' in a non-illuminated gate subsequent to a detection in the illuminated gate. One way of implementing this is to trigger the event timer with a laser trigger pulse, and operate the event timer in multi-stop mode, where all detector-generated events are time-tagged.

The data is analysed after the measurement; only events corresponding to a 'click' in the illuminated gate and a first subsequent 'click' in a non-illuminated gate are used for elapsed time calculations.

Other ways of recording first 'clicks' subsequent to a detection in the illuminated gate may be employed.

Measurements shall be obtained by recording data for sufficiently large R, in order to record counts at long-time intervals where dark counts dominate. This shall be established by trial and error.

The range of the event timer scan may be set to encompass many laser pulses (see figure 15.3). Collecting data over many scans is used to obtain temporal histograms of laser triggers and detections.

15.6.6.2.2 Environment

The temperature and humidity of the environment during the measurement shall be recorded.

15.6.6.2.3 Operational settings

The control settings of the DUT shall be recorded, where possible.

Clause 5 provides guidance on the settings to be recorded.

15.6.6.2.4 Calculations of intrinsic dark count and after-pulse probabilities

i) Create a histogram of the number of first clicks versus elapsed time subsequent to a detection in the illuminated gate.

ii) Convert counts into a probability by dividing each count value in the histogram by the total number of detections in the illuminated gate.

iii) Analyse the logarithm of the probability of a count versus linear elapsed time.

iv) After-pulses are expected to be significant only at shorter time-intervals; the long time-interval region may be used to provide an initial estimate of the behaviour of the dark count probability.

v) Fit the intrinsic dark counts to a straight line with negative slope on a log(probability of a count) vs linear(elapsed time) graph. See clause 15.5.7.vii and equations 15.2, 15.3 for further details.

vi) Additional probabilities are assumed to be due to after-pulses.

vii) Fit the probability data to an analytic function (intrinsic darks and after-pulses), or a mixture of analytic (intrinsic darks) and numeric (after-pulses) functions, accounting for the possibility of intrinsic darks and after-pulses coinciding within the same gate. See clause 15.5.7 ix).

viii) The intrinsic dark count probability per gate is obtained from the function for the intrinsic dark count probability behaviour as a function of elapsed time obtained from steps i) to vii).

ix) The total after-pulse probability, p_{after_total} , is the sum of all terms in p_{after_all}, which in turn can be derived from p_{after_first} terms.

x) The total after-pulse probability in gate N can be estimated by applying equation 15.5 to each complete cycle of gates in the scan, and taking the average of the values obtained.

The total after-pulse probability is then given by:

$$p_{after\_total} = p_{after\_all}(1.\Delta T) + p_{after\_all}(2.\Delta T) + \ldots + p_{after\_all}([R-1].\Delta T) \tag{15.8}$$

15.6.6.2.5 Uncertainties

The process described in clause 15.5.7 ix) and equations (15.3) and (15.4) define the measurement equations for p_{idark} and p_{after_first}.

Equation 15.8 defines the measurement equation for p_{after_total}.

Information relating to uncertainty evaluation can be found in Annexes A and B.

15.6.6.3 Processes specific to method 3

15.6.6.3.1 Measurement

An event timer, with dead time less than the time between consecutive detector gates, is used to record the incident laser trigger pulses, the 'clicks' in the illuminated gate, as well as the first 'clicks' in a non-illuminated gate subsequent to a detection in the illuminated gate. One way of implementing this is to trigger the event timer with a laser trigger pulse, and operate the event timer in multi-stop mode, where all laser triggers and detector 'clicks' are time-tagged.

The data is analysed after the measurement: the total number of laser triggers and the total number of 'clicks' in the illuminated gate are calculated, and only events corresponding to a 'click' in the illuminated gate and a first subsequent 'click' in a non-illuminated gate are used for elapsed time calculations.

Other ways of recording laser triggers, clicks in the illuminated gate, and the first 'clicks' subsequent to a detection in the illuminated gate may be employed.

Measurements shall be obtained by recording data for sufficiently large R, in order to record first subsequent 'clicks' at long-time intervals where dark counts dominate. This shall be established by trial and error.

The range of the event timer scan may be set to encompass many laser pulses. Collecting data over many scans is used to obtain temporal histograms of laser triggers and detections.

15.6.6.3.2 Environment

The temperature and humidity of the environment during the measurement shall be recorded.

15.6.6.3.3 Operational settings

The control settings of the DUT shall be recorded, where possible.

Clause 5 provides guidance on the settings to be recorded.

15.6.6.3.4 Calculation of intrinsic dark count and after-pulse probabilities

i) The calculations described in clause 15.6.6.2.4 shall be applied for calculating intrinsic dark count and after-pulse probabilities.

15.6.6.3.5 Calculation of detection efficiency

For pulses from an attenuated laser operating above threshold with a mean number of photons per pulse, μ, the probability of there being N photons in a pulse is assumed to follow the Poisson distribution, and the probability of a true detection (i.e. one due to the detection of a photon, and not a dark count or an after-pulse) with a non-photon-number-resolving detector is given by:

$$p_{true} = 1 - \exp(-\mu\eta) \tag{15.9}$$

where η is the detection efficiency to be measured.

Therefore:

$$\eta = -\frac{1}{\mu}\ln(1 - p_{true}) \tag{15.10}$$

i) convert counts in the illuminated gate into a probability, p_i, by dividing the number of clicks by the number of source triggers;

ii) the after-pulse probability for the illuminated gate is taken to be approximately the same as for gate R, where gate 1 is the illuminated gate;

iii) the true detection probability, p_{true}, is obtained from the click probability in the illuminated gate, the dark count probability (derived as in clause 15.6.6.2.4, or otherwise), and the after-pulse probability in gate R (derived as in clause 15.6.6.2.4, or otherwise) from which p_{true} may be derived:

$$p_i = 1 - [1 - p_{true}][1 - p_{idark}(1.\Delta T)][1 - p_i\, p_{after\_first}(R.\Delta T)] \tag{15.11}$$

iv) the detection efficiency, η, is calculated from equation 15.10, using the derived true detection probability and the mean photon number, μ, of the illuminating source.

15.6.6.3.6 Uncertainties

The measurement of p_{true} requires that the calibrating probe pulses are maintained at the same point within the single-photon detector gate. The variation in p_{true} due to instability in this will be a component of uncertainty, although this component may not be separable from other instability factors which lead to a variation in measured p_{true}. However, the uncertainty in maintaining the probe pulse at the required position can be evaluated, and shall be reported - see clause 15.6.7.1.

The process described in clause 15.5.7 ix) and equations (15.3) and (15.4) define the measurement equation for p_{idark} and p_{after_first}.

Equation (15.8) defines the measurement equation for p_{after_total}.

Equation (15.11) defines the measurement equation for p_{true}.

Equation (15.10) defines the measurement equation for η.

Information relating to uncertainty evaluation can be found in Annexes A and B.

15.6.6.4 Processes specific to method 4

15.6.6.4.1 Measurement

An event timer, with dead time less than the time between consecutive detector gates, is used to record the incident laser trigger pulses, the 'clicks' in the illuminated gate, as well as the 'clicks' in the non-illuminated gates. One way of implementing this is to trigger the event timer with a laser trigger pulse, and operate the event timer in multi-stop mode, where all laser triggers and detector-generated events are histogrammed in time-bins (without requiring time-tagging).

This method cannot separate dark counts into their constituent intrinsic dark counts and their after-pulses.

This method records first and secondary after-pulses.

Time-tagging of all detector-generated 'clicks' may be performed to extract first after-pulses, which can then be analysed as described for method 3.

The data is analysed after the measurement: the total number of laser triggers and the total number of 'clicks' in the illuminated gate and each non-illuminated gate are calculated.

Other ways of recording laser triggers, clicks in the illuminated gate and 'clicks' in the non-illuminated gates may be employed.

The range of the event timer scan shall be set to encompass many laser pulses. Collecting data over many scans is used to obtain temporal histograms of laser triggers and 'clicks'.

15.6.6.4.2 Measurement variants

a) the counts in the final non-illuminated gates do not reach a constant level;

b) the counts in the final non-illuminated gates reach a constant level, which is taken to be the dark count level;

c) the counts in the final non-illuminated gates are at constant level for non-illuminated gate numbers ranging over at least an order of magnitude; the extrapolated calculated after-pulse level is two orders of magnitude below the dark count level at gate R.

15.6.6.4.3 Environment

The temperature and humidity of the environment during the measurement shall be recorded.

15.6.6.4.4 Operational settings

The control settings of the DUT shall be recorded, where possible.

Clause 5 provides guidance on the settings to be recorded.

15.6.6.4.5 Calculations for variant "a"

The first detector gate in the cycle is illuminated, and gates 2 to R are non-illuminated:

i) The click probability in the illuminated gate, p_{click_i}, is obtained by dividing the number of clicks in the illuminated gate C_i by the number of source triggers N_{trig}.

ii) p_{click_i} is the combination of the true detection probability, p_{true}, and the probability of 'other' clicks, $p_{other}(R.\Delta T)$, due to dark counts and after-pulses of 'true' counts in the preceding illuminated gates:

$$p_{click\_i} = \frac{C_i}{N_{trig}} = 1 - (1 - p_{true})(1 - p_{other}(R.\Delta T)) \tag{15.12}$$

p_{true} may be estimated by approximating $p_{other}(R.\Delta T)$ with $p_{other}([R-1].\Delta T) = C_R/N_{trig}$, where C_R is the number of counts in gate R (non-illuminated). This may slightly overestimate $p_{other}(R.\Delta T)$:

$$p_{true} = 1 - \frac{1 - C_i / N_{trig}}{1 - C_R / N_{trig}} \tag{15.13}$$

Alternatively, the value of $p_{other}(R.\Delta T)$ may be estimated by extrapolation, based on knowledge of C_2 *to* C_R.

iii) The detection efficiency is calculated from the derived true detection probability, p_{true}, and the mean photon number, μ, of the illuminating source, using equation (15.10).

iv) p_{dark} is measured in a separate measurement. The illuminating source is switched off and the number of counts N in M gates is recorded, where M is an integer multiple of R. p_{dark} is calculated using equation (15.1).

v) The click probability in non-illuminated gate X (X=2 to R), p_{click_X}, is obtained by dividing the number of clicks in the non-illuminated gate, C_X, by the number of source triggers N_{trig}.

vi) The after-pulse probability p_{after_X} in non-illuminated gate X is obtained by subtracting the probability of a dark count p_{dark} from p_{click_X} , while accounting for coincidences, and dividing the result by p_{true}:

$$p_{after\_X} = \left[1 - \frac{1 - C_X / N_{trig}}{1 - p_{dark}}\right] \frac{1}{p_{true}} \tag{15.14}$$

vii) C_{ni} is the average of counts over all (R-1) non-illuminated gates in a cycle of gates:

$$p_{after\_av} = \left[1 - \frac{1 - C_{ni} / N_{trig}}{1 - p_{dark}}\right] \frac{1}{p_{true}} \tag{15.15}$$

where p_{after_av} is the after-pulse probability averaged over the $(R-1)$ non-illuminated gates.

viii) The total after-pulse probability is the sum of all non-illuminated gate after-pulse probabilities, plus the after-pulse probability for gate ($R+1$) which is approximated by the after-pulse probability in the non-illuminated gate R:

$$p_{after\_total} = (R-1)\, p_{after\_av} + p_{after\_R} \tag{15.16}$$

where, from (15.14):

$$p_{after\_R} = \left[1 - \frac{1 - C_R / N_{trig}}{1 - p_{dark}}\right] \frac{1}{p_{true}} \tag{15.17}$$

Alternatively, $p_{after\_(R+1)}$ may be estimated by extrapolation, based on knowledge of C_2 to C_R.

15.6.6.4.6 Calculations for variant "b"

The analysis for variant "b" is similar to the analysis for variant "a" except for the following:

iv) The number of dark counts in each non-illuminated gate is estimated from the region of constant count level obtained for large values of R. The dark count probability per gate is obtained by dividing this number by the number of source triggers.

vi) The terms for p_{after_X} calculated using equation (15.14) will be a reasonable approximation to the terms in p_{after_all}, i.e. equation (15.14) becomes:

$$p_{after\_X} = \left[1 - \frac{1 - C_X / N_{trig}}{1 - p_{dark}}\right] \frac{1}{p_{true}} = p_{after\_all}\left([X-1]\Delta T\right) \tag{15.18}$$

15.6.6.4.7 Calculations for variant "c"

The analysis for variant "c" is similar to the analysis for variant "b" except for the following:

vi) the terms for p_{after_X} will be a better measure of the terms in p_{after_all}.

15.6.6.4.8 Uncertainties

The measurement of p_{true} requires that the calibrating probe pulses are maintained at the same point within the single-photon detector gate. The variation in p_{true} due to instability in this will be a component of uncertainty, although this component may not be separable from other instability factors which lead to a variation in measured p_{true}. However, the uncertainty in maintaining the probe pulse at the required position can be evaluated, and shall be reported - see clause 15.6.7.1.

Equation (15.1) defines the measurement equation for p_{dark} (variant "a").

The process described in clause 15.6.6.4.6 iv) defines the measurement equation for p_{dark} (variants "b" and "c").

Equation (15.16) defines the measurement equation for p_{after_total} (all variants).

Equation (15.14) defines the measurement equation for the terms in p_{after_all} (variants "b" and "c").

The magnitude of p_{after_R} indicates how closely the p_{after_X} terms can represent the p_{after_all} terms, in the absence of other sources of uncertainty.

Equation (15.13) defines the measurement equation for p_{true} (all variants).

Equation (15.10) defines the measurement equation for η (all variants).

Further information relating to uncertainty evaluation can be found in Annexes A and B.

15.6.7 Results

15.6.7.1 Reporting measurement on dark count probability, after-pulse probability and detection efficiency

The following measurements on dark count probability, after-pulse probability and detection efficiency shall be reported:

1) Unique identification number of DUT.

2) Measurement date(s).

3) Measurement duration.

4) Probe pulse duration and its uncertainty.

5) Probe pulse mean photon number and its uncertainty.

6) Position of probe pulse and its uncertainty. This can be stated as the position of maximum measured DE, or some other stated point relative to the detector gate (see clause 19).

7) Polarization of probe pulse at input port to DUT and its uncertainty. This can be for random polarized light or some other stated polarization (see clause 17).

8) The triggering frequency division ratio, R.

9) The detector dead-time and recovery time where these are longer than the detector gate period (clause 18).

10) Gate duration.

11) Gate repetition rate.

12) Measurement wavelength (or spectral frequency).

13) The following derived properties (where they have been measured):

  a) Dark count probability and its uncertainty.

  b) First after-pulse probabilities and their uncertainties.

  c) Total after-pulse probability and its uncertainty.

  d) Detection efficiency and its uncertainty.

14) Measurement environment (temperature, humidity).

15) DUT operational settings - see clause 5.

16) Exceptions or deviations from procedure.

17) Measurement operator(s).

15.6.7.2 Other information to be reported

The following information may be reported:

1) Measurement set-up.

2) Make and model number of key measurement equipment.

3) Measurement method.

4) Description of calculation.

5) Traceability to SI.

16 Measurement of detection efficiency linearity factor

16.1 Definitions, symbols and units

Definitions, symbols and units relevant to this clause can be found in clause 3.

16.2 Procedure scope

This procedure covers the measurement of the detection efficiency linearity factor.

The CIE definition of a linear detector is a "detector is that for which the output is proportional to the input over a specified range of inputs, so that the responsivity of the detector is constant over that range" [i.21].

The first clause is not directly applicable to non-photon-number-resolving single-photon detectors responding to a photon number distribution, as seen from equation 15.10. The second clause which states that the responsivity, i.e. detection efficiency, shall be constant, remains valid.

16.3 Measurement

The mean photon number, μ, of the incident optical pulses is varied from μ_A to μ_B, and the detection efficiency, η, is measured at each value of μ, as described in clause 15.

The measurement shall be performed at an input pulse rate and mean photon number such that detector dead-time does not affect the measurements.

16.4 Environment

The temperature and humidity of the environment during the measurement shall be recorded.

16.5 Operational settings

The control settings of the DUT shall be recorded.

Clause 5 provides guidance on the settings to be recorded.

16.6 Calculations

The minimum, η_{min}, and maximum, η_{max}, measured detection efficiencies are identified.

The linearity factor $F_L(\eta_{min},\eta_{max})$ shall be defined as the ratio of the minimum detection efficiency to the maximum detection efficiency for the applied range of input mean photon numbers, i.e.

$$F_L(\eta_{\min},\eta_{\max}) = \frac{\eta_{\min}}{\eta_{\max}} \tag{16.1}$$

If F_L is unity, the detector is linear across the range of mean photon numbers. It is important that the limits μ_A to μ_B over which the measurement has been made are stated.

16.7 Uncertainties

Uncertainties in the values of η_A, η_B and μ_A, μ_B shall be obtained as described in clause 15.

Further information relating to uncertainty evaluation can be found in Annexes A and B.

16.8 Results

16.8.1 Reporting measurement on detection efficiency linearity factor

The following measurements on detection efficiency linearity factor shall be reported:

1) Unique identification number of DUT.
2) Measurement date(s).
3) Measurement duration.
4) Range of input mean photon number.
5) Detection efficiency linearity factor and its uncertainty.
6) Measurement environment (temperature, humidity).
7) DUT operation settings - see clause 5.
8) Exceptions or deviations from procedure.
9) Measurement operator(s).

16.8.2 Other information to be reported

The following information may be reported:

1) Measurement set-up.

2) Make and model number of key measurement equipment.

3) Measurement method.

4) Detection efficiencies as a function of input mean photon number, and their uncertainties. See clause 15 for reporting requirements.

5) Description of calculation.

6) Traceability to SI.

17 Measurement of detection efficiency range due to polarization variation of input pulses

17.1 Definitions, symbols and units

Definitions, symbols and units relevant to this clause can be found in clause 3.

17.2 Procedure scope

This procedure covers the measurement of the DE of a single-photon detector as the input polarization is varied over all pure states in order to obtain the maximum DE values for polarized light, and the average value for randomly polarized light.

Optimization strategies may be employed to avoid the need to carry out a full mapping of DE over the surface of the Poincaré sphere.

Measurement of DE is performed as described in clause 15.

17.3 Equipment

17.3.1 Equipment required

Refer to clause 15.

In addition, the following are required:

1) A polarization controller is required to adjust the polarization of the input pulses, as well as a means for controlling it.

2) A polarization scrambler is required to randomize the polarization state of the input pulses.

17.3.2 Equipment specifications

Refer to clause 15.

1) Polarization controller: A fibre-coupled polarization controller is required to adjust the polarization state of the input optical pulses. A four-axis controller is recommended, to facilitate smooth transition from one state to another.

2) Polarization scrambler: A fibre-coupled polarization scrambler is required. It shall be possible to disable the scrambling function such that any input states is mapped consistently to a constant output basis while the scrambling function is disabled. When enabled no significant time-averaged polarization information shall be preserved.

3) Polarizers: Fibre-coupled polarizers. These should be of a type offering a high extinction ratio otherwise they will introduce uncertainly under clause 17.4.3.

17.4 Measurement

17.4.1 Measurement set-up

Figure 17.1 (adapted from figure 15.2) shows the experimental arrangement modified by the addition of a linear polarizer, a polarization controller, and a polarization scrambler. Electronic connections are shown in dashed black lines, fibre-optic connections in solid blue lines. The output of the polarization scrambler shall be connected to either the calibrated power meter or the photon counter/QKD receiver. The master clock may be part of the QKD receiver.

All components of the set-up in which polarization changes will alter the measured result shall be stable enough that changes to the evolution of the polarization state within each individual component are not large enough to alter the measured result significantly over the duration of the polarization optimization and DE measurement (except within the polarization scrambler when enabled and within the polarization controller while adjustments are being made).

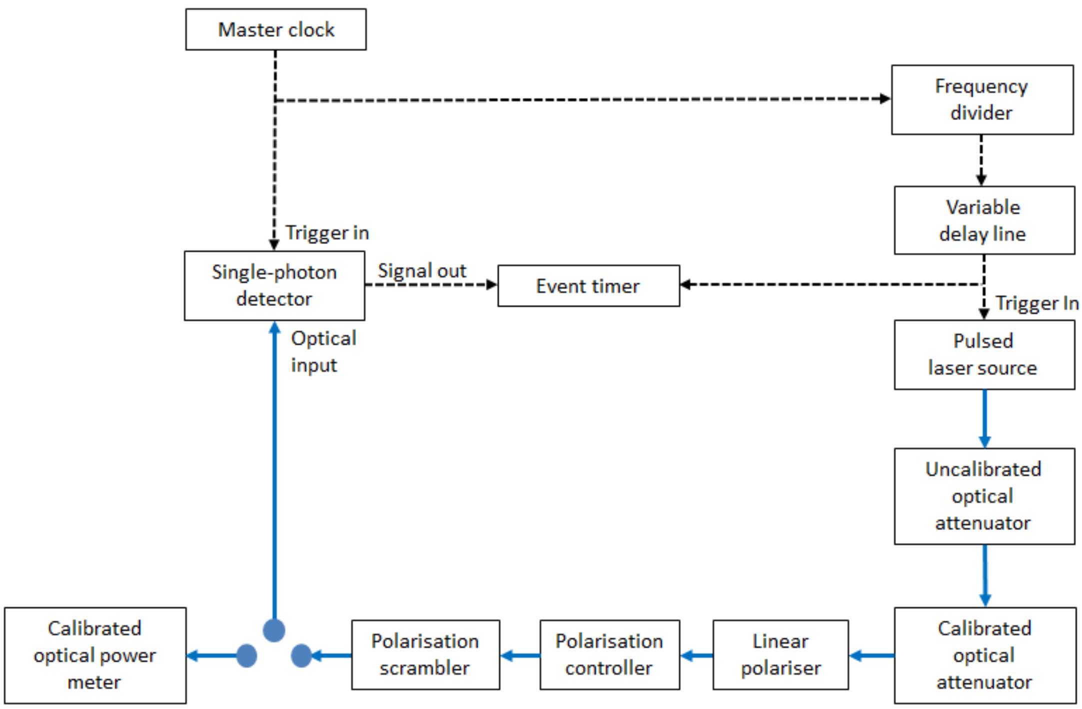


Figure 17.1: Set-up for measuring variation of DE with polarization of input state (adapted from figure 15.2)

Electronic connections are shown in black dashed arrows, fibre-optic connections in blue arrows.

17.4.2 Measurement position

The point at which measurements are referenced to. In this case it shall be the input port of the single-photon detector.

17.4.3 Verification of the operation of the polarization scrambler

17.4.3.1 Tests and measurement set up

Tests on the polarization scrambler shall be carried out to check that:

1) it does not scramble the polarization state significantly when disabled;
2) it effectively scrambles the polarization to the required degree;
3) its attenuation does not change significantly when enabled.

The polarization scrambler tests should include laser light in a single polarization state, a polarization controller, a polarization scrambler, a polarizer and a detector but if the polarization scrambler used to measure the detector DUT above is also providing the polarization control an additional separate polarization control shall be used for testing the polarization scrambler.

The experimental arrangement used for verifying the operation of the polarization scrambler can be the same as in figure 17.1 but with the addition of an additional polarization controller and polarizer inserted after the polarization scrambler. Performance of the polarization scrambler may be verified at optical power levels at which low-noise measurements can be obtained using the optical power meter rather than using the photon counter / QKD receiver. For testing the operation of the polarization scrambler a separate polarization controller is required before the polarization scrambler under test. If both of these functions are to be provided by the same device for measuring the DE of a single photon detector, an additional polarization controller is required to test the performance of the polarization scrambler.

For the test described in clause 17.4.3.4 an additional polarization scrambler shall be inserted immediately after the first linear polarizer.

17.4.3.2 Verify does not scramble the polarization when disabled

With the polarization scrambler disabled the second polarization controller shall be adjusted to minimize the signal on the detector. Any residual signal shall be accounted for in the errors on the DE for randomly polarized input light.

17.4.3.3 Verify effective scrambling when enabled

With the polarization scrambler disabled the second polarization controller shall be adjusted to maximize the signal on the detector. On enabling the polarization scrambler the signal on the detector should reduce to half the previous value. The first polarization controller shall then be adjusted looking for any increase or decrease in signal on the detector. The maximum stable variation from half the signal on the detector shall be accounted for in the errors on the DE for randomly polarized input light.

17.4.3.4 Verify attenuation does not change when enabled

With an additional polarization scrambler inserted and enabled immediately after the first linear polarizer the signal on the detector shall be measured with the polarization scrambler under test disabled. The polarization scrambler under test shall then be enabled and any change in the signal on the detector recorded. Any such change shall be accounted for in the errors on the DE for randomly polarized input light.

17.4.4 Measurement process

Light in a single polarization is passed through a polarization controller and a polarization scrambler before being input into the DUT as shown in figure 17.1. The polarization controller shall first be adjusted to optimize the count rate on the detector with the polarization scrambler disabled. The optimization may be done manually or using an optimization algorithm such as a random walk (optimized to use appropriate step sizes etc.) or using a system that can map out the count rate over the entire Poincaré sphere and set the polarization to the state for which the maximum was found. The operator shall satisfy themselves that the maximum stable signal has been found to within the reported error. The polarization controller shall then be fixed under this condition and the maximum detection efficiency for polarized light measured using the procedure in clause 15 without altering the polarization state incident on the DUT. The signal shall be stable and not a transient fluctuation and the DE measurement shall meet all the requirements of clause 15.

The polarization scrambler shall then be enabled and the corresponding detection efficiency for randomly polarized light shall be measured as prescribed in clause 15.

17.5 Environment

The temperature and humidity of the environment during the measurement shall be recorded.

Good environmental stability or isolation from environmental changes may be required to satisfy the polarization stability requirements in clause 17.4.1.

17.6 Operational settings

The control settings of the DUT shall be recorded.

Clause 5 provides guidance on the settings to be recorded.

17.7 Uncertainties

There will be uncertainties due to the use of the polarization optics - polarizer, controller, and scrambler.

Other uncertainty components can be evaluated as described in clause 15 (and other clauses referenced therein).

Information relating to uncertainty evaluation can be found in Annexes A and B.

17.8 Results

17.8.1 Reporting measurement on detection efficiency range due to polarization variation of input pulses

The following measurements on detection efficiency due to polarization variation of input pulses shall be reported:

1) Unique identification number of DUT.
2) Measurement date(s).
3) Measurement duration.
4) Measurement wavelength (or spectral frequency).
5) Maximum detection efficiency for a single polarization, and its uncertainty. Refer to clause 15.6.7 for related reporting requirements.
6) Detection efficiency, and its uncertainty, for randomly polarized input light.
7) Measurement environment (temperature, humidity).
8) DUT operation settings - see clause 5.
9) Exceptions or deviations from procedure.
10) Measurement operator(s).

17.8.2 Other information to be reported

The following information may be reported:

1) Measurement set-up
2) Make and model number of key measurement equipment

3) Measurement method

4) Description of calculation

5) Traceability to SI

The measured minimum detection efficiency for a single polarization shall not be reported. This should be deduced from the maximum detection efficiency for a single polarization and the detection efficiency for randomly-polarized input light.

18 Measurement of dead time, recovery time, partial recovery time, reset time

18.1 Definitions, symbols and units

Definitions, symbols and units relevant to this clause can be found in clause 3.

NOTE 1: The definition of dead time may not lend itself to practical measurement, and therefore an alternative definition, [partial recovery time (low) - see definition in clause 3.1] may be used.

NOTE 2: The dead time is stated in s.

NOTE 3: The recovery time is stated in s.

NOTE 4: The partial recovery time (low) is stated in s.

NOTE 5: The partial recovery time (high) is stated in s.

NOTE 6: The reset time is stated in s.

18.2 Procedure scope

This procedure covers the measurement of dead time, recovery time, partial recovery time(s), and reset time of a single-photon detector, which may be part of a QKD receiver.

Since a QKD receiver may have more than one single-photon detector, it is understood that the operator has the ability to control and take readings from the detector of his/her choosing.

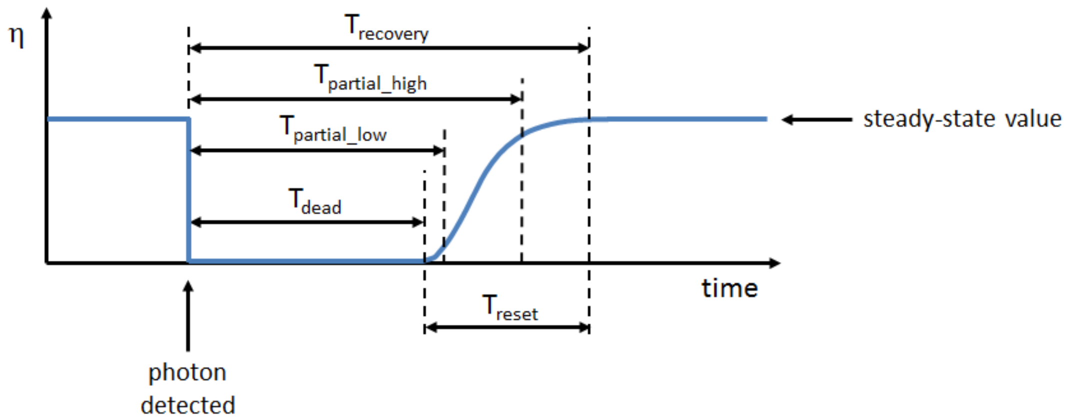


Figure 18.1: Schematic of detection efficiency as a function of time. Adapted from [i.10] and [i.14]

The dead time, recovery times and reset time shall be measured using the two-pulse method [i.18], [i.9] and [i.19]. A train of double pulses of equal intensity, separated by a tunable time ΔT, and attenuated to the single-photon level, are sent to the detector. In the case of gated detectors, the photons will be synchronized to the detector gates, and their time separation incremented in steps equal to a gating period. The probabilities of detecting the first photon, p_1, the second photon p_2, and both photons, p_{12} shall be recorded as a function of ΔT. The time between pairs of pulses should exceed the expected recovery time, and, in the case of SPAD detectors, be long enough to ensure a negligible after-pulse probability.

Partial recovery times are introduced since it may be impractical to reliably measure the dead time (t_{dead}), i.e. the point at which p_{12} becomes non-zero; and impractical to measure the recovery time ($t_{recovery}$), i.e. the time at which $p_2 = p_1$, which may be approached in an exponentially-decaying fashion.

18.3 Equipment

18.3.1 Equipment required

1) Function generator.
2) Pulsed laser.
3) Tunable delay line.
4) Calibrated optical attenuator.
5) Event timer.

18.3.2 Equipment specifications

1) DUT: Access to single-photon detector optical input:
   i) Access to the single-photon detector optical input shall be available.
   ii) The gate trigger signal input shall be available.
   iii) The DUT detection signal shall be available.
2) Function generator: A two-channel function generator is required to provide two synchronized signals to trigger the detector gates and the laser.
3) Pulsed laser.
4) Tunable delay line: This is required for synchronizing the arrival of a pulse or photon at the detector within the detector gate.
5) Calibrated optical attenuator.
6) Event timer.

18.4 Set-up

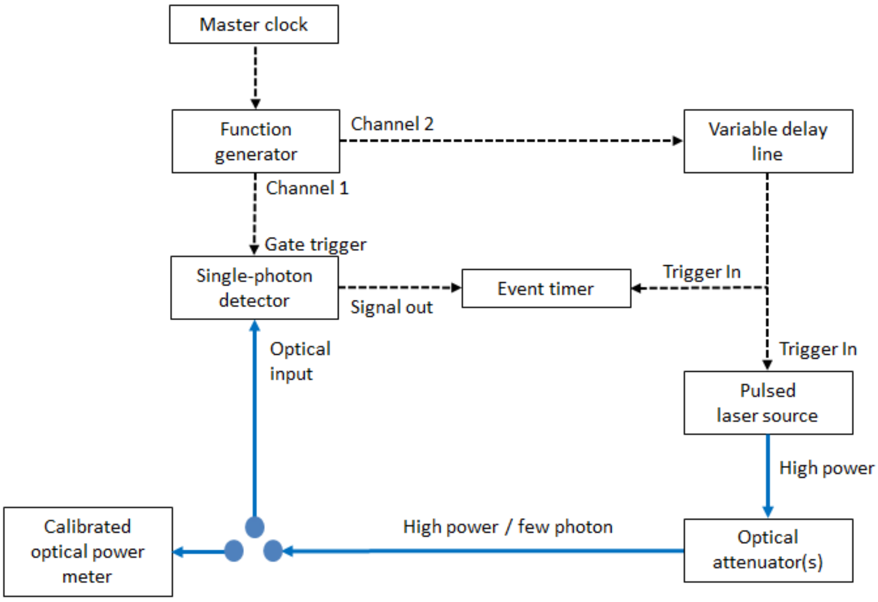


Figure 18.2: Set-up for measurement of dead time and recovery time of QKD photon counter(s)

Electronic connections are shown in dashed black lines, fibre-optic connections in solid blue lines.

NOTE: The output of the calibrated optical attenuator is connected to either the calibrated power meter or the photon counter / QKD receiver. The master clock may be part of the function generator.

18.5 Measurement

The incident optical pulse train is created, and coupled to the DUT such that each pulse is at the same position within the detector gate, and the mean photon number, μ, of each pulse is set to a level similar to that for which it will used ($\mu < 1$). This may be done with a pulse emitted at the same frequency as the detector gate. See clause 15.6.6 for guidance on how to achieve this.

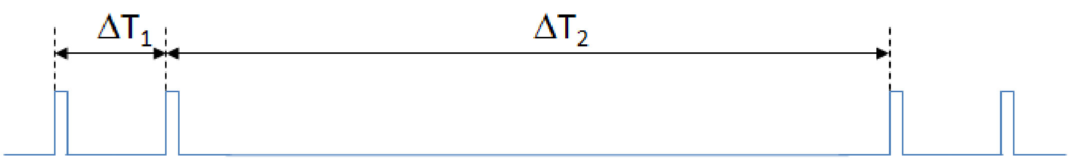


Figure 18.3: Illustration of double-pulse technique.

ΔT_1 = spacing between pulses within pair; ΔT_2 = spacing between second pulse of a pair and first pulse of next pair.

An optical pulse train with: $\Delta T_1 = 1$ (in units of gate intervals), and $\Delta T_2 >> T_{recovery}$ (expected) is generated and synchronized with the detector gates. ΔT_2 shall be chosen such that the probability of an after-pulse from a detection of the previous pulse-pair is negligible. If this is not feasible, equations 18.1 to 18.3 shall be modified accordingly.

A timer/counter, operating in multi-stop mode with dead time less than the time between consecutive detector gates, is triggered by one of the laser pulse triggers (e.g. the first pulse trigger). The time-span over which stop events is collected shall be long enough to collect detection events corresponding to at least one pulse pair. Repeated triggering is used to obtain a temporal histogram of detections. The number of counts corresponding to detections of the first pulse of the pulse pair is denoted by C_1, the number of counts corresponding to detections of the second pulse of the pulse pair gate is denoted by C_2, and the number of counts corresponding to detections of both pulses of the pulse pair gate is denoted by C_{12}. The number of laser triggers (i.e. scans) is denoted by N_{trig}. ΔT_1 is then successively incremented by one gate interval, and the measurement repeated.

18.6 Environment

The temperature and humidity of the environment during the measurement shall be recorded.

18.7 Operational settings

The control settings of the DUT should be recorded.

Clause 5 provides guidance on the parameters to be recorded.

18.8 Calculations

18.8.1 Detection probabilities

For a given value of ΔT_1, p_1, p_2 and p_{12} can be evaluated from the following relationships:

$$\frac{C_1}{N_{trig}} = 1 - (1 - p_1)(1 - p_{dark}) \tag{18.1}$$

$$\frac{C_2}{N_{trig}} = 1 - (1 - p_2)(1 - p_{dark})(1 - p_1 p_a) \tag{18.2}$$

$$\frac{C_{12}}{N_{trig}} = 1 - (1 - p_{12})(1 - p_1 p_{dark})(1 - p_{dark} p_2)(1 - p_{dark} p_{dark})(1 - p_1 p_1 p_a)(1 - p_{dark} p_1 p_a) \tag{18.3}$$

where p_1 is the probability of a true detection from the first pulse, p_2 is the probability of a true detection from the second pulse, p_{12} is the probability of a true detection of both pulses, p_{dark} is the probability of a dark count and its after-pulses, and the after-pulse probability p_a is the value of $p_{after\_all}(\Delta T_1)$ for the particular value of ΔT_1 employed, measured using methods 4 (b) or 4 (c) described in clause 15.

The 4th and 6th brackets in equation 18.3 may be ignored if p_1, p_2 >> p_{dark}, $p_{after}(\Delta T_1)$, as is usually the case.

18.8.2 Dead time

The dead time T_{dead} is the value of ΔT_1 at which C_{12} becomes non-zero.

18.8.3 Partial recovery time (low)

The partial recovery time (low) shall be chosen to be the time at which p_2 becomes a certain stated sub-unity multiple of p_1, e.g. 0,05 or 0,1.

i.e. $T_{partial\_low}$ is the value of ΔT_1 at which $p_{12} = PR\, p_1^2$, i.e. $p_2 = PR\, p_1$, where PR is selected to some value less than 1, such as 0,05 or 0,10.

18.8.4 Partial recovery time (high)

The partial recovery time (high) can be chosen to be the time at which p_2 becomes a certain stated sub-unity multiple of p_1, e.g. 0,9 or 0,99.

i.e. $T_{partial\_high}$ is the value of ΔT_1 at which $p_{12} = PR\, p_1^2$, i.e. $p_2 = PR\, p_1$, where PR is selected to some value less than 1, such as 0,9 or 0,99.

If the detection efficiency recovery is non-monotonic (e.g. it exhibits ringing), then the recovery time shall be the longest time at which $p_2 = PR\, p_1$.

18.8.5 Recovery time

The recovery time $T_{recovery}$ is the value of ΔT_1 at which $p_{12} = p_1^2$, i.e. $p_2 = p_1$.

If the detection efficiency recovery is non-monotonic (e.g. it exhibits ringing), then the recovery time shall be the longest time at which $p_2 = p_1$.

18.8.6 Reset time

The reset time T_{reset} is given by $T_{reset} = T_{recovery} - T_{dead}$. If the dead time cannot be measured reliably, then the reset time shall be approximated by $T_{reset} = T_{recovery} - T_{partial\_low}$.

18.9 Uncertainties

The measurement equations are given explicitly in equations 18.1 to 18.3, and as parameter values in clauses 18.8.2 to 18.8.6

Information relating to uncertainty evaluation can be found in Annexes A and B.

18.10 Results

18.10.1 Reporting measurement on dead time, recovery time, partial recovery time, and reset time

The following measurements on dead time, recovery time, partial recovery time, and reset time shall be reported:

1) Unique identification number of DUT.

2) Measurement date(s).

3) Measurement duration.

4) Measurement data, showing calculated values of p_{12} as a function of time between pulses of the pulse-pair. This is important for understanding the recovery profile of the detector.

5) The following properties (where they have been measured):

   a) Dead time, and its uncertainty.

   b) Partial recovery time (low), and its uncertainty.

   c) Partial recovery time (high), and its uncertainty.

   d) Recovery time, and its uncertainty.

   e) Reset time, and its uncertainty.

6) Measurement environment (temperature, humidity).

7) DUT operation settings - see clause 5.

8) Exceptions or deviations from procedure.

9) Measurement operator(s).

18.10.2 Other information to be reported

The following information may be reported:

1) Measurement set-up.
2) Make and model number of key measurement equipment.
3) Measurement method.
4) Description of calculation.
5) Traceability to SI.

19 Measurement of detector signal jitter and detection efficiency profile

19.1 Definition Definitions, symbols and units

Definitions, symbols and units relevant to this clause can be found in clause 3.

NOTE: The detector signal jitter is stated in s.

19.2 Procedure scope

This procedure covers the measurement of detector signal jitter and detection efficiency profile

Measurements shall ideally be referenced to the time at which the optical test pulse is emitted from the end of the optical fibre that is connected to the input optical port of the DUT. The procedures described in clauses 19.5.3 and 19.5.4 shall be carried out.

If this is not required, then it shall be appropriate to perform measurements referenced to an arbitrary point in time. The procedure described in clause 19.5.3 may therefore be omitted.

19.3 Equipment

19.3.1 Equipment required

Refer to clause 15.

In addition, the following are required:

1) High bandwidth photodiode and amplifier
2) Sampling oscilloscope
3) Event timer

19.3.2 Equipment specifications

Refer to clause 15.

A sampling oscilloscope is preferred to an event timer for the measurement described in clause 19.5.3, whereas an event timer is required for the measurement described in clause 19.5.4.

See Annex B for further details. Where no specifications are listed here, those listed in Annex B are sufficient.

19.4 Set-up

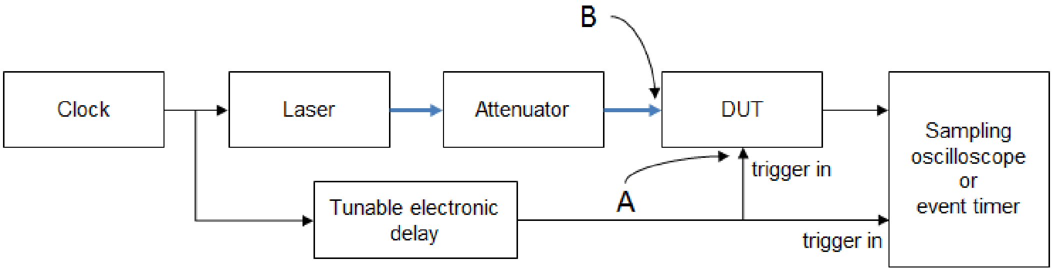


Figure 19.1: Measurement set-up

19.5 Measurement

19.5.1 Applicable methods

The measurement is based on that used to measure detection efficiency, as described in clause 15.

An intense pulse and high-bandwidth photodiode/amplifier combination is used to measure the arrival times of the optical pulses at the end of the optical fibre that is to be connected to the DUT port with respect to the gate trigger to the single-photon detector.

The source emission temporal profile of the optical pulses (clause 12) shall be significantly smaller than the detector signal jitter expected to be measured.

The tunable electronic delay is used to vary the arrival time of the optical pulses at the input port of the DUT with respect to the gate trigger to the single-photon detector.

A time histogram of detection output signals is recorded, relative to the gate trigger to the single-photon detector (DUT), for each setting of the variable delay.

Measurements shall be carried out with pulses incident at different times within the detector gate to see if the detector jitter varies as a function of pulse position within the gate. This shall be done by changing the value of the electronic delay. A comprehensive set of measurements is recommended, where the incident pulse arrives before the detector gate (i.e. before the position at which few detections are observed), and is then stepped through the gate until it arrives after the detector gate (i.e. after the position at which few detections are observed).

19.5.2 Measurement set-up

The set-up shown in figure 19.1 is used.

A high-bandwidth photodiode (together with a high-bandwidth amplifier) is used in place of the single-photon detector (DUT). This enables the measurement of the time between a gate trigger (indicated by A in figure 19.1) and the arrival of the corresponding optical pulse at the end of the fibre (indicated by B in figure 19.1) which is to be connected to the DUT.

The source emission temporal profile with respect to the gate trigger of the DUT (single-photon detector or QKD receiver) is measured before attenuation to the single-photon level, as described in clause 12.

The optical pulses are then attenuated to the single-photon level, and the high-bandwidth photodiode replaced with the single-photon detector (DUT). The tunable electronic delay is used to synchronize the arrival of pulses within the detector bias gates.

19.5.3 Initial measurement with a fast photodiode

19.5.3.1 Overview

This measurement is carried out in order to determine the arrival time, relative to the gate trigger signal, of the optical pulse at the end of the input fibre that will be connected to the DUT.

The attenuators are set to produce intense pulses that can be measured with a fast photodiode/amplifier combination - see clause 12.

The tunable delay is set to some known delay setting.

A histogram of detection times should be observed by correlating many successive detection events with the signal triggering the detector gates.

The time between the detector gate and the detection signal comprises:

i) the time between the gate trigger signal and the optical pulse arriving at the output end of the fibre;

ii) the time between an optical pulse arriving at the input port of the fast photodiode and an amplified signal produced at the output of the amplifier;

iii) any dead-times and latencies in the recording devices;

iv) any time differences in the electrical cabling from the gate trigger signal and amplifier output to the timer/counter.

Times ii) to iv) shall be calibrated separately, in order to calculate i).

19.5.3.2 Measurement with an oscilloscope

An oscilloscope is recommended for this measurement.

The oscilloscope is set to a mode such that a history of sampled points from the trace produced by the fast photodiode/amplifier, as a function of time relative to the trigger, is accumulated.

The mean signal level for each point on the time axis is then calculated to obtain the resulting curve, which represents the source emission temporal profile.

The time between the gate trigger signal and the optical pulse arriving at the output end of the fibre is calculated from the time of the maximum of the curve.

19.5.3.3 Measurement with an event timer

An event timer can also be used to perform this measurement.

The event timer is set to a mode such that a histogram of sampled points from the trace produced by the fast photodiode/amplifier, as a function of time relative to the gate trigger, is accumulated.

If the signal from the amplifier is positive-going, data shall be collected as the event timer threshold level is varied from ground up to the maximum value of the photodiode signal (rising edge trigger) and then as the threshold level is reduced back down to ground (falling edge trigger).

If the amplifier is an inverting amplifier, data shall be collected as the event timer threshold level is varied from ground down to the minimum value of the photodiode signal (falling edge trigger) and then as the threshold level is increased back up to ground (rising edge trigger).

The mean time for each threshold level is calculated, and the resulting data plotted as signal level versus time delay from the trigger. This will produce an inverted version of the source emission temporal profile.

The time between the gate trigger signal and the optical pulse arriving at the end of the fibre is calculated from the time corresponding to the minimum of the plotted data.

Curve-analysis shall be employed to estimate the position of the minimum.

The curve obtained by inverting the original plotted curve about its half-height represents the source emission temporal profile.

19.5.3.4 Uncertainties

The uncertainty in i) comprises the uncertainties in ii) to iv), as well as uncertainties due to the jitter of the gate trigger and amplifier signals. The jitter due to the oscilloscope or event timer is likely to be negligible, as is any uncertainty in the calibration of their time values.

19.5.4 Measurement of DUT

19.5.4.1 Overview

The output fibre is removed from the fast photodiode, and connected to the DUT input port.

The detection efficiency of the DUT is measured, as described in clause 15.

A histogram of points should be observed for each setting of the tunable delay, and each point in the histogram shall be converted to a value of detection efficiency (see clause 15).

The time associated with the resulting histogram of DE values shall be corrected for the time between the gate trigger signal and the optical pulse arriving at the end of the fibre (see clause 19.5.3).

19.6 Environment

The temperature and humidity of the environment during the measurement shall be recorded.

19.7 Operational settings

A comprehensive set of measurement is recommended, where the incident pulse arrives before the detector gate, and is then stepped through the gate until it arrives after the detector gate.

The threshold setting for the event timer used to record the DUT detection events shall be recorded.

Clause 5 provides guidance on the settings to be recorded.

19.8 Calculations

19.8.1 Detector signal jitter

It is reasonable to deconvolve the source emission temporal profile (see clauses 12.4 and 12.5) from the observed DE histograms, which yields the detector signal jitter(s).

If the observed DE histograms do not vary in width or shape with photon arrival time, the intensity and time-offset values need only be reported for each pulse arrival time, together with the FWHM and span of a single deconvolved detector signal jitter curve.

Figure 19.2 illustrates this situation, where the photon pulse is moved through the detector gate in nine equally-spaced steps, and the histograms only differ in intensity (within experimental uncertainty). The histograms at each end of figure 19.2 denote that no detector events were recorded at these positions.

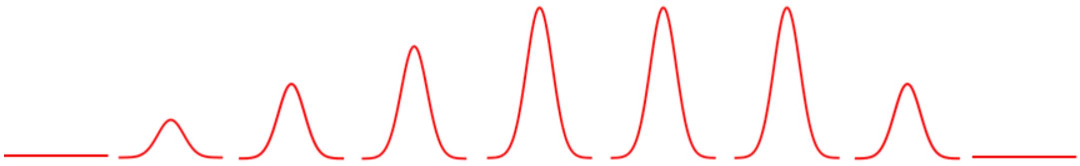


Figure 19.2: Sequence of histograms as step through detector gate, where only intensity changes

If the observed DE histograms vary in width or shape with photon arrival time, the FWHM and span of each detector jitter curve resulting from the deconvolution described above shall be reported for each recorded DE histogram.

Figure 19.3 illustrates this situation, where the shape and intensities of the histograms are the same as in the corresponding histograms in figure 19.2, but the widths change. Note however, that the shape of the individual histograms can also change. The individual histograms are offset vertically for compactness, but it shall be understood that the wings of each histogram represent the baseline event level.

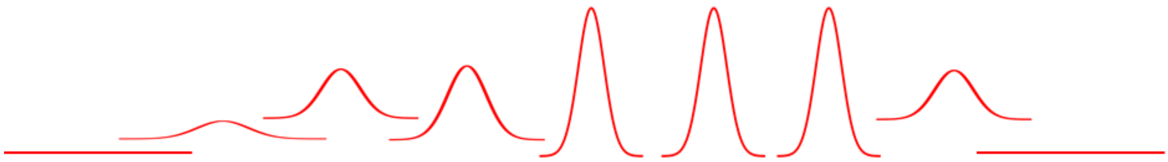


Figure 19.3 Sequence of histograms as step through detector gate, where intensity and width change

The span of a detector jitter curve shall be the central range of DE values which encompass a stated fraction of all values. The remaining values shall be split equally on either side of the central range. Values for the stated fraction may be 0,90, 0,95, 0,99, or any other stated value.

19.8.2 Detector efficiency profile

The detection efficiency value for each detector efficiency histogram is obtained by summing all the DE values in that histogram.

The detection efficiency profile is obtained by plotting these values as a function of the respective pulse arrival time relative to the gate trigger, as illustrated in figure 19.4 for the curves of figures 19.2 and 19.3.

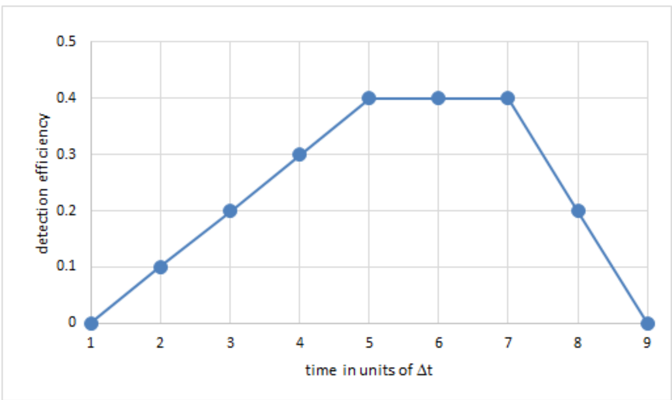


Figure 19.4: Example of a detection efficiency profile

19.9 Uncertainties

Information relating to uncertainty evaluation can be found in Annexes A and B.

19.10 Results

19.10.1 Reporting measurement on detector signal jitter and detection efficiency profile

The following measurements on detection signal jitter and detection efficiency profile shall be reported:

1) Unique identification number of DUT.

2) Measurement date(s).

3) Measurement duration.

4) The following properties (where they have been measured):

   a) Detector signal jitter, i.e. the FWHM, span, and uncertainties, as a function of photon arrival time at the DUT input port.

   b) Detector efficiency profile, and the uncertainties of its constituent values.

5) Measurement environment (temperature, humidity).

6) DUT operation settings - see clause 5.

7) The threshold setting for the event timer trigger and stop signals used to record the DUT detection events.

8) Exceptions or deviations from procedure.

9) Measurement operator(s).

19.10.2 Other information to be reported

The following information may be reported:

1) Measurement set-up.

2) Make and model number of key measurement equipment.

3) Measurement method.

4) Description of calculation.

5) Plots of the measured DE histograms, and the deconvolved detector signal jitter curves.

6) Traceability to SI.

20 Measurement of spectral responsivity

20.1 Definitions, symbols and units

Definitions, symbols and units relevant to this clause can be found in clause 3.

20.2 Procedure scope

This procedure covers the measurement of the spectral responsivity of a single-photon detector.

20.3 Measurement

The spectral frequency, ν (Hz), or wavelength, λ (nm), of the incident optical pulses is varied, and the detection efficiency, η, is measured at each value of ν or λ, as described in clause 15.

20.4 Environment

The temperature and humidity of the environment during the measurement shall be recorded.

20.5 Operational settings

The control settings of the DUT shall be recorded.

Clause 5 provides guidance on the parameters to be recorded.

20.6 Uncertainties

The uncertainties in ν (Hz), or wavelength, λ (nm), and $\eta(\nu)$ or $\eta(\lambda)$, shall be evaluated as described in clauses 13 and 15.

Information relating to uncertainty evaluation can be found in Annexes A and B.

20.7 Results

20.7.1 Reporting measurement on spectral responsivity

The following measurements on spectral responsivity shall be reported:

1) Unique identification number of DUT.
2) Measurement date(s).
3) Measurement duration.
4) Measurement wavelength (or spectral frequency).
5) Incident mean photon number.
6) Detection efficiency and its uncertainty. See clause 15.6.7 for reporting requirements.
7) Measurement environment (temperature, humidity).
8) DUT operation settings - see clause 5.
9) Exceptions or deviations from procedure.
10) Measurement operator(s).

20.7.2 Other information to be reported

The following information may be reported:

1) Measurement set-up.
2) Make and model number of key measurement equipment.
3) Measurement method.
4) Description of calculation.
5) Traceability to SI.

Annex A (informative): Uncertainties

A.1 Guidelines

The *Guide to the Expression of Uncertainty in Measurement* (GUM) [1] provides guidance on the evaluation of uncertainties, and is one of the reference documents in the field of measurement, another being the *International Vocabulary of Metrology - Basic and General Concepts and Associated Terms* (VIM) [2]. See the recent *Metrologia* special issue on the 20th Anniversary of the GUM [i.15].

Since the GUM was first published, two Supplements to it have been published - GUM-S1 [3] and GUM-S2 [4] - which address limitations in the GUM without having to modify the GUM itself. GUM-S1 moves away from dependence on the Central Limit Theorem, and GUM-S2 tackles multivariate measurands (the quantities intended to be measured). The Supplements make use of the significant developments in computing power and software applications that have taken place since the GUM was published.

A revision of the GUM is currently being undertaken, which aims to: address inconsistencies in the present document and with its published Supplements; remove reliance on the Central Limit Theorem for the evaluation of coverage intervals [1]; emphasize the use of probability density functions (PDFs) to describe knowledge about the quantities involved in a measurement. The revision is expected to be a shorter and more readable document than the current GUM.

References [5] and [i.16] may be found helpful in understanding the GUM.

A.2 Uncertainty (of measurement)

Measurement uncertainty is defined as "The parameter, associated with the result of a measurement, that characterizes the dispersion of the values that could reasonably be attributed to the measurand" [1].

NOTE 1: The parameter may be, for example, a standard deviation (or a given multiple of it), or the half-width of an interval having a stated level of confidence.

NOTE 2: Uncertainty of measurement comprises, in general, many components. Some of these components may be evaluated from the statistical distribution of the results of series of measurements and can be characterized by experimental standard deviations. The other components, which also can be characterized by standard deviations, are evaluated from assumed probability distributions based on experience or other information.

NOTE 3: It is understood that the result of the measurement is the best estimate of the value of the measurand, and that all components of uncertainty, including those arising from systematic effects, such as components associated with corrections and reference standards, contribute to the dispersion.

A.3 Calculation of measurand uncertainty

The Measurement Equation is the basis for uncertainty evaluation, and expresses the measurand as a function of the input quantities. The measurement equation for each measurand can be derived from the relationships given in the calculation paragraphs of each clause.

The uncertainty components may be combined algebraically using partial derivatives of the measurement equation and then applying the Central Limit Theorem, or numerically by applying Monte Carlo methods for combining probability density functions.

Details of how these uncertainty components should be calculated, and combined to give a final uncertainty, can be found in the literature [1] to [5] and [i.15] to [i.17] and references therein.

A.4 Evaluation of uncertainty components

In each measurement sub-division clause of the present document, the dominant uncertainty components that need to be considered are identified.

Table 1 of reference [3] gives information that can be used to infer the appropriate PDF to be used for a particular uncertainty component.

Where no information is available, or where the relationships are too complex to handle, recourse may be made to making repeated measurements. The results of these measurements are assumed to be from a Gaussian distribution of unknown mean and standard deviation, yielding a mean that follows a t-distribution. Note that systematic errors may not be uncovered when using this approach.

When evaluating the uncertainty of the mean of a number of measurements, the systematic uncertainty components (as opposed to random, or time-varying uncertainty components), where these are available, they are not subject to the averaging process.

Further details are available in [1] to [5] and [i.15] to [i.17] and references therein.

A.5 Measurement instrumentation

Calibration data or specifications provided from manufacturers can be used for uncertainty evaluation, once this data is stated to be traceable to national standards.

Where there may be some doubt as to whether this calibration data is valid, e.g. due to the elapse of time, then it is recommended that the instrumentation be re-calibrated.

Uncertainty can also be introduced due to variation in the environmental conditions.

All instrumentation should be in calibration when certified measurements are performed.

Annex B (normative): Equipment specifications, and uncertainty considerations, for commonly-used measurement instrumentations

B.1 Optical fibre connections

The transmission loss of a fibre connector can be uncertain each time when disconnecting and re-connecting fibre. This uncertainty should be measured and bounded by experiments. All optical measurement devices shall be able to take a connectorized single mode fibre as the optical input or output.

B.2 Pulsed laser

The laser shall emit only at the wavelength at which the measurement is to be performed.

The duration of the output pulses (source emission temporal profile) shall be narrower than the detector gate, the narrower the better.

The short laser pulses can be obtained from a pulsed laser, e.g. a gain-switched laser diode.

The short laser pulses can also be obtained by carving pulses from the output of a CW laser with an intensity modulator. Since the duration of these pulses shall be narrower than the duration of the detector gate, the narrower the better, an equal duty cycle modulation signal will not be adequate. High modulation extinction is also required to reduce the number of photons outside of the pulses to a negligible level so that mean photon number can be reliably estimated from the measurement of the optical power.

The pulsed laser, or the intensity modulator, shall be capable of being driven by an external clock signal.

Uncertainty components (informative):

There can be an uncertainty in the wavelength. The metric for defining the wavelength is left to the operator, but shall be stated.

The temporal and spectral profile of the pulses can be a function of the intensity setting, the repetition rate, and the trigger level used.

If pulses are carved from a CW laser, perfect extinction outside the pulses can be impossible, and this can lead to an overestimate in the measurement of the average photon flux within each pulse duration.

Noise in the laser signal.

B.3 CW laser

The laser shall emit only at the wavelength at which the measurement is to be performed.

Uncertainty components (informative):

There can be an uncertainty in the wavelength. The metric for defining the wavelength is left to the operator, but shall be stated.

Noise in the laser signal.

B.4 Optical attenuator

An optical attenuator is required to attenuate optical radiation, from the level at which it can be measured with a power meter, to the single photon level.

Its attenuation shall be calibrated before it is used to attenuate a CW or pulsed laser of a certain calibrated optical power to a desired mean photon number.

An uncalibrated attenuator can be calibrated using a calibrated power meter.

Uncertainty components (informative):

Interference effects can be caused between the components of the attenuator (internal interference), or between the attenuator and other optical components in the DUT and/or measurement system

Attenuators comprising absorbing filters can produce internal interference effects - the presence of which should be investigated.

Attenuators operating by proximity variation between the end of fibre can also exhibit interference, which should be investigated.

Attenuators comprising absorbing filters can have a different response to high power radiation (which may heat up the absorbing filters), compared to the response to low power radiation. This should be investigated.

Mechanical backlash in the operation of the attenuator should also be investigated, or nullified by always changing the attenuation with respect to the highest attenuation, or where there is a shutter available, by closing the shutter, and changing the attenuation with respect to the lowest attenuation.

B.5 Shutter

An optical shutter is required to block optical radiation.

The shutter may be a separate device, or integrated within an optical attenuator.

Its blocking ability shall be verified before its use.

Uncertainty components (informative):

The shutter can have a different response to high power radiation (which may heat up the shutter, leading to thermal radiation being emitted), compared to the response to low power radiation. This should be investigated.

B.6 Tunable electronic delay

The tunable electronic delay is used to vary the time delay between the signal used to trigger the detector and the signal used to trigger the laser, in order to synchronize the arrival of the laser pulse within a detector gate. It shall have the range and resolution to optimize this. Jitter introduced by the delay shall be significantly less than the duration of the detector gate so that there is negligible proportion of photons arriving outside the detection gate. (Note that the photon pulses shall also be significantly narrower than the detector gate, and therefore the combined effect of the source emission temporal profile and jitter due to the delay shall be such that a negligible proportion of photons arrive outside the detector gate).

The time scale shall be calibrated traceably to the SI.

Uncertainty components (informative):

Calibration of the delay values (time scale).

Variation with respect to intensity and shape of signals being delayed - the output signals shall be inspected for each input signal used, to estimate its jitter.

B.7 High-bandwidth photodiode and amplifier

B.7.1 Counting pulses

When counting pulses, the analogue detector and amplifier shall be capable of temporally resolving the individual pulses emitted by the DUT (before attenuation to the single-photon level), with low jitter. The responsivity of the analogue detector and amplifier shall extend to a frequency which is greater than the expected optical pulse repetition rate, and which is ideally a least an order of magnitude greater.

B.7.2 Measuring temporal profile and jitter

When measuring properties such as temporal profile and jitter of the optical pulses, the responsivity of the analogue detector plus amplifier combination shall extend to a frequency which is at least two times greater than the inverse of the expected optical pulse width.

B.7.3 Linearity

The linearity of the photodiode (and any amplifier used to amplify the raw detector signal) shall be calibrated.

B.7.4 Uncertainty components (informative):

Noise in the photodiode signal

Additional noise introduced by the amplifier.

Non-linearity in the photodiode can lead to distortion in the measured temporal emission profile of an optical signal. However, this does not affect the measurement of pulse repetition rate.

Non-linearity in the amplifier can lead to distortion in the measured temporal emission profile of an optical signal. However, this does not affect the measurement of pulse repetition rate.

The non-linearity effects can be estimated using an in-line optical attenuator, the attenuation of which is uniform in the spectral region of interest, between the DUT and the analogue detector.

Any changes in the measured signal shapes resulting from optical attenuation can be used to estimate an uncertainty. If the measured shapes are found to vary significantly with applied attenuation, the attenuation can be increased until the changes are insignificant, while retaining useable signal-to-noise ratio. If signal-to-noise ratio precludes this, the change in measured shape as a function of applied attenuation can be used to estimate an uncertainty due to this component.

Distortion due to high frequency gain roll-off.

B.8 Event timer

The event timer shall be able to generate histograms of recorded events as a function of time relative to the trigger pulses, or provide raw data from which such histograms can be generated.

The counter/timer shall be capable of operating in multi-stop mode.

The dead-time of the stop channel(s) shall be less than the period of any signal under investigation, and should ideally be as short as possible

The threshold level range(s) of the event timer input shall be able to accommodate the input signals from the experimental set-up.

Greater flexibility is provided by being able to set the inputs to trigger on either the rising or falling edges of the input signals.

The temporal resolution of the timer/counter shall be such that the observed full-width at half-maximum (FWHM) of the feature of interest spans a minimum of 10 time bins.

The time scale shall be calibrated traceably to the SI.

The time-jitter shall be calibrated traceably to the SI.

Dead-times shall be calibrated traceably to the SI.

Uncertainty components (informative):

The time-scaling factor correction can have an uncertainty component that scales with the length (duration) of the measured signal, an uncertainty component that is constant for every measurement point, and jitter that can scale with the length (duration) of the measured signal.

Jitter due to inappropriate setting of the trigger level.

Multiple or no signals due to inappropriate setting of the trigger level.

B.9 High-bandwidth sampling oscilloscope

The time scale shall be calibrated traceably to the SI by using an appropriate frequency standard.

The time-jitter shall be calibrated traceably to the SI by using an appropriate frequency standard.

The linearity of the intensity axis shall be calibrated where it is necessary to measure the true shape of a signal

The data interval shall be such that the observed full-width at half-maximum (FWHM) of the feature of interest spans a minimum of 10 data points.

Uncertainty components (informative):

The time scaling factor correction can have an uncertainty component that scales with the length (duration) of the measured signal, an uncertainty component that is constant for every measurement point, and jitter that can scale with the length (duration) of the measured signal.

Aliasing due to inappropriate triggering frequency.

If in-built software functions are used to derive measured quantities, e.g. calculation of frequency from a recorded trace, the uncertainties due to this software shall be evaluated, or values available from the manufacturer's documentation applied.

Distortion due to high frequency roll-off.

B.10 High-bandwidth real-time oscilloscope

The time scale shall be calibrated traceably to the SI.

The time-jitter shall be calibrated traceably to the SI.

The linearity of the intensity axis shall be calibrated where it is necessary to measure the true shape of a signal.

The data interval shall be such that the observed full-width at half-maximum (FWHM) of the feature of interest spans a minimum of 10 data points.

Uncertainty components (informative):

The time scaling factor correction can have an uncertainty component that scales with the length (duration) of the measured signal, an uncertainty component that is constant for every measurement point, and jitter that may scale with the length (duration) of the measured signal.

If in-built software functions are used to derive measured quantities, e.g. calculation of frequency from a recorded trace, the uncertainties due to this software shall be evaluated, or values available from the manufacturer's documentation applied.

Distortion due to high frequency roll-off.

B.11 Frequency counter

The frequency counter shall be able to operate in the expected frequency regime of interest.

The threshold level range of the frequency counter shall be able to accommodate the output pulses from the DUT and measurement set-up.

A frequency counter can usually be operated in one of two modes:

i) It can count the number of events in a pre-set time;

ii) It can count the time taken to count a pre-set number of events.

It shall be calibrated in the frequency regime in which it is expected to be operated.

The frequency counter, operating as a stand-alone instrument, shall be calibrated traceably to the SI. A reference frequency standard operating in the expected frequency region of interest is suitable for this purpose.

The frequency counter, if used with an SI-calibrated external reference clock signal of frequency $f_{ref} \pm \Delta f$ and given waveform, shall be calibrated in this mode for use in the relevant frequency range, in order to estimate the uncertainty Δf_{meas} in the measured frequency f_{meas}. A reference frequency standard operating in the expected frequency region of interest is suitable for this purpose.

Uncertainty components (informative):

It can be seen that setting a long pre-set time in i) reduces errors caused by a non-integer number of events occurring exactly within the pre-set time.

Modern frequency counters usually have very accurate clocks referenced to internal crystal oscillators; in this case, method (ii) will not be affected by graininess in the time scale of the counter, and this mode is preferred. Nevertheless, the pre-set number of events should be large to minimize errors.

The time scaling factor correction can have an uncertainty component that scales with the length of the measurement time, as well as an uncertainty component that is constant.

B.12 Power meter

The power meter should ideally be able to measure from 0 dBm to -60 dBm (1 mW to 1 nW) for CW radiation at the wavelength of interest

The optical power responsivity shall be traceably calibrated over its entire input power range to the SI in the spectral region of interest. This may take the form of measurement of optical power responsivity at a single input power level, combined with measurement of the linearity of response over the entire input power range.

Its frequency response shall be measured, in order to establish at what repetition rate pulsed radiation is measured as CW. This is important if its responsivity is calibrated using CW radiation.

Uncertainty components (informative):

Calibration uncertainty - responsivity (and linearity), calibration wavelength, any measured spectral variation in responsivity (and linearity)

Digital resolution

Temperature sensitivity

Polarization sensitivity

Inter-reflections

B.13 Single-photon detector

The single-photon detector shall have single-photon sensitivity at the wavelength of interest.

It shall ideally have high detection efficiency, low dark count and after-pulse probabilities, and short recovery times. It should have a high dynamic range, and is desired to be polarization insensitive.

The values of detection efficiency, dark count probability, after-pulse probabilities, and recovery times which are used in any calculations shall correspond to the:

i) arrival time of the photons, with respect to the detector gate (trigger), used in the measurement;

ii) the gate repetition rate and gate durations used in the experiment;

iii) the approximate incident mean photon number used in the measurement.

All properties required for analysing measurement data shall be calibrated traceably to the SI.

Uncertainty components (informative):

Dark count probability

After-pulse probabilities

Detection efficiency and linearity

Dead-time, recovery times, reset times

Jitter

Saturation

Polarization sensitivity

APD temperature uncertainty

Bias voltage uncertainty

Bias pulse width uncertainty

B.14 Spectrometer

The spectrometer shall be sensitive at the wavelength of interest, and shall ideally cover all wavelengths where emission may occur.

It shall ideally have single-photon sensitivity.

Spectrometers may be based on diffraction gratings, Fabry-Perot interferometry, Michelson interferometry, etc.

Each type of device has its own characteristic sources of uncertainty and error, and therefore only generic properties are listed here - the operator will need to investigate those relevant to the spectrometer in question.

The frequency or wavelength scale of the spectrometer shall be calibrated traceably to the SI.

The linearity of the intensity axis shall be calibrated.

The stray-light of the spectrometer shall be calibrated.

Uncertainty components (informative):

Abscissa uncertainty. Any uncertainty in the frequency or wavelength scale should be expressed in terms of components (e.g. due to offset or uncertainty in the calibration equation) which are correlated over all or many frequency/wavelength values and components (such as noise and random uncertainty) which are uncorrelated between spectral measurement points. Where the mean spectral value of a spectral feature is calculated, it is expected that uncorrelated uncertainties should be diminished through the calculation process, whereas correlated uncertainties should not.

Ordinate non-linearity

Ordinate uncertainty

Mechanical backlash errors

Overlapping orders, as may be observed in a grating or Fabry-Pérot spectrometer

Aliasing, as may be observed in a Fourier-transform spectrometer

Inter-reflections

B.15 Clock

The clock shall provide a clock signal at the required frequency and with the required waveform.

It is expected that the master clock uncertainties will be negligible

However, jitter on an instrument clock, when triggered by an external clock, can be significant, and shall be investigated.

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History

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