Application Note

Single-photon sources for multi-photon applications.

Many promising applications of single photons requires a number (N) of single indistinguishable photons to be simultaneously available on N different ports, which is called a N-photon event or an N photon state. Such an application could be optical quantum simulators [1,2,3]. A Sparrow Quantum deterministic single-photon source generates a single-photon with a high efficiency for each excitation pulse. This means that the photons will be emitted consecutively with a time difference given by the excitation rate and to use this for a multi-photon application the photons must be time domain demultiplexed. A photonic application circuit that requires multi-photon states can be seeded by a deterministic single-photon source as illustrated in the diagram in figure 1 below.

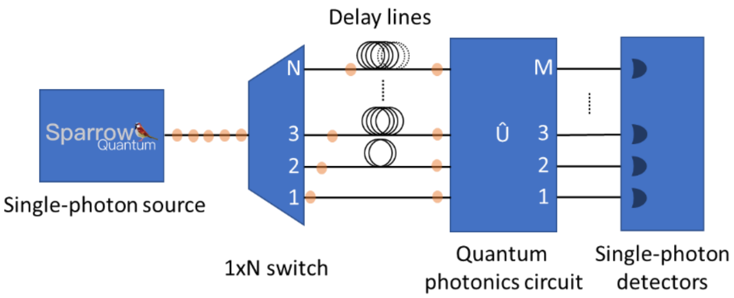

Figure 1: General Multi-photon application using a single-photon source.

The multi-photon generation from the single-photon source is done by a time domain de-multiplexing setup consisting of an optical switch and a number of delay lines. The optical switch routes the emitted photons into the required number of ports and a delay line in each port aligns the photons on the input of the photonic application circuit.

The central component is the optical switches which can be implemented using different technologies depending on the requirements for scalability, cost efficiency and speed of the application. Several technologies are available for this such as: Lithium niobate integrated switches or other electro-optical modulators, acousto-optical, Pockels cells and polarization optics or MEMS mirror switches

Currently the most efficient way of implementing the demultiplexer is through bulk switches. An efficient way would also be to implement integrated photonic switches with e.g. thermos-optics switches [4] or lithium niobate [5] or other technologies used in telecom systems [6] integrated with the single photon source [7]. However, the latter are not currently commercially available.

A possible implementation of a 1x8 switch using Pockles cells are shown in figure 2 below.

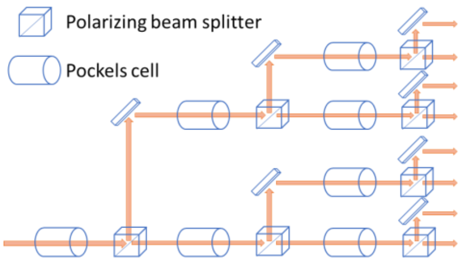

Figure 2: Optical switching circuit using Pockels cells and polarizing beam splitter. The Pockels cells turns the polarization based on the applied voltage to route the photons to the output ports. A high efficiency can be achieved in this setup due to the low loss (~1%) of Pockels cells, beam splitters and mirrors.

Calculating the multi-photon probability

The efficiency of an active time domain de-multiplexing setup for generating a multi-photon state can be calculated from the efficiency of the source and setup, the number of photons needed and the repetition rate of the source. The rate of N-photon event (R(N)) can be calculated as

$$R(N) = R_p \times \frac{\eta^N}{N},$$

Where η is the efficiency of the single-photon system including the source i.e. the probability that a single photon will be transmitted from the source and through the demultiplexer after a trigger. All channels are assumed to have the same efficiency, N is the photon number and R_p is the excitation or pump rate.

A plot of different generation rates as a function of the number of photons are shown in figure 3 below, where the pump rate is 500 MHz.

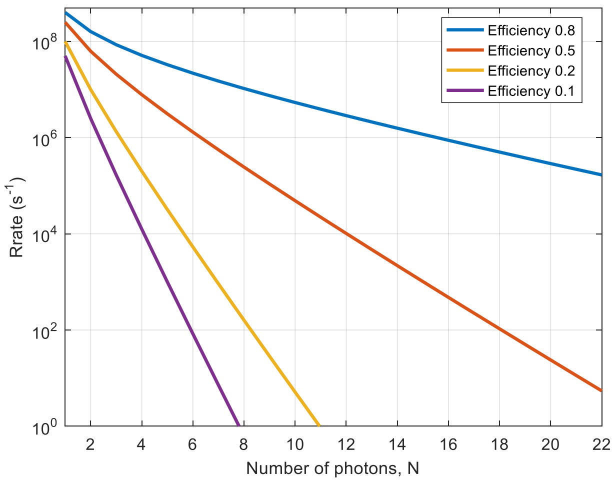

Figure 3: Multi-photon generation rate for different system efficiencies for an excitation rate of 500 MHz.

As it can be seen from the equitation and figure 3 the most important parameter is the system efficiency. The figure shows that a 11-photon experiment can be realized with one event per second for a 20% efficiency

Excitation frequency

The excitation frequency can be adjusted as required by the application, however, to properly split the photons the pump rate (R_p) must be significantly lower than the decay rate of the emitter (Γ). For less than 2 % overlap of consecutive photons the emitter decay rate should be more than 4 times the excitation rate. With a decay rate of 2 ns^{-1} this results in a maximum recommended excitation frequency of 500 MHz.

Typically, an excitation rate of round 80 MHz is used due to the available excitation sources (diode lasers or mode locked Ti:Saph laser). A possible solution for a higher excitation rate is to use the same source followed by a passive time domain multiplexer formed using beam splitters and delay lines.

Indistinguishability of multiple photons

For many multi-photon applications, the indistinguishability between the different photons (V) in the N-photon state is important. Depending on the specific circuit the dependency of efficiency on the indistinguishability can vary but in the general case is scales as V^N.

The indistinguishability is known to vary depending on the distance between the photons but measurements on quantum dot sources as used by Sparrow Quantum shows that a 10% reduction is seen after 20 photons at 13 ns separation (approx. 0.2 µs) but a high indistinguishability is still kept for up to 10 µs [8]. A minor dependency on the excitation rate is also expected but for Sparrow Quantum sources no difference is seen between a 2.5 ns or 13 ns excitation period [9].

Examples:

As an example of the achievable multi-photon event rates we take a source with an efficiency of 12 % that is excited at 500 MHz and feeding an 8-photon multiplexing setup as shown in figure 2 with an efficiency in each step of 98% for a total efficiency of $0.12 * 0.98^3 = 11.3$ %. This configuration will yield 8-photon events with a generation rate of 1.2 s^{-1}.

Using the same configuration for a 16-photon demultiplexer a source with an efficiency of 50 % will generate 16-photon states at a rate of 10 s^{-1}.

References

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