Application Note: Characterization of a Quantum Entanglement Photon Pair Source

Polarization-entangled photon sources and single-photon detectors are critical in many quantum applications. Here we demonstrate how to characterize such a source by coupling Single Quantum SNSPDs to Qunnect's Qu-SRC[1]. This source uses Spontaneous Four-Wave Mixing in warm Rubidium-87 vapor to generate photon-pairs in polarization-entangled states $1/\sqrt{2}\,(|\mathbf{HH}\rangle + |\mathbf{VV}\rangle)$. Because the detectors are polarization sensitive, the output polarization is collapsed to H/V and the counts maximized using fiber paddles. Each SNSPD's electrical output is coupled to a Time Tagger Ultra channel (Swabian Instruments). Coincidence rates (**b**), cross-correlation function (**c**), and heralding ratios (**d**) are measured offering insights into mutual device characteristics.

Fig. 1: Rubidium level diagram for SFWM process and schematic of measurement setup.

(a) Detection Efficiency: the probability of a photon being successfully detected. Figure 2 shows how detection efficiency decreases as the single-photon rate increases due to the finite dead-time of the detector, with separate curves for 1324 nm (blue) and 795 nm (red). Such detectors are required to match the source's output wavelength. The SNSPDs' efficiency as a function of count rate η_{cr} is accurately characterized before the experiment together with the optical setup's transmission T, and is used to estimate the rate of single photons emitted at each wavelength at the source output $R_{singles}$ from the measured count rate R_{meas}:

$$R_{singles} = \frac{R_{meas}}{T\eta_{cr}}$$

(b) Coincidence Rates: the number of detected photon-pairs/s, reflecting the source's rate. This is measured by detecting a signal photon and its corresponding idler photon within a fixed temporal window of 200 ps and correcting the measured value for optical path losses and detector efficiency, similarly as for the singles rates. As shown in Fig. 2, these reach up to $> 70 \times 10^6$ pairs/s with increasing pump power driving the photon-pair generation process. However, the relationship becomes non-linear at higher powers due to atomic saturation effects. To characterize high rates, detectors need high efficiency, short dead-times (< 20 ns) - and all setup components require negligible jitters compared to the distribution's width.

(c) 2nd Order Intensity Correlation: the g_{si} metric quantifies statistical correlations between photon pairs, representing the likelihood that a photon in the signal channel has a corresponding idler partner. It is an important metric for balancing high rates with entanglement quality ($g_{si} > 4$ describes non-classical correlations) - high values indicate strong quantum correlations, while lower values suggest noise, multipair events, or decoherence affecting the measurements. It is calculated by measuring the coincidence rates C at two detectors within a temporal window Δt, normalized by the signal S and idler I rates:

$$g_{si} = \frac{C}{S_t I_t \Delta t}$$

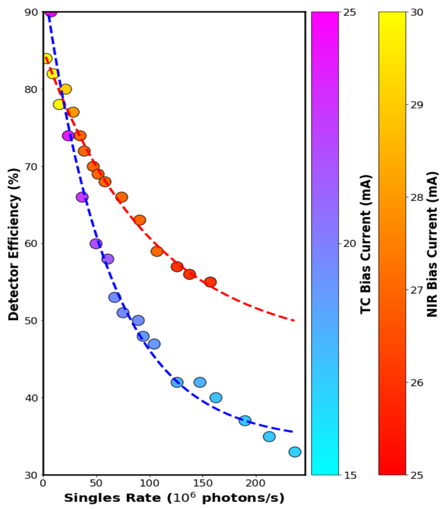


Fig. 2: Efficiency vs. generated photon rate for two SNSPDs, operating at 795 nm and 1324 nm.

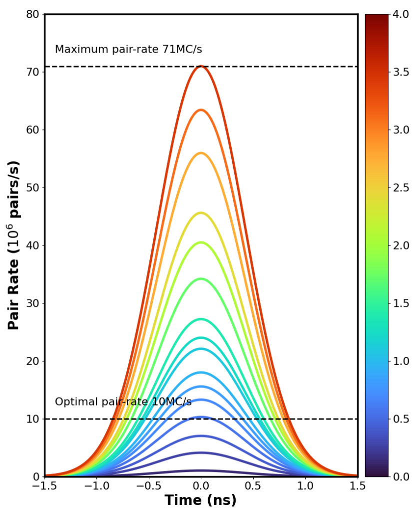
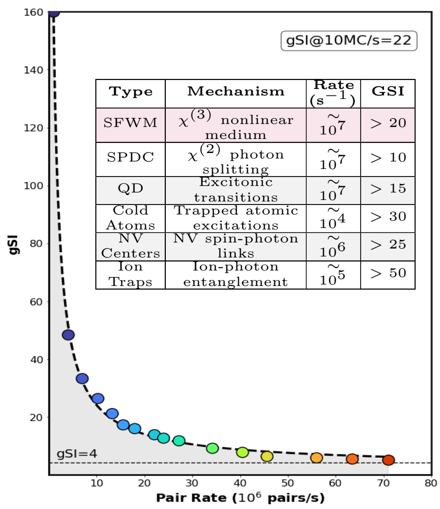


Fig. 3: Correlation peak showing coincidence rates vs. pump power. Dashed lines indicate optimal and maximum rates.



Type	Mechanism	Rate (s^{-1})	GSI
SFWM	$\chi^{(3)}$ nonlinear medium	$\sim 10^7$	> 20
SPDC	$\chi^{(2)}$ photon splitting	$\sim 10^7$	> 10
QD	Excitonic transitions	$\sim 10^7$	> 15
Cold Atoms	Trapped atomic excitations	$\sim 10^4$	> 30
NV Centers	NV spin-photon links	$\sim 10^6$	> 25
Ion Traps	Ion-photon entanglement	$\sim 10^5$	> 50

Fig. 4: g_{si} as a function of coincidence pair rate. The inset shows a comparison with other commercial sources.

(d) Heralding Efficiency: measures the probability that a detected photon in one path indicates the presence of a corresponding photon in the other - calculated as the rates C/S and C/I. It is a critical metric for determining the reliability of the individually detected photons. For this system, heralding efficiency was measured as 46.2% for 795 nm $\Longrightarrow$ 1324 nm and 24.5% in the reverse.

[1]Reference: High-rate sub-GHz linewidth bichromatic entanglement source for quantum networking, PhysRevApplied.21.034012