What is the efficiency of a single photon source?

PROBLEMATIC

Researchers and engineers using single photon sources often use different metrics to characterize the source efficiency. Many use the **count rate** on a single photon detector, others the **single photon rate** at the output of a single mode fibre, other the maximum single photon rate available for a given single photon purity. Such different points of views make it difficult to compare different technologies. For instance, count rates depend on the detector efficiency, which itself depends on the photon wavelength. Similarly, a photon rate (in Hz) gives no information without the source operation regime, whether it is continuous-wave or pulsed driven, or at which repetition rate the source is run.

UNIVERSAL METRICS FOR PULSED SOURCES

*The following metrics allow comparing **pulsed fibered single photon sources**.*

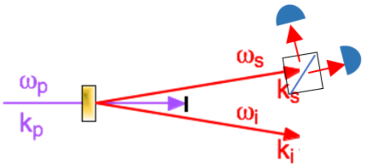
A single photon source ideally delivers one single photon per laser-pulse. In practice, some pulses do not contain a photon, only vacuum. One can thus define the **brightness B as the probability to have a single photon per pulse** at the output of the fibre, a figure of merit for any single photon source.
The **single photon rate G** is **then** $\boldsymbol{G = B \times R}$ **where R is the excitation repetition rate.**
The detected **count rate D** is then $\boldsymbol{D = G \times \eta = B \times R \times \eta}$ where $\boldsymbol{\eta}$ **is the detector efficiency**.

Finally, the probability $\boldsymbol{P_s(>1)}$that the source emits more than one photon at once is measured by the second order intensity correlation function. $\boldsymbol{g^{(2)}(0) \approx \frac{2P_s(2)}{P_s(1)^2}}$ **where** $\boldsymbol{P_s(n)}$ **is the probability to have n photons per pulse.** $g^{(2)}(0)$ is equal to zero in the case of an ideal single photon purity (never more than one photon per pulse).

BRIGHTNESS VERSUS SINGLE PHOTON PURITY IN SPDC SOURCES

The light generated by a spontaneous parametric down-conversion process is:

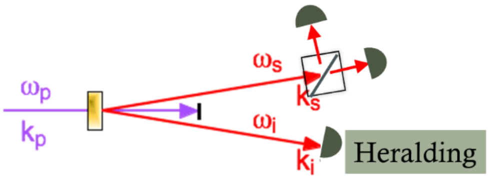
$$|\psi\rangle = \sqrt{1 - |\lambda|^2} \sum_n \lambda^n |n_s, n_i\rangle$$



For ($|\lambda| \ll 1$), this state can be rewritten as $|\psi\rangle \approx |0_s, 0_i\rangle + \lambda|1_s, 1_i\rangle + \lambda^2|2_s, 2_i\rangle$

The probability of having a photon-pair per pulse, or **brightness is** $\boldsymbol{B = |\lambda|^2}$

Note: Such state shows thermal photon statistics with $g^{(2)}(0) \approx \frac{2P_s(2)}{P_s(1)^2} = 2\frac{\lambda^4}{\lambda^4} = 2$ on one output light pulse.



When a click is detected on the herladed (idler) path, the photon state becomes:

$$|\psi\rangle \approx \frac{\lambda}{|\lambda|}|1_s\rangle + \frac{\lambda^2}{|\lambda|}|2_s\rangle$$

And the heralded second order correlation on the signal path

$\boxed{g^{(2)}(0) = \frac{2P_s(2)}{P_s(1)^2} = 2|\lambda|^2}$ **which can be very close to zero only for $B = |\lambda|^2 \ll 1$.**

The above equations show the compromise that is intrinsic to SPDC sources. **When the brightness $B = |\lambda|^2$ increases , the probability of having two photons increases. This intrinsic limitation puts strong limits to the source efficiency, especially if ones requires very low $g^{(2)}(0)$ as it is required for quantum computing, highly secure quantum communication protocols.**

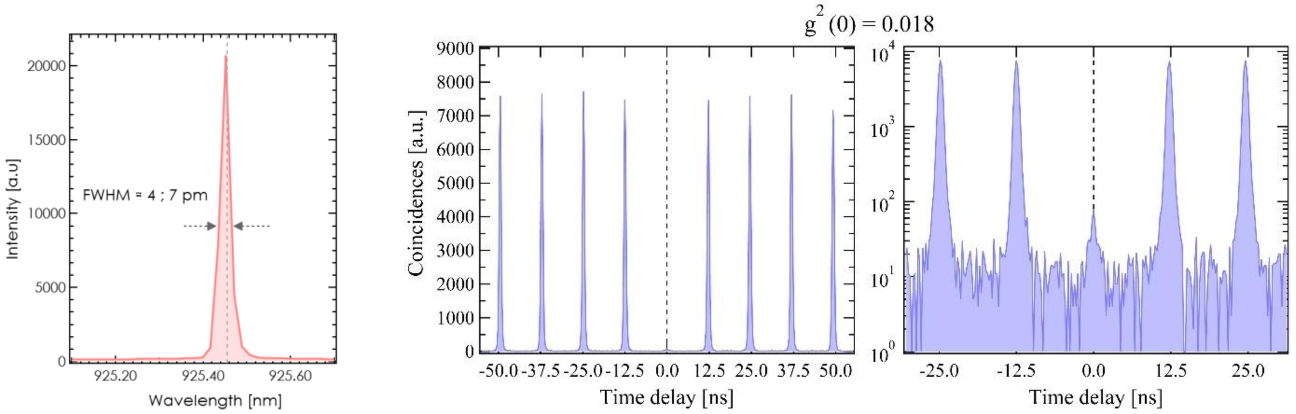
Note: A way to improve the efficiency of heralded sources is to ***multiplex*** many high purity (i.e. low efficiency) heralded single photon sources. This can be done using **time multiplexing** (using time loops to store photons to increase the probability of having a photon per pulse) **at the cost of decreasing the operation rate R hence the single photon rate** $G = B \times R$ or, using **spatial multiplexing** (fabricate N>>1 sources and use N>>1 detectors to announce when a single photon is detected and route it toward the source output) at the cost of strong overheads (N sources, N detectors, and photon routers).

BRIGHTNESS AND PURITY OF A QUANDELA SOURCE

QUANDELA single photon sources are made of a single quantum dot inserted in an optical micropillar cavity. The quantum dot is an artificial atom that can only emit one photon at the time, and the cavity ensures the efficient collection of the emitted photons.

The quantum dot is driven resonantly by weak laser pulses (around 1 nW time average power at 80 MHz) to bring the artificial atom into its excited state. The quantum dot then recombines by emitting a photon.

As opposed to SPDC heralded single photon sources, the $g^{(2)}(0)$ of a quantum dot single photon source does not heavily compromise the brightness. eDelight Quandela sources show high single photon purity (with a typical value for $g^{(2)}(0)$ lower than 0.02) at the maximum of brightness.



(Left) Emission spectrum under resonant excitation. The single photons present a spectral linewidth around 4 to 7 pm, corresponding to a photon lifetime below 300 ps. (Middle and Right) Measurement of second-order correlation in linear a logarithmic scale under resonant excitation. The absence of coincidences at zero delay shows the high single photon purity of the photon stream ($g^{(2)}(0) < 0.02$). The single photon rate at the output of the fiber, just before the detectors, is 4.5MHz (with an excitation rate of 80MHz).

UNIVERSAL PURPOSE SINGLE PHOTON SOURCE

A universal N photon source generates N single photons in orthogonal modes (spatial mode, time bins, etc). It can be used to implement any quantum protocol where all photons can physically interfere with each other. These sources are required to implement complex quantum computation schemes, such as Boson sampling (an intermediate quantum computing task).

Both heralded single photon sources and Quandela single photon sources can be universal N photon sources.

- **A Quandela source is a universal N-photon source**: it generates N photons in different time bins. Using an active demultiplexer, they can be efficiently routed to different spatial modes if needed (for on-chip quantum protocols for instance).

- **A universal N-photon source based on SPDC requires N photon pairs and N detectors**. One click on each of the N detector announces the creation of the N-photon state.

To obtain a N universal photon source with $g^{(2)}(0) < 0.02$, one can use a Quandela single photon source with a fibered brightness **B** operated at rate R. If using time encoding, the N-photon rate will be $\boldsymbol{G_N = B^N \times \frac{R}{N}}$. If using a spatial encoding, one can use a Quandela single photon source with a time to spatial demultiplexer of efficiency $\mu = 0.75$. In such case, the N-photon rate will be $\boldsymbol{G_N = (B \times \mu)^N \times \frac{R}{N}}$

To obtain a N universal photon source with $g^{(2)}(0) < 0.02$ using SPDC technology, **one must operate the SPDC source at B=1%**. Assuming an operation rate R, perfect coupling to a single mode fibre, and perfect heralding efficiency, the SPDC-Universal N-photon source rate will be $\boldsymbol{G_N = B^N \times R}$**.**

Note: Due to the low brightness of SPDC based sources, some protocols have been implemented using, for instance, 4 photons—each in a separate spatial mode—obtained from 2 SPDC pairs and 2 crystals. In such case, **the photonic circuit needs to be carefully designed to ensure that** not every photon interferes with every other photon, and that **one can still post-select at the end of the circuit the events corresponding to the protocol that was intended**. Such tricks have been applied to obtain 12-photon entanglement with 6 SPDC pairs, or computing with 4 photons from 2 SPDC pairs. However, these approaches result in strongly reduced success probabilities for the implemented protocols.

Moreover, **Boson sampling, or any advanced quantum computing scheme relying on multiparticle quantum interference with many photons, can only be implement with a universal source**.

Note: It should be noted that unity heralding efficiency is a very demanding experimental challenge. The above equation when including the **heralding efficiency** ϵ becomes $G_N = (B \times \epsilon)^N \times R$. **All numbers given below are therefore an upper bound for SPDC sources.**

*: Note that in practice most SPDC sources are operated at 80 MHz, the typical operation rate of commercial pulsed lasers, due to limited available power. On the contrary, since only 1 nW is needed to excite a Quandela source, one can seamlessly multiply the laser's repetition rate with enough power left to pump many quantum dot sources.

Comparison of various universal single photon sources

We compare below Quandela sources with state of the art heralded single photon sources. The order in the table is meant to favour a comparison between sources with similar indistinguishabilities.

	Single photon purity	Fibered brightness (probability per pulse)	Operation rate	Indistinguishability	Single photon rate	Detected single photon rate		2 photon rate	3 photon rate	5 photon rate	8 photon rate
						SSPN $\eta = 0.9$	**Silicon APD** $\eta = 0.3\ or\ 0.6^*$				
	$g^{(2)}(0)$	B	R	M	$G = B \times R$	$D = B \times R \times \eta$		$G_2 = (B \times \mu)^2 \times \frac{R}{2}$	$G_3 = (B \times \mu)^3 \times \frac{R}{3}$	$G_5 = (B \times \mu)^5 \times \frac{R}{5}$	$G_8 = (B \times \mu)^8 \times \frac{R}{8}$
Delight	<0.02	0.3	300 MHz	< 0.8	90 MHz	80 MHz	27 MHz		1.15 MHz	35 kHz	245 Hz
Delight	<0.02	0.3	80 MHz	< 0.8	24 MHz	21 MHz	7 MHz		300 kHz	9.5 kHz	65 Hz
ppKTP source [1]+	0.02-0.05	0.01 (@20 mW) 0.05 (@100 mW)	80 MHz	< 0.8	0.8 MHz 4 MHz	0.72 MHz 3.6 MHz	0.48 MHz 2.4 MHz		10 Hz 1.5 kHz	0.5 mHz 1 Hz	1.10^{-10} Hz $5\ 10^{-5}$ Hz
eDelight	<0.02	>0.05	500 MHz	>0.9	>25 MHz	>22.5 MHz	>7.5 MHz	> 700 kHz	9 kHz	10 Hz	0.5 mHz
eDelight	<0.02	>0.05	80 MHz	>0.9	>4 MHz	>3.6 MHz	>1.2 MHz	>112 kHz	1.5 kHz	1 Hz	$4\ 10^{-5}$ Hz
aKTP source [1]+	0.02-0.05	0.0035 (@20 mW) 0.017 (@100 mW)	80 MHz	≈0.9 (@20 mW) ≈0.85 (@100 mW)	0.28 MHz 1.36 MHz	0.25 MHz 1.22 MHz	0.17 MHz 0.8 MHz	275 Hz 6.5 kHz	0.5 Hz 55 Hz	$2\ 10^{-6}$ Hz 5 mHz	$2\ 10^{-14}$ Hz $7\ 10^{-9}$ Hz
[2] ++	?	0.006 (@44mW)	80 MHz	0.9	0.5 MHz	0.45 MHz	0.3 MHz	810 Hz	2.5 Hz	$3\ 10^{-5}$ Hz	$1\ 10^{-12}$Hz

*The detection efficiency of standard silicon APD is around $\eta = 0.3$ at 930 nm (Quandela source wavelength) and $\eta = 0.6$ at 800 nm

+We deduce B from reference [1] by considering the coincidence counts CC (4 kHZ/mW for aKTP, 11.25 KHz/mW for ppKTP), heralding efficiency $\epsilon = 0.53$ and the repetition rate R=80 MHz using $B = \frac{CC}{\epsilon^2 R}$

++We deduce B from reference [2] by considering the brightness (defined as the photon pairs generation rate) C=12 MHz/W and the repetition rate R=80 MHz using $B = \frac{C}{R}$

[1] Optica Vol. 5, Issue 5, pp. 514-517 (2018)

[2] Phys. Rev. Lett. 117, 210502 (2016)