Redefining Measurement

Use Case: Integrated Quantum Photonics

On-chip ultra-bright single-photon sources

Customer: Stevens Institute of Technology	
Research Field: Nanophotonics	
Country: USA	

Customer Need	Solution	Results
To perform ultrafast photon correlation measurements, generated by state-of-the-art on-chip micro-ring resonators	ID281 SNSPDs with > 85% Quantum Efficiency paired with the ID900 Time Controller	Successful demonstration of a high-fidelity and low-noise ultrabright telecom-wavelength single-photon source

Context

To reap the benefits of a quantum internet, we need to be able to faithfully transmit qubits over long distances. This sounds simple enough—we regularly send and receive information across the world at dazzling speeds—but the technological requirements for creating and handling flying qubits are staggering.

To encode our qubits, we need a single-photon source, where we know that in a given time interval, we expect one—and only one—photon to be created. Attenuated laser light doesn't meet this requirement: when you have an average of one laser photon per time interval, you're actually more likely to have either zero photons or more than one photon.

We want to minimize the loss of transmission, so we prefer sources emitting photons natively around the optical fibre low-absorption window (the telecom C-band, 1530-1565 nm). To scale our quantum infrastructure, we want the possibility to create rich photonic circuits, so we prefer compact light sources embedded in a solid-state substrate. And of course, to send qubits at as fast a rate as possible, we want our light source to be bright: as many single-photons as our timing electronics can manage.
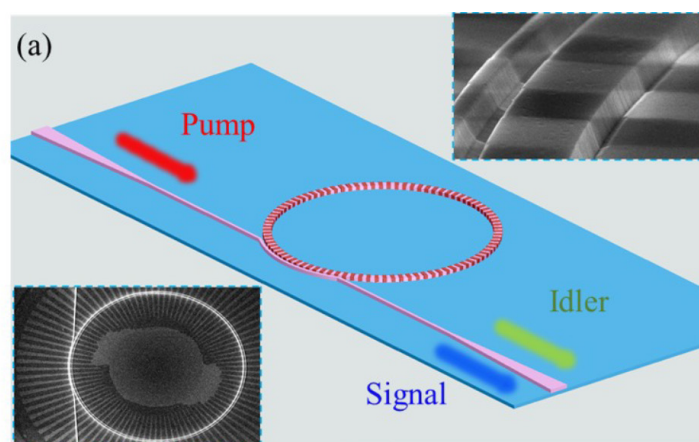
Figure 1: (from Zhaohui Ma *et al.* [1]) Schematic of the PPLN micro-ring resonator—with inset scanning electron microscopy images of the device—where incoming visible pump photons (~775 nm) are down-converted to pairs of telecom-wavelength photons (~1550 nm).

Enter Zhaohui Ma and Jia-Yang Chen, with the Laboratory for Quantum Enhanced Systems and Technology (QuEST) at the Stevens Institute of Technology, who have developed a state-of-the-art on-chip source of telecom-wavelength single photons [1] [2].

Their device (see Figure 1) is based on a periodically-poled lithium niobate (PPLN) micro-ring resonator, where incoming photons interact with each other through the material's non-linear optical properties to create photons with double (e.g. spontaneous parametric down conversion, SPDC) or half (e.g. second-harmonic generation, SHG) the wavelength of the incoming light. Utilising the photon pairs generated by SPDC, Zhaohui and Jia-Yang's device can be operated as a heralded single-photon source, where the spectrally-distinct signal and idler photons are filtered into separate optical paths, and the detection of a signal photon tells you that you should simultaneously have exactly one idler photon in the other arm.

Customer Need

To characterize the performance of their device, Zhaohui and Jia-Yang would like to measure some key figures-of-merit, including:

- **The Pair Generation Rate (PGR)**: the rate at which photon pairs are generated in the device

- **The Brightness**: how the PGR 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.

The primary challenge, however, is to demonstrate the performance of their nanophotonic device as a single-photon emitter. For this, they would need to show strong antibunching in the heralded single-photons, through measuring their second-order autocorrelation function, or $g^{(2)}(\tau)$, in a Hanbury Brown and Twiss (HBT) experiment.

Hanbury Brown and Twiss measurements

The HBT setup that Zhaohui and Jia-Yang used is shown in Figure 2. The measurement of the $g^{(2)}(\tau)$ second-order autocorrelation function is a histogram of start-stop time delays between the two detectors in the idler photon's arm, telling you the likelihood of observing a second photon on one detector at time delay τ after observing a photon in the first detector. The zero-delay value $g^{(2)}(0)$ serves as the standard measure for single-photon purity.

For a laser, each photon arrival time is independent to every other photon, so you would see a uniform $g^{(2)}$ curve. For a single-photon source, you would see (ideally) no coincidences at the zero delay, and a uniform positive background of uncorrelated coincidences far away from the zero delay.

For this kind of nanophotonic device, measuring the $g^{(2)}$ curve poses several technical challenges:

1. Timing Resolution

The temporal width of the $g^{(2)}$ curve is typically on the order of a nanosecond or shorter. Detectors with a high amount of jitter will not be able to resolve such sharp features in the curve, and thus the experiment will not observe a statistically significant antibunching dip. In the case of the QuEST lab, they are limited in time to the order of the cavity lifetime of their device, approximately 80 ps, and so detectors with timing jitter on a comparable timeframe are needed, and a factor two shorter timeframe is preferred (i.e. detectors with timing resolution of 40-80 ps).

2. Efficiency

A regular HBT experiment records double-detection events on two detectors, so the signal improves with the square of the average single-photon count rates. Strictly, a heralded arrangement relies on triple-detection coincidences, so the signal scales with the cube of the average count rates. Even at relatively high single-photon count rates, double and triple-detection events can be rare, requiring minutes, hours or days to build up a statistically-significant measurement.

Given that photon detection statistics in TCSPC follow a Poisson distribution, an improvement in the detector efficiency will reduce the time needed to build equivalent statistics by between a power of two to three. Doubling the efficiency of the detectors could mean the difference been measuring for 300 seconds or 300 days.
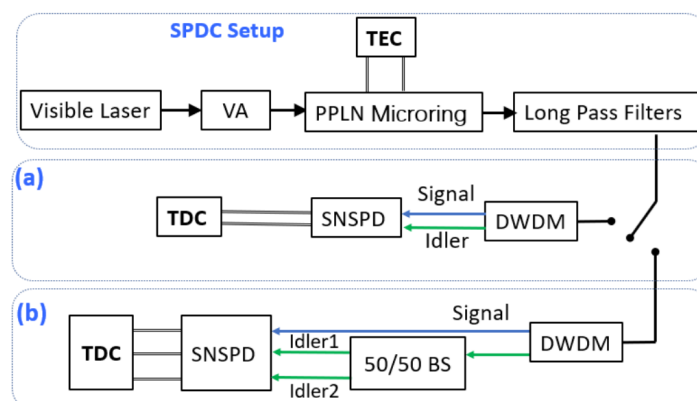

Figure 2: (from Zhaohui Ma *et al.* [1]) Experimental setup for characterizing (a) photon-pair generation rates, brightness and multi-photon noise, and (b) fidelity of the heralded single-photon generation. VA: Variable Attenuator, TEC: Thermoelectric cooler, BS: Beam Splitter, PPLN: Periodically-Poled Lithium Niobate, DWDM: Dense Wavelength-Division Multiplexing, SNSPD: Superconducting Nanowire Single-Photon Detector, TDC: Time-to-Digital Converter.

3. Noise Floor

At high pump-powers, the noise in the experiment will be dominated by multi-photon-pair emission from the micro-ring device, while at low-powers, the detector dark counts will dominate. Noise in the measurement will increase the minimum dip in the observed $g^{(2)}$ curve. Therefore, to demonstrate the single-photon purity of the device as faithfully as possible, minimizing the detector dark count rate is paramount.

Solution

To meet the QuEST lab's quantum sensing needs, ID Quantique provided an array of ID281 superconducting nanowire single-photon detectors paired with an ID900 Time Controller. The high efficiency (> 85% at 1550 nm), timing resolution (< 46 ps) and low dark count rate (50-100 Hz) of the SNSPDs, coupled with the timing precision of the ID900, allowed for the successful ultrafast execution of all key single-photon and photon-pair TCSPC measurements.

Results

Measuring the output of the micro-ring resonator device with the ID281 SNSPD / ID900 Time Controller combination, the QuEST lab were able to demonstrate the performance of a state-of-the-art ultra-compact telecom-wavelength single-photon source.

The brightness and pair generation rate Zhaohui and Jia-Yang's device was orders of magnitude greater than similar devices. The characteristic single-photon antibunching dip was very close to zero at low pump powers—$g^{(2)}(0) = 0.0080(7)$ at 3.4 µW pump power—signifying a high-quality single-photon source. Even at higher pump powers, the light was convincingly sub-Poissonian, with $g^{(2)}(0) = 0.097(76)$ at a pump power of 13.4 µW, demonstrating promise as a scalable single-photon technology. Given the relative increase in multi-pair emission at higher pump powers, by using a photon number-resolving detector arm the signal photon arm it may be possible to improve the high-power single-photon purity even further.

The ultra-low dark count rate of the ID281 SNSPDs allowed for a negligible contribution to the noise of the measured $g^{(2)}$ curves, providing a faithful demonstration of the device itself. The low timing jitter of the ID281 and ID900 combination allowed for a highly-resolved $g^{(2)}$ curve to be measured, while the ID281's high detection efficiency allowed for a range of repeated TCSPC measurements at varying experimental conditions in reasonable timeframes, even at very low excitation powers.

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> *By upgrading our TCSPC apparatus to an ID281 SNSPD and ID900 Time Controller setup, we were able to better show the real performance of our state-of-the-art ultra-bright on-ship quantum photon source. Without the efficiency, low noise, and precise timing of the SNSPDs, our experiments would have taken impractical times to acquire lower-quality data.*
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> Zhaohui Ma
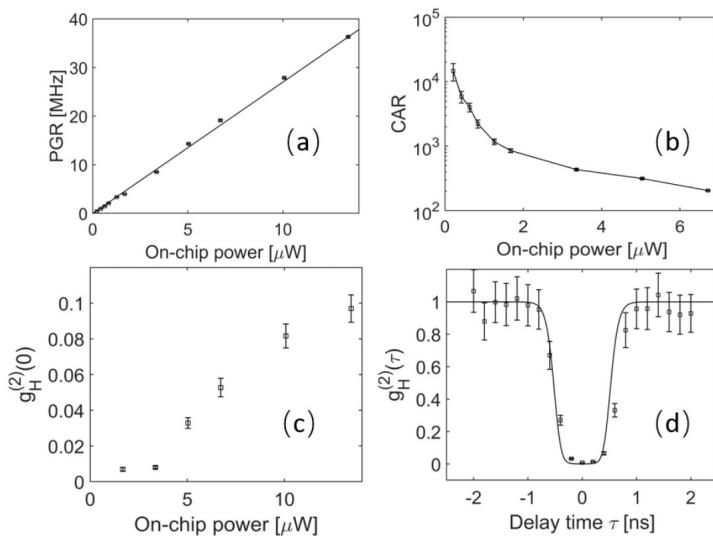> PhD researcher at Stevens Institute of Technology

Figure 3: (from Zhaohui Ma *et al.* [1]) Experimental results of the light source's (a) Pair Generation Rate as a function of incoming pump power, (b) the Coincidence-to-Accidental Ratio of the generated photon pairs as a function of pump power, (c) the zero-delay $g^{(2)}(0)$ antibunching dip as a function of pump power, and (d) a single $g^{(2)}$ measurement for the heralded idler photons, corresponding to $g^{(2)}(0) = 0.0080(7)$ at 3.4 µW pump power.

In all, such a device represents a promising candidate technology for integrated photonic circuits in a quantum network. It has strong demonstrable performance as a compact and bright source of telecom-wavelength single photons, and has the possibility to integrate the micro-resonator chip into more complex devices capable of advanced light/matter interaction.

A high-performance single-photon source such as this has myriad applications, from use in quantum communication, computing, metrology, microscopy and more. For example, cascading these devices on a single chip could provide an elegant entanglement source for a long-haul quantum relay, and perhaps a practical quantum repeater, letting you share richer qubit states over even greater distances. These photonic building-block technologies will give us exactly the resources we need to scale a powerful and future-proof quantum internet.

MEET THE PRODUCTS

ID281 Superconducting Nanowire

ID900 Time Controller Series

[1] 'Ultrabright Quantum Photon Sources on Chip', Zhaohui Ma et al., 2020, Phys. Rev. Lett. 125, 263602
[2] 'Photon Conversion and Interaction on Chip', Jia-Yang Chen et al., 2021, arXiv:2105.00275