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High performance heralded single photon source

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We report on a guided wave heralded photon source based on the creation of non-degenerate photon pairs by spontaneous parametric down conversion in a Periodically Poled Lithium Niobate waveguide. 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 0.38. At the same time the multi-photon emission probability is reduced by a factor of 10 compared to poissonian light sources. Relying on guided wave technologies such as integrated optics and fiber optics components, our source offers stability, compactness and efficiency and can serve as a paradigm for guided wave devices applied to quantum communication and computation using existing telecom networks.

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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. Motivated by fundamental investigations as well, several teams have proposed realizations approximating such ideal sources. Among the most successful are weak laser pulses, single two-level quantum systems, and quantum dots. We will briefly discuss each in order to permit comparison with a heralded single photon source, based on spontaneous parametric down-conversion in a nonlinear optical waveguide, we describe in this letter. The figures of merit we use are P_1 , the probability of creating a single photon when expected, and $g^{(2)}(0)$ the second-order autocorrelation function. The latter allows the comparison between any SPS and typical poissonian light sources that show a probability of creating two photons P_2 equal to $\frac{P_1^2}{2}$. According to this, $g^{(2)}(0)$ corresponds to the ratio between the P_2 of a given SPS and the P_2 of a poissonian light source running at equivalent P_1 :

$$g^{(2)}(0) = \frac{P_2^{SPS}}{P_2^{poisson}} = \frac{2P_2^{SPS}}{(P_1^{SPS})^2} \quad (1)$$

Weak laser pulses are a very simple solution for approximating SPS behavior. As the associated photon statistics are poissonian, a low mean number of photons per pulse avoids two-photon pulses but lead to a high probability of empty pulses. In quantum key distribution, the resulting decrease in bit rate may not be important but in practice leads to transmission errors due to detector

dark counts. Furthermore faint laser pulses are characterized by $g^{(2)}(0)=1$, whereas an ideal SPS would have $g^{(2)}(0)=0$. Quasi-SPS's exhibiting a very low $g^{(2)}(0)$ have already been demonstrated. For example, in two-level quantum systems, such as single organic dye molecules [2, 3], the excited molecule cannot emit two photons at the same time, but such sources offer limited life spans (≈ 160 ms) due to photo-bleaching. Using the same idea, other candidates are Nitrogen-Vacancy centers in diamond [4, 5] at room temperature. However both types of sources are handicapped by very low collection efficiencies (about 0.1%). To overcome this, another approach based on the recombination of electron-hole pairs in semiconductor quantum dots [6, 7] has been proposed. By using a microcavity surrounding the quantum dot, collection efficiencies of 36.6% were obtained but only at temperatures of around 50 mK. While all these solutions are interesting regarding the photon emission process itself, they suffer from drawbacks that make them unsuitable for practical applications. 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 nonlinear 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 the most efficient source of down-converted photon pairs realized to date [8]. Since these two photons are simultaneous to bet-

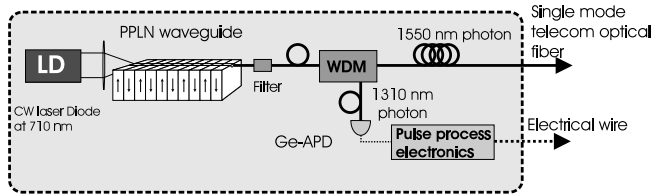


FIG. 1: Schematic of our Heralded Single Photon Source. It has an electrical output which allows heralding the arrival of a single photon at the single mode optical fiber output.

ter than 100 fs [9], 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 [10]. 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 $13.6 \mu\text{m}$) 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 RG1000 highpass 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 efficiency of 7%. 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. 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 2 photons (as with faint laser beams), one has to think in terms of a time-window containing 0, 1 or 2 photons.

In order to determine the SPS behavior of the 1550 nm photons, we wish to measure the probabilities P_0 , P_1 and

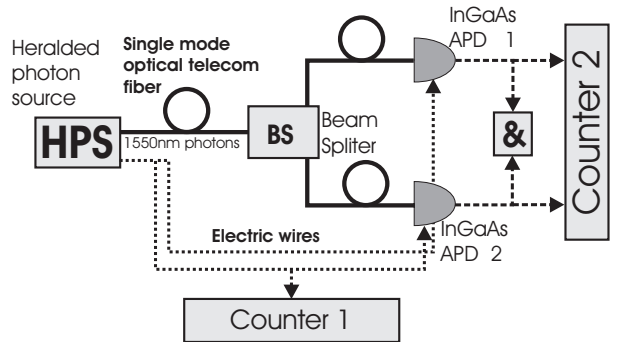


FIG. 2: Setup for measuring the SPS behavior of the HSPS. We count the total number of events N_T using the counter 1 while counter 2 yields the total number $S_1 + S_2$ of detected photons. The third counter from the *And*-gate which displays two-photon events R_c is not represented.

P_2 of having 0, 1 and 2 photons within ΔT . To do this we carried out measurements in the single photon counting regime as depicted in FIG. 2. The heralding electrical pulses from the HSPS are sent simultaneously to “counter 1” recording the raw number of events ($N_T = S_{Ge}^{net} + D_c$), and to the InGaAs-APDs 1 & 2 (courtesy of the University of Geneva and Id-Quantique). As one InGaAs-APD is not able to resolve the number of photons arriving within its time-window (ΔT), possible two-photon events are detected using a 50/50 single mode fiber beam-splitter (BS). Net single counts coming from the InGaAs-APDs (S_1^{net} and S_2^{net}) are obtained from counter 2 and an *And*-gate enables to retrieve the net coincidence events (R_c^{net}). In this configuration, $\frac{R_c^{net}}{N_T}$ leads to the “probability of two-photon events” (P_2), $\frac{S_1^{net} + S_2^{net}}{N_T}$ to the “single photon probability” (P_1) and the “probability of empty opened time-windows” (P_0) is approximated as $1 - P_1 - P_2$. As a consequence a perfect SPS with perfect detectors should exhibit $R_c^{net} = 0$ and $S_1^{net} + S_2^{net} = N_T$. But in practice all these figures are subjected to poor detection efficiencies, dark counts in detectors and the fact that 50% of the possible two-photon events are missed at the beam-splitter. Taking these points into account, a correction model proposed by Mandel [10] has been adapted to calculate P_0 , 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 $10 \mu\text{W}$. We report in the first two columns of TABLE I the raw data and the associated experimental probabilities of finding 0, 1 or 2 photons. Our HSPS exhibits a probability of having an available single 1550 nm photon of 0.38 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 the best value 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 . Moreover TABLE I also reports the experimental prob-

abilities 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_0 , P_1 and P_2 have been given, our P_1 is much better than all other solutions when measured at the output of a collection device such as a lens or an optical fiber.

However, our result is quite far from the predicted 100% “preparation efficiency” announced by Mandel in 1986 [10]. This corresponds to the probability to have the idler photons available when the associated signal photons have been detected [14]. 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 a standard optical fiber exhibits an attenuation close to 0.20 dB/km at 1550 nm the losses arise mainly from the collection efficiency γ between the waveguide and the fiber. This defines an upper limit to the probability of having a single photon which can be seen as the collection efficiency after subtraction of the empty states due to the dark counts in the trigger detector. Thus in the next section, we describe the role of γ in the experimental results.

Calling S_{Ge}^{net} the net counting rate the Ge-APD and noticing that the detection of the idler photon is conditioned by the detection of the corresponding signal photon, it becomes:

$$S_1^{net} + S_2^{net} = \gamma \times \eta \times S_{Ge}^{net} \quad (2)$$

where $\eta=0.103$ represents the quantum efficiency of both InGaAs-APDs. We experimentally found $\gamma=0.45$ which is in reasonable agreement with the measurement of $P_1=0.38$, since the latter value corresponds to the collection efficiency minus the probability of dark counts in our Ge-APD. Future developments using a pulsed laser to achieve gated detection of the trigger should lead to lower dark counts and therefore to a P_1 closer to the value of γ . As previous experiments based on bulk crystals showed photon collection efficiencies ranging from 0.03 to 0.85 [14, 15, 16], our waveguiding structure does not improve this. However, it is important to note here that only one fiber is necessary to obtain high collection efficiency thanks to the collinear PPLN guiding structure. 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 ($\tau_c < 1 \text{ ps}$) is much less than the integration time ($\Delta T \approx 3 \text{ ns}$), 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 [17] is given by:

$$P_{\bar{n}}(n=0) = e^{-\gamma\mu\Delta T} \quad (3)$$

where $\bar{n}=\gamma\mu\Delta T$ is the mean number of photons per time-windows and μ is the mean emission rate. The probability of having one or more additional photons in this ΔT is then:

$$P_2 = 1 - e^{-\gamma\mu\Delta T} \approx \gamma\mu\Delta T \quad \text{with} \quad \mu\Delta T \ll 1 \quad (4)$$

Furthermore, the probability of an empty opened time-window only depends on dark counts in the Ge-APD and the losses encountered by the idler photons. We therefore obtain:

$$P_0 = \frac{D_c + (1-\gamma)S_{Ge}^{net}}{D_c + S_{Ge}^{net}} \quad (5)$$

where D_c is the dark count rate and S_{Ge}^{net} the net counting rate in the Ge-APD. It follows that the probability of having a single photon is given by:

$$P_1 = 1 - P_0 - P_2 \approx \gamma \left(\frac{S_{Ge}^{net}}{D_c + S_{Ge}^{net}} - \mu\Delta T \right) \quad (6)$$

And finally using eq. (1), $g^{(2)}(0)$ can be expressed as:

$$g^{(2)}(0) \approx \frac{2\mu\Delta T}{\gamma \left(\frac{S_{Ge}^{net}}{D_c + S_{Ge}^{net}} - \mu\Delta T \right)^2} \quad (7)$$

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 $\mu=4.656 \cdot 10^6 \text{ s}^{-1}$ and $\gamma=0.45$ the first two columns in TABLE II 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.

The last column of TABLE II deals with the predicted probabilities (P_0 , P_1 and P_2) $\gamma=0.7$, when P_2 is maintained at $6.3 \cdot 10^{-3}$, which is approximatively the faint laser pulse value. In this case, the HSPS would exhibit a P_1 of 0.59, better than any reported to date.

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. In practice this configuration could increase the probability of having a single photon from 0.59 to 0.7, with a 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 of quasi-phase-matched PDC in a PPLN waveguide associated with optical fiber components to realize a Heralded

TABLE I: P_i experimental probability to find $i=0,1$ or 2 photons for the HSPS compared to some of the other existing SPS

Data (counts/sec)	HSPS	PDC [11]	Molecule [2]	NV center [12]	Quantum Dot ^b [6]	Faint Laser source
$N_T = 135000^a$	$P_0 = 0.617 \pm 0.8\%$	$P_0 = 0.744$	$P_0 = 0.953$	$P_0 = 0.978$	$P_0 = 0.917$	$P_0 = 0.905$
$S_1^{net} + S_2^{net} = 5430$	$P_1 = 0.376 \pm 1.4\%$	$P_1 = 0.247$	$P_1 = 0.047$	$P_1 = 0.022$	$P_1 = 0.083$	$P_1 = 0.090$
$R_c^{net} = 11$	$P_2 = 6.3 \cdot 10^{-3} \pm 1.6\%$	$P_2 = 9 \cdot 10^{-3}$	$P_2 = 5 \cdot 10^{-5}$	$P_2 = 2 \cdot 10^{-5}$	$P_2 = 4 \cdot 10^{-4}$	$P_2 = 4.5 \cdot 10^{-3}$
	$g^{(2)}(0) = 0.089 \pm 4.4\%$	$g^{(2)}(0) = 0.28$	$g^{(2)}(0) = 0.046$	$g^{(2)}(0) = 0.07$	$g^{(2)}(0) = 0.14$	$g^{(2)}(0) = 1$

^a $N_T = S_{Ge}^{net} + D_c$ with constant dark counts rate $D_c = 19000$ counts/sec

^b P_1 includes the losses at the initial collection lens, and recently $g^{(2)}(0)$ has been improved up to 0.02 [13]

TABLE II: P_i calculated probability to find $i=0,1$ or 2 photons in a $3ns$ time-window when the trigger had been detected taking $\gamma=0.7$. The last two columns allow comparison between experimental and calculated results.

Experimental	calculated $\gamma=0.46$	HSPS($\gamma=0.7$)
$P_0 = 0.617$	$P_0 = 0.612$	$P_0 = 0.398$
$P_1 = 0.376$	$P_1 = 0.382$	$P_1 = 0.594$
$P_2 = 6.3 \cdot 10^{-3}$	$P_2 = 6.3 \cdot 10^{-3}$	$P_2 = 6.3 \cdot 10^{-3}$
$g^{(2)}(0) = 0.089$	$g^{(2)}(0) = 0.086$	$g^{(2)}(0) = 0.035$

Single-Photon-Source at $1550nm$. Using a CW laser we observed a P_1 of 0.38 of having a single photon at the output of a telecom 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 also have shown that realistic improvement of the collection efficiency could be achieved using a fiber pigtailed to the end of the PDC waveguide source. This would increase the P_1 up to 0.7 enabling this source to well adapted to experiments over long distances. This, together with the high efficiency previously reported in [8], 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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