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High performance guided-wave asynchronous heralded single photon source

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We report on a guided wave asynchronous heralded single photon source based on the creation of non-degenerate photon pairs by spontaneous parametric down conversion in a Periodically Poled Lithium Niobate waveguide. We show that using the signal photon at 1310 nm as a trigger, a gated detection process permits announcing the arrival of single photons at 1550 nm at the output of a single mode optical fiber with a high probability of 0.37. At the same time the multi-photon emission probability is reduced by a factor of 10 compared to poissonian light sources. Furthermore, the model we have developed to calculate those figures of merit is shown to be very accurate. This study can therefore serve as a paradigm for the conception of new quantum communication and computation networks. © 2010 Optical Society of America

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Using the fact that quantum systems are perturbed by measurements and cannot be cloned with perfect fidelity, Bennett and Brassard proposed in 1984 [1] the possibility of distributing in absolute confidentiality a cryptographic key between two partners (commonly called Alice and Bob). Since the security of this protocol relies on the ability to encode information on only one photon at a time, single photon sources (SPS) are required. Weak laser pulses are a very simple solution for approximating SPS behavior but as the associated photon statistics are poissonian [2] (i.e. $g^{(2)}(0)=1$), following reference [3], the communication is limited to relatively short distances. On the contrary, an ideal SPS would have a mean number of photons close to one associated with a $g^{(2)}(0)=0$, allowing a dramatic increase of the transmission distance.

Quasi-SPS’s exhibiting a very low $g^{(2)}(0)$ have already been demonstrated [4–6]. While all these solutions are interesting regarding the photon emission process itself, they suffer from drawbacks that make them unsuitable for practical applications at the present time. Furthermore, the emitted photons of the demonstrated solutions are in the visible spectrum which is incompatible with communication using installed telecom fiber networks.

In this letter we report on an alternative solution to the aforementioned problems. Taking advantage of non-linear integrated optics and guided wave technology, we built a heralded single photon source (HSPS) exhibiting excellent figures of merit and offering a very practical experimental implementation.

The HSPS relies on photon pairs generated by spontaneous parametric down-conversion (PDC) in a Periodically Poled Lithium Niobate (PPLN) optical waveguide. Some of us have previously shown such a structure to be

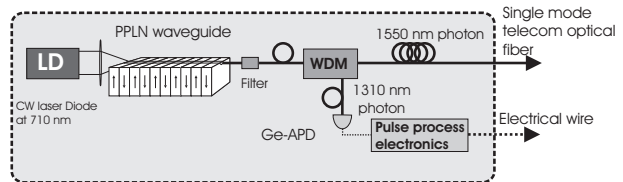


Fig. 1. Schematic of our Heralded Single Photon Source. It has an electrical output which allows heralding the arrival of a single photon at the single mode optical fiber output.

the most efficient source of down-converted photon pairs realized to date [7]. Since these two photons are simultaneous to better than 100 fs [2], the idea is to use one of them to herald the arrival of the second photon by gating the associated detector only when it is expected [8]. This greatly reduces the number of empty pulses that hinder long distance quantum communication experiments. In our setup the quasi-phase-matching configuration (for a PPLN period of 13.6 μm) allows the conversion of pump photons at 710 nm into pairs of photons whose wavelengths are centered at 1310 nm and 1550 nm respectively. As depicted in FIG. 1, taking advantage of the guided structure, the photon pairs are collected by a single mode telecom fiber butt-coupled (but not attached) to the output of the waveguide. After discarding the remaining pump photons (using a filter in a U-bracket), the pairs are separated by a standard fiber optic wavelength demultiplexer (WDM). The short wavelength photons (commonly called “signal”) are detected using a LN_2 cooled Germanium Avalanche Photodiode (Ge-ADP) operated in geiger mode with a quantum effi-

ciency of 6%. The resulting electrical signals are used as “heralds” for the arrival of the long wavelength photons (“idler”) which are the expected single photons. Note that a fiber delay is used to insure the arrival of these 1550 nm photons after the heralding electrical pulses at the two outputs of the HSPS box. Experimentally, the detection of the single photons amounts to counting a coincidence between the two photons of the pairs. Therefore, the creation time of the pairs is not important and this allows pumping the crystal with a CW laser and having the single photon at 1550 nm isolated from others thanks to the gated detection. Essentially, this is a quantum equivalent of the classical “asynchronous transfer mode” [9]. Upon receiving the electrical heralding pulses, the detector is turned on during a given time-window ΔT (gated mode) ranging from 3 ns to 50 ns. In this context, instead of thinking in terms of optical pulses with 0, 1 or several photons, one has to think in terms of a time-window containing 0, 1 or several photons.

In order to determine the SPS behavior of the 1550 nm photons, we wish to measure the probabilities P_1 and P_2 of having 1 or 2 photons within ΔT (the probability of having more than 2 photon being negligible). To do this we carried out measurements in the single photon counting regime using a test bench consisting of a gated detection Hanbury-Brown & Twiss type setup [10]. In order to evaluate the actual performance of the source, we have to take into account the poor detection efficiencies, dark counts in detectors and the fact that 50% of the possible two-photon events are missed at the beam-splitter which are all parts of the test bench. Taking these points into account, a correction model proposed by Mandel [8] has been adapted to calculate P_1 and P_2 at the output of the HSPS. The experimental setup was run with time-windows of 3 ns and a pump power of 10 μW . We report in the first two columns of TABLE 1 the raw data and the associated experimental probabilities of finding 1 or 2 photons. Our HSPS exhibits a probability of having an available single 1550 nm photon of 0.37 at the output of the single mode optical fiber. This result is four times better than that of faint laser pulses and represents to our knowledge one of the best values for any single photon source. On the other hand the multi-photon emission probability in a 3 ns time-window is reduced by a factor of 10 at equal P_1 compared to faint laser pulses. Moreover TABLE 1 also reports the experimental probabilities of some existing SPS based on PDC, molecules, NV centers and quantum dots. Although the comparison is limited to devices for which explicit values of P_1 and P_2 have been given, our P_1 is much better than all other techniques when measured at the output of a collection device such as a lens or an optical fiber and is close to those using PDC in bulk configuration.

However, our result is quite far from the predicted 100% “preparation efficiency” announced by Mandel in 1986 [8]. This corresponds to the probability to have the idler photons available when the associated signal photons have been detected. In practice when a SPS is

approximated using PDC, the limiting factors are the dark counts in the trigger detection and the losses experienced by the heralded photons. As we measure the losses of the optical fiber components (filter, WDM and the spool of hundred meters of standard fiber) to be 1.1 dB at 1550 nm, we can then infer the “preparation efficiency” Γ from the overall collection efficiency γ . The latter can be easily estimated by considering the single detections in the previous setup after subtraction of the empty states due to the dark counts in the trigger line.

Calling N_T the raw heralding rate from the Ge-APD and $D_c \approx 20k Hz$ its dark counts and noticing that it conditions the detection of the idler photon, we can write :

$$\text{Single detections rate} = \gamma \times \eta \times (N_T - D_c) \quad (1)$$

where $\eta=0.10$ represents the quantum efficiency of both InGaAs-APDs. We experimentally found $\gamma=0.46$. Thus the preparation efficiency Γ , which can be seen as the “guide-to-single mode fiber” coupling efficiency, was found to be 0.59. As previous experiments based on bulk crystals showed photon collection efficiencies ranging from 0.03 to 0.83 [12–14], our waveguiding structure does not improve the best results. However, it is important to note here that only one butt-coupled fiber is necessary to obtain high collection efficiency thanks to the collinear PPLN guiding structure thus offering better stability and ease to use. It is then interesting to analyze the impact of γ on P_1 and $g^{(2)}(0)$ in order to estimate the potential for improvement of the HSPS.

We begin this analysis by calculating the expected experimental probability, P_2 , of having another photon in addition to the heralded one within a time-window ΔT . As the coherence time of the single photons ($\tau_c < 1 ps$) is much less than the integration time ($\Delta T \approx 3 ns$), the number of photons during ΔT follows a poissonian distribution and the probability that the interval from one photon to the next is equal to or greater than ΔT is given by [15] :

$$P_{\bar{n}}(n = 0) = e^{-\gamma\mu\Delta T} \quad (2)$$

where $\bar{n}=\gamma\mu\Delta T$ is the mean number of photons per time-window and μ is the mean emission rate. Considering that $\gamma\left(\frac{N_T-D_c}{N_T}\right)$ is the probability of having a heralded photon inside ΔT , where D_c is the dark count rate and N_T the raw counting rate in the Ge-APD, the probability of having one or more additional photons in this ΔT is then :

$$P_2 \approx \gamma^2 \mu \Delta T \left(\frac{N_T - D_c}{N_T} \right) \quad \text{with} \quad \mu \Delta T \ll 1 \quad (3)$$

Furthermore, the probability of having a single photon inside the opened time-windows depends on having either a heralded photon or an additional photon that fills an empty state coming from a dark count in the trigger

Table 1. P_i experimental probability to find $i=1$ or 2 photons for the HSPS compared to some of the other existing SPS. Note that, for Quantum Dot, P_1 includes the losses at the initial collection lens.

| Data (cts/s) | HSPS | PDC [11] | Molecule [4] | NV center [5] | Quantum Dot [6] |
|------------------|------------------------------|-------------------------|-------------------------|-------------------------|-------------------------|
| $N_T = 124302$ | $P_1 = 0.37 \pm 0.02$ | $P_1 = 0.61$ | $P_1 = 0.047$ | $P_1 = 0.022$ | $P_1 = 0.083$ |
| Detections= 4702 | $P_2 = 0.005 \pm 0.001$ | $P_2 = 2 \cdot 10^{-4}$ | $P_2 = 5 \cdot 10^{-5}$ | $P_2 = 2 \cdot 10^{-5}$ | $P_2 = 4 \cdot 10^{-4}$ |
| Coincidences= 8 | $g^{(2)}(0) = 0.08 \pm 0.02$ | $g^{(2)}(0) = 0.002$ | $g^{(2)}(0) = 0.046$ | $g^{(2)}(0) = 0.07$ | $g^{(2)}(0) = 0.14$ |

detection or from a lost heralded photon :

$$P_1 \approx \gamma \left\{ \left(\frac{N_T - D_c}{N_T} \right) \left[1 - 2\gamma\mu\Delta T \right] + \mu\Delta T \right\} \quad (4)$$

Then $g^{(2)}(0)$ corresponds to the ratio between the P_2 of a given SPS and the $P_2 = P_1^2/2$ of a poissonian light source running at equivalent P_1 :

$$g^{(2)}(0) \approx \frac{2\mu\Delta T \left(\frac{N_T - D_c}{N_T} \right)}{\left(\mu\Delta T + \left[1 - 2\gamma\mu\Delta T \right] \left(\frac{N_T - D_c}{N_T} \right) \right)^2} \quad (5)$$

In our experiment the mean emission rate μ was estimated taking into account the detection efficiency of the Ge-APD and the losses in the trigger line. Taking $\mu=6.6 \cdot 10^6 s^{-1}$ and $\gamma=0.46$ the first two columns in TABLE 2 report the experimental probabilities and their associated calculated values. Note the good agreement validating the theoretical analysis and therefore allowing us to estimate the performance expected for a better collection efficiency using a ‘‘pigtailed’’ fiber. In this particular configuration the fiber is actually attached to the waveguide using refractive index matching glue in order to eliminate Fresnel reflections and to fully exploit the waveguiding structure of the source. Γ of 0.7 are standard in this configuration. Furthermore, efforts underway to develop new PPLN waveguides enabling down-conversion from 532 nm to 810 nm and 1550 nm could take advantage of passively quenched silicon detectors showing much higher quantum efficiency (0.6) for the trigger at 810 nm and considerably lower noise.

Table 2. P_i probability to find $i=1$ or 2 photons.

| Experimental | calculated | predicted |
|---------------------|------------------------------|-------------------------|
| $P_1 = 0.37$ | $P_1 = 0.38 \pm 0.02$ | $P_1 = 0.54$ |
| $P_2 = 0.005$ | $P_2 = 0.003 \pm 0.001$ | $P_2 = 7 \cdot 10^{-4}$ |
| $g^{(2)}(0) = 0.08$ | $g^{(2)}(0) = 0.05 \pm 0.02$ | $g^{(2)}(0) = 0.005$ |

The last column of TABLE 2 deals with the predicted probabilities (P_1 and P_2) when using a silicon APD and a fiber pigtailed to the waveguide. In this case, the HSPS would exhibit a P_1 of 0.54, close to the best results reported to date and the multi-photon emission probability reduced by a factor of 200 compared to usual poissonian light sources at equal P_1 .

In this letter we have investigated the performance attained using quasi-phase-matched PDC in a PPLN

waveguide associated with optical fiber components to realize a Heralded Single-Photon-Source at 1550 nm. Using a CW laser we observed a P_1 of 0.37 of having a single photon at the output of a telecom single mode optical fiber, whereas the multi-photon emission probability is reduced by a factor of 10 compared to weak laser poissonian light sources at equal P_1 . We have also described an accurate model that allows estimating the expected figures of merit of any asynchronous single photon source. This, together with the high efficiency previously reported in [7], demonstrates the potential of waveguide technologies for building efficient, stable, and compact sources for quantum communication experiments. Furthermore, integrated optics could also be used to realize complex passive and active circuits, permitting a simple implementation of experiments in the fields of quantum communication and computation.

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