SPARROW QUANTUM

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Application Note

Integration of the Sparrow Quantum Single-Photon Chip with the Montana Instruments Cryo-Optic X-Plane system.

The Sparrow Quantum Single-Photon Chip requires a suitable cryostat with optical access for effective use. Montana Instruments provides such a solution with the Cryo-Optic® product line. This application note describes an integrated system including the interface optics for exciting the chip and efficiently extracting single photons. It also describes an optical filter and a correlation setup to demonstrate the single-photon nature of the emission. The complete setup is mounted in an enclosure with a compact footprint.

This complete single photon source provides a user friendly and reliable laboratory tool for quantum technology research that enables the researcher to focus on applications requiring single photons.

Single-photon chip

The Sparrow Quantum Single-Photon Chip is the world's first commercially available monolithic Single Photon Chip. This chip is based on self-assembled InGaAs quantum dots coupled to a slow-light photonic-crystal waveguide made using a unique processing technology. The slow-light sections feature a low group velocity to increase the coupling efficiency to a record level. The end of the photonic-crystal waveguide structure is coupled to a carefully engineered suspended nano-beam waveguide and out-coupling grating. The increased coupling efficiency from the quantum dot to the waveguide relies on the strong suppression of radiation modes together with an enhanced coupling into the waveguide mode. This makes the Sparrow single photon chip very robust to spatial and spectral dispersity, meaning that the quantum dots are efficiently coupled within a broad frequency band [1, 2]. The specifications of the single-photon chip are shown in the table below.

Specifications	
Waveguide mode coupling efficiency	> 90 %
Second order coherence, $g^{(2)}(0)$	< 0.1
Emission wavelength	910 - 960 nm
Excitation wavelength	800 - 960 nm
Operating temperature	< 15 K
Excitation power	1-4000 nW
Excitation pulse width (recommended)	1- 10 ps
Decay time	Typ. 1 ns
Chip Dimensions (WxDxH)	4 x 2 x 0.5 mm

To use the single-photon chip, an excitation laser is directed at the quantum dot in the photonic-crystal waveguide perpendicular to the chip and the emitted photons are collected from the grating, as illustrated in Figure 1.

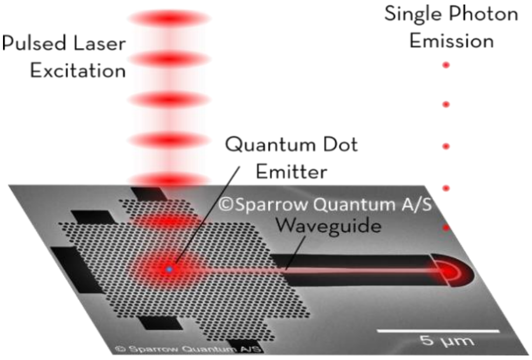


Figure 1: Single-photon chip excitation and emission

Cryo-Optic® X-Plane system

The Montana Instruments Cryo-Optic® X-Plane system is a perfect match for utilizing the singe-photon chip. It provides an automated and controlled cryogenic environment combined with a compact tabletop design, ensuring a simple and flexible setup. The Cryo-Optic X-Plane geometry allows setups to be built in-plane with the optical table which simplifies the optical design and increases the robustness and stiffness of the opto-mechanical system compared to typical setups with a vertical optical axis. This is exemplified in the setup where all optical paths are in the plane of the table. The recommended minimum NA for the chip is 0.6 and the X-Plane provides an integrated high NA (0.75) objective for undetectable optical drift, so that refocusing is not required. In addition, the objective provides a small diffraction limited excitation spot that minimizes the required excitation laser power and thereby the scattering.

Excitation and collection optics

The excitation and collection optics are assembled in an enclosure that attaches to the X-Plane. The X-Plane system includes optics and piezoelectric positioners for chip alignment and high collection efficiencies. The enclosure provides a low light leak, protected environment for stable, optimal performance. A sketch of the setup is shown in Figure 2 and a picture is shown in Figure 3.

Excitation

The excitation source is connected to the excitation fiber port and aligned to the excitation spot using mirror M1 and M2. The focus is adjusted on the fiber coupler. In normal operation, only small adjustments of M2 are necessary. The polarization is controlled by the linear polarizer (LP1) which is fixed under normal operation and the half wave plate (HWP 1) is used to turn the polarization to match the chip orientation. Excitation perpendicular to the waveguide is preferred for maximum single-photon purity as this will limit the amount of laser excitation onto the waveguide and thereby excitation of other quantum dots in the structure.

For monitoring or stabilizing the excitation power, an optional power monitor port may be added at the open port of BS1. The excitation source for the demo is a picosecond diode laser (ALDS PiLas) at 850 nm which operates at up to 80 MHz with a pulse width of ~40 ps.

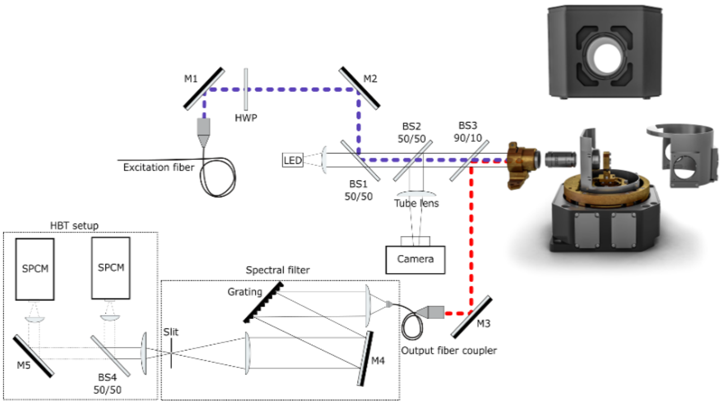


Figure 2: Sketch of the complete optical setup.

Collection

The photons collected by the objective are reflected on the first beam splitter (BS3) and coupled to the output fiber. The spot size is decided by the fiber coupler and the fiber core acting as the confocal pinhole. The collection fiber coupler is chosen to match the objective and the spot size of the chip emission. Initial alignment of the spot is performed using light at the emission wavelength sent backwards from the detection fiber port while the position and focus on the sample is pre-aligned based on the beam splitter (BS3) and the fiber coupler. In normal operation, the detection path should not be readjusted and only the chip position and focus along with the excitation mirror (M2) should be changed.

To filter the excitation light from the emission a linear polarizer and a quarter wave plate can be placed between BS3 and M3. This would also make it possible to use the setup for resonant or quasi resonant excitation.

Imaging

A CCD camera and an LED are mounted for visual inspection of the sample and the alignment. A 940 nm LED is used to get the same focus as the emitted light. It is collimated with a condenser lens to properly fill the objective aperture. A monochrome camera from Point Grey (Chameleon3, 1.3 MP Mono USB3 Vision, Sony ICX445) is used as it provides a good compromise between NIR sensitivity, pixel size, and dynamic range.

Filtering the single-photon emission

The emission from the single-photon chip must be filtered to isolate the single-photon emission from other QDs in the single-photon chip. This is implemented using a compact grating based monochromator using lenses. It consists of a 25 mm, 1100 g/mm blazed grating lens with a focal length of 100 mm, and a slit of 10 µm, which results in a resolution of just below 0.2 nm and a throughput of 70%.

Depending on the excitation scheme, the linewidth of the single-photon emission is narrower than the filter implemented. A narrower filter will increase the purity of the single photon emission. Furthermore, the indistinguishability of the photons may be improved by implementing resonant or quasi-resonant excitation [3]. Using a bandwidth of 0.2 nm makes the setup more robust to mechanical and temperature fluctuations and allows for simpler and widely tuneable filter implementations.

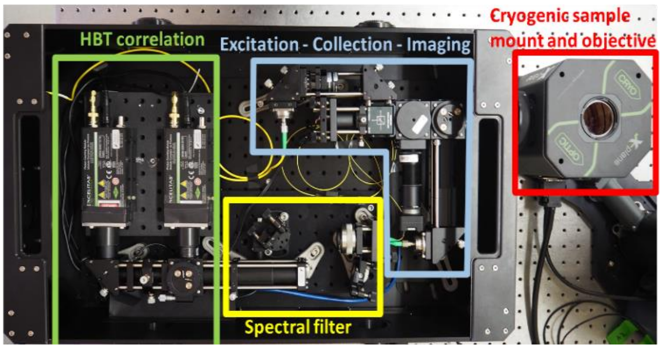
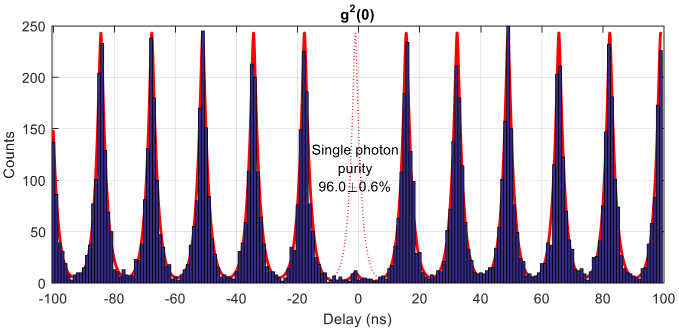


Figure 3: Image of the optical setup from above.

Correlation measurement

To demonstrate the single-photon nature of the emission, the setup integrates a Hanbury-Brown and Twiss measurement. It consists of a 50/50 beam splitter (BS4) and two single-photon counters (Excelitas SPCMs). The time correlation is done with a [Swabian Instruments TimeTagger 20](), which enables a simple interface and live view of the correlation histogram. An example of a measured correlation histogram is shown below.



The histogram shows the correlation of the two detectors for an excitation frequency of 60 MHz. The data are shown in blue and the solid red line shows the fitted theoretical curve used to extract the single-photon purity. The data clearly demonstrate the single-photon emission with a $g^2(0)$ of 4 %. This corresponds to a single-photon source purity of 96%. In addition, the equal heights of the peaks illustrate that the source is stable and does not suffer from emitter blinking.

References:

[1] Arcari et al, Physical Review Letters 113, 093603 (2014).
[2] P. Lodahl et al, Rev. Mod. Physics 87, 347 (2015).
[3] Kirsanske et al, arXiv:1701.08131 (2017).