Redefining Measurement

Use Case: Quantum Optics

The Power of Entanglement

Customer Name: CNRS National Centre for Scientific Research, Institut de Physique de Nice (INPHYNI), Université Côte d'Azur	
Research Field: Quantum Optics/Photonics	
Country: France	

Customer need	Solution	Result
In characterizing and exploiting (heralded)-entanglement photon-pair sources, CNRS-INPHYNI needed to collect photons as efficiently and as cleanly as possible.	ID281 SNSPDs with > 85% Detection Efficiency, < 45 ps FWHM jitter and < 100 Hz Dark Count Rate at 1550 nm.	Successful realization of high-performance photon-pair-generating nanophotonic chips [1][2] and development of a versatile and ultra-precise quantum photonics characterization tool [3].

Context

Entanglement is as wondrous as it is useful. It describes systems where—counter to our everyday intuition of probability—the full state cannot be described as a product of its constituents, and the measurement of one portion of an entangled ensemble will affect the other parts instantaneously, regardless of the separation in space and time. Together with the interference of coherently prepared quantum amplitudes, it gives rise to the strange and wonderful pantheon of quantum phenomena.

In a series of recent works—involving the Quantum Photonics and Information group led by Sébastien Tanzilli [1][2][3], of the Institut de Physique de Nice, associated with the National Centre for Scientific Research (CNRS) and Université Côte d'Azur; the Photonic Systems Laboratory at EPFL led by Camille Sophie Brès [2]; and the Fibre Photonics and Coherent Sources group led by Philippe Roy at the XLIM institute, associated with the CNRS and the Université de Limoges [3]—great strides have been made towards practical and scalable high-performance photonic entanglement sources [1][2] and their exploitation in material characterization [3].

Looking to the future, the Quantum Photonics & Information group at CNRS-INPHYNI has been able to develop advanced integrated photonic chips capable of generating configurable two-photon states with demonstrable entanglement and indistinguishability ('Configurable heralded two-photon Fock-states on a chip', X. Hua *et al.*, 2021 [1])—useful for exploring complex quantum information protocols—and have demonstrated entanglement and superb indistinguishability from a silicon-based photonic chip ('Near perfect two-photon interference out of a down-converter on a silicon photonic chip', R. Dalidet *et al.*, 2022 [2])—opening the door the enabling scalable Quantum Internet applications.

In shorter timescales, in the journey to smaller, more versatile, and higher-power sources of laser light, greater manufacturing precision is required. By using similar entanglement sources and exploiting a quantum optical method based on Hong-Ou-Mandel interferometry, they demonstrate the quantum-enhanced precision needed to characterize the very materials (such as highly nonlinear specialty fibres) necessary to fabricate state-of-the-art fibre-based coherent light sources ('Quantum-limited determination of refractive index difference by means of entanglement', M. Reisner *et al.*, 2022 [3]). Such fibre lasers promise to revolutionize scientific and industrial applications, from biomedical research to industrial material processing.

Customer Need

The entanglement sources developed and used in the three referenced works are based around spontaneous parametric down conversion (SPDC), albeit in various designs, configurations and material systems. In general, to characterize the performance of such devices, the key figures-of-merit to measure include:

- **The Pair Coincidence Rate (PCR)**: the rate at which photon pairs are generated in the device
- **The Brightness**: how the PCR varies with the incoming pump power
- **Coincidence-to-Accidental Ratio (CAR)**: a measure of spurious multi-photon emissions present in the output
- **$g^{(2)}(0)$, the zero-delay second-order autocorrelation**: standard measure for the purity of a single-photon signal.

Each of these metrics requires time-correlated single-photon counting (TCSPC) to measure, i.e. they have a need for single-photon detectors and time controller electronics. These measurements are all improved by having a higher detector efficiency, fewer detector dark counts, and a high degree of timing resolution. However, the most critical measurement is often the $g^{(2)}(0)$ parameter.

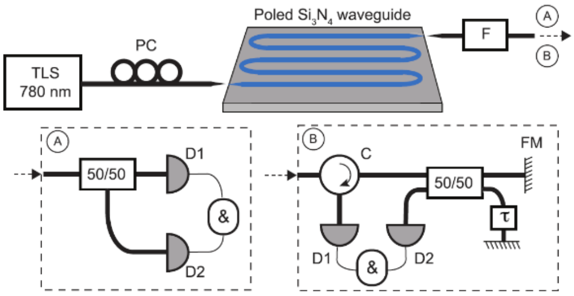

Figure 1: (From R. Dalidet, *et al.* [2]) Schematic of the experimental setup, where the output of the Si_3N_4 waveguide is sent to a Hanbury Brown & Twiss detection configuration, to determine the single-photon purity, or a folded-Franson interferometer configuration, to determine the quality of the generated entanglement.

There are two variations of $g^{(2)}$ measurement in the referenced works. A single SPDC source generates pairs of photons, in general at distinct energies, where one photon is referred to as the 'idler', the presence of which heralds the existence of the other 'signal' photon.

In the case of R. Dalidet *et al.* [2], the $g^{(2)}$ measured, whether in a Hanbury Brown & Twiss configuration (Figure 1A) or in a Franson interferometer configuration (Figure 1B), was always a two-fold coincidence between a signal and an idler photon, and as such the coincidence rate was proportional to the square of the detector efficiency. Assuming Poissonian counting statistics, this means that the uncertainty associated with each bin of the $g^{(2)}$ histogram improves linearly with improvements to the overall single-photon detector efficiency.

In X. Hua *et al.* [1], however, the case is different. Similar two-photon coincidences are measured, but these are between the signal photons of two different SPDC sources, which themselves have been heralded by a double idler-photon coincidence, such that the resulting measurement is in fact a four-photon coincidence. Now, the rate of coincidences in each bin of the $g^{(2)}$ histogram is proportional to the fourth power of the detector efficiency, and the statistics will improve quadratically with the detector efficiency. Therefore, maximizing detector efficiency and minimizing spurious detector noise is paramount in being able to perform a sufficiently clean measurement in a practical timeframe.

Solution

Particularly challenging are the four-fold coincidence measurements required to characterise the configured two-photon states from the photonic chip presented in [1]. Since the photon detection statistics in TCSPC follow a Poissonian distribution, detector efficiency and the detector dark count rate were of primary importance. An improvement in the efficiency would see a corresponding decrease in the time needed to build equivalent statistics by between a power of two and three. A decrease in the dark count rate would have a similar improvement on the quality of the measured statistics.

To meet the needs of the CNRS laboratories, ID Quantique provided an array of ID281 superconducting nanowire single-photon detectors. The high efficiency (> 85% at 1550 nm), the high timing precision (< 45 ps FWHM timing jitter) and low detector noise (< 100 Hz dark counts) allowed for the successful characterization of their entanglement sources, the configured two-photon states, and the execution of their quantum-enhanced metrology experiment for fibre core/cladding refractive index differences.

> “*Our IDQ superconducting detection system runs with almost all of our high-end quantum photonics experiments, not only simplifying them in terms of data acquisition time, but overall by making them just feasible!*”

Sébastien Tanzilli
CNRS Research Directeur at INPHYNI, Leader of the QPI group

Results

In the first work, X. Hua *et al.* [1] were able to successfully demonstrate a heralded source of two-photon states. Within a single complex integrated photonic device (see Figure 2A), consisting of twin photon-pair generation, wavelength demultiplexing, and tuneable two-photon interference, the team could herald configured two-photon states at a rate of 200 pairs per second.

Further, the device can switch between unentangled and highly entangled photon states in less than 1 ms. Confirmation of the entanglement properties of the heralded two-photon-states were confirmed by a Hong-Ou-Mandel interference visibility of 94%, requiring the observation of four-fold coincidences at a rate of approximately 59 events per 2 hours (see Figure 2B). With lower-efficiency and/or higher-noise detectors, this measurement would have taken impractically long to acquire, or suffered considerable degradation of the experimental statistics.

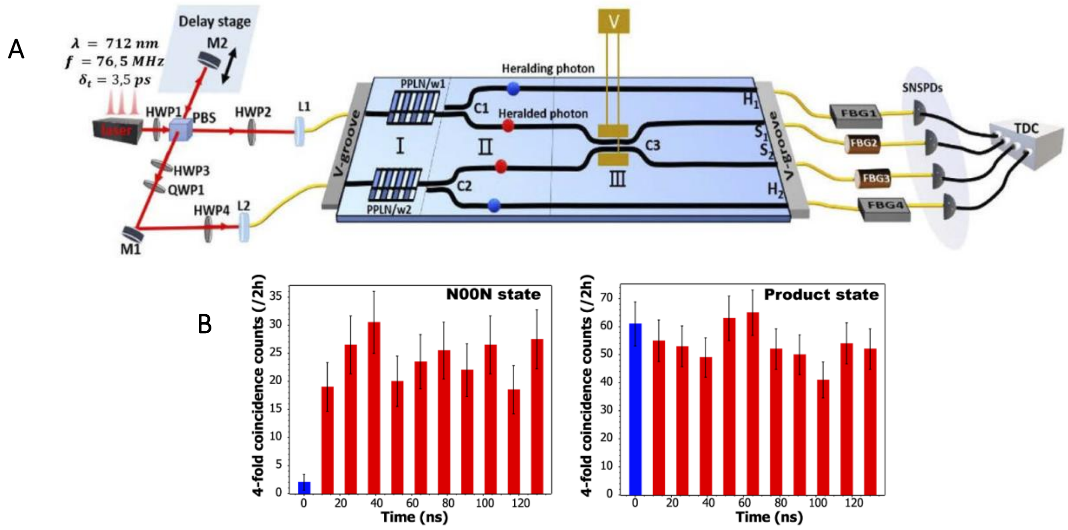

Figure 2: (From X. Hua *et al.* [1]) (A) Schematic of the configurable two-photon source, including the monolithic photonic chip and associated optical pump and detection apparatus. (B) The four-fold coincidence measurements required to characterize the Hong-Ou-Mandel interference visibility, as a function of the pulse offset time between the two PPLN waveguides, for a highly-entangled (N0ON) state and an unentangled (product) state.

In the later work, R. Dalidet *et al.* [2] were successfully able to demonstrate, for the first time, the realization of an SPDC-mediated entangled photo-pair source on a Si-based integrated photonic chip. The internal brightness of this source is estimated at approximately 5×10^{-3} pairs/s/mW/MHz, and demonstrated a CAR as high as 1635. Furthermore, the device exhibited entanglement with a near-ideal interference visibility of 99.36 ± 1.94% (see Figure 3), well above the threshold of 71% required for the relevant Bell-Clauser-Horne-Shimony-Holt inequalities.

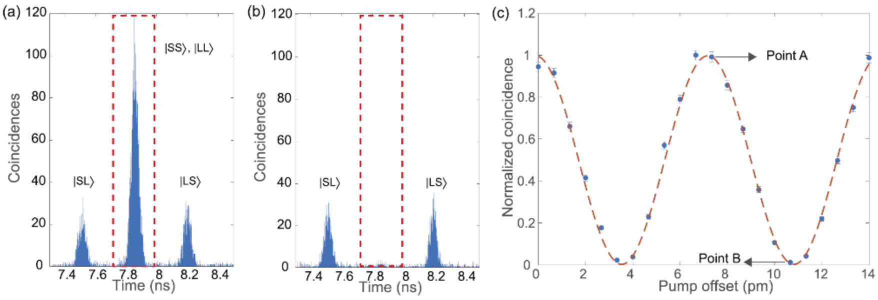

Figure 3: (From R. Dalidet *et al.* [2]) Interference measurements of the generated photon pairs, demonstrating energy-time entanglement. Shown are coincidence histograms for (a) constructive interference, with a pump offset of 7.35 pm, and (b) destructive interference with a pump offset of 10.65 pm, as well as (c) the interference fringes as a function of pump offset.

MEET THE PRODUCTS

ID281 Superconducting Nanowire Series

References

[1] 'Configurable heralded two-photon Fock-states on a chip', X. Hua, T. Lunghi, F. Doutre, P. Vergyris, G. Sauder, P. Charlier, L. Labonté, V. D'Auria, A. Martin, S. Tascu, M. P. De Micheli, S. Tanzilli, O. Alibart, Opt. Express 29, 415-424 (2021)

[2] 'Near perfect two-photon interference out of a down-converter on a silicon photonic chip', R. Dalidet, F. Mazeas, E. Nitiss, O. Yakar, A. Stroganov, S. Tanzilli, L. Labonté, C-S. Brès, Opt. Express 30, 11298-11305 (2022)

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