Characterization of an asynchronous source of heralded single photons generated at a wavelength of 1550 nm

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We make a thorough analysis of heralded single photon sources regarding how factors such as the detector gate-period, the photon rates, the fiber coupling efficiencies, and the system losses affect the performance of the source. In the course of this we give a detailed description of how to determine fiber coupling efficiencies from experimentally measurable quantities. We show that asynchronous sources perform, under most conditions, better than synchronous sources with respect to multiphoton events, but only for nearly perfect coupling efficiencies. We apply the theory to an asynchronous source of heralded single photons based on spontaneous parametric downconversion in a periodically poled, bulk, KTiOPO4 crystal. The source generates light with highly non-degenerate wavelengths of 810 nm and 1550 nm, where the 810 nm photons are used to announce the presence of the 1550 nm photons inside a single-mode optical fiber. For our setup we find the probability of having a 1550 nm photon present in the single-mode fiber, as announced by the 810 nm photon, to be 48%. The probability of multiphoton events is strongly suppressed compared to a Poissonian light source, giving highly sub-Poissonian photon statistics.

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I. INTRODUCTION

Sources of single photons are fundamental building blocks in all areas of quantum information processing using photonic qubits, such as linear-optics quantum computing and quantum communication. Consequently, many types of single photon sources have been developed, e.g. molecule or atom emission, nitrogen vacancies in diamond, and quantum dots, all having different properties like repetition rate, single-photon probability, and emission frequency. A promising alternative is so-called heralded single-photon sources (HSPS) where photon pairs produced by spontaneous parametric downconversion (SPDC) are used to prepare conditional single photons. One property of single-photon sources, essential to most applications, is that the single photons are prepared in a well defined temporal and spatial mode. In contrast to most other sources, HSPS have shown to successfully meet the spatial mode requirement by optimizing the coupling into single-mode fibers. However, there is still room for improvements on the photon statistics in time, here referred to as the temporal mode. Moreover, HSPS via SPDC also provide a great flexibility in the choice of frequency for the single photons.

The basic idea of HSPS can be simply stated as having the detection event of one of the single-photons of a pair announce the presence of its partner. The name “heralded” originates from the fact that the single-photons are not created on demand but rather announced by an external electrical signal. In the realization presented here, this signal is asynchronous due to the use of a continuous wave (CW) pump laser for the SPDC process, in contrast to when a synchronously pulsed pump laser is used. For HSPS of both sorts one can avoid “empty pulses” to a high degree, in contrast to when weak coherent pulses are used as single-photon sources. In essence, the temporal statistics of the heralded photons is controlled by utilizing a priori information extracted from the photon pairs. For pulsed sources, as long as the coherence time of the emission, $\Delta t_c$, is longer than the duration of the pump pulse (easily obtained when using ultrashort (fs) pulsed pump lasers), a single process of stimulated emission will take place giving an original photon number distribution (i.e. the distribution before the heralding) which is thermal. In contrast, when a CW pump laser is used, as long as $\Delta t_c$ is much shorter than the gate-period of the detector, a large number of mutually incoherent SPDC processes will be present, each thermally distributed in photon number, but collectively giving a Poisson distribution. Hence, we have different original distributions which can then be altered by the heralding. This gives the opportunity to choose between the two cases depending on the needs and requirements of a specific application. The Poisson distribution obtained with a CW pump is suitable for single-qubit applications like, e.g., quantum cryptography where it is essential for security to have few multiphoton events, while a single thermal distribution is needed in multiqubit applications, where different qubits need to be in the same temporal single-mode for interference-effects to take place. The latter property is important for the realization of logic gates for qubits.

In this paper, we analyze heralded single photon sources, giving an experimental method to characterize...
HPS in order to determine photon rates and fiber coupling efficiencies, with the goal to fill the empty space between theory and experiments. We describe in detail how to determine relevant fiber coupling efficiencies and photon rates from experimentally measured quantities such as detected photon rates, detector efficiencies, dark counts etc., factors all affecting the performance of the source. We give a straightforward scheme to determine coupling efficiencies from experimental data not only for HPS, but for other fiber-coupled downconversion sources as well. We compare the use of a CW pump and a pulsed pump in HPS. The temporal selection made by conditional gating applied to one of the photons in a photon pair emitted from a continuously pumped SPDC process modifies the photon number statistics. By determining the autocorrelation value \( g^{(2)}(0) \) of the heralded photon from the coupling efficiencies and photon rates we show that either super-Poissonian, Poissonian, or sub-Poissonian behavior can be obtained depending on the chosen gate-period of the detector and the heralding rate. In addition to lowering the probability of empty gates (corresponding to pulses), the probability for more than one photon occupying a gate, can now also be decreased by using a shorter gate-period.

Following this analysis, we report the experimental results of a source of heralded single-photons created by a quasi-phase-matched nonlinear crystal made of periodically poled potassium titanyl phosphate (KTiOPO\(_4\)). The heralded photons have a wavelength of 1550 nm, which makes them suitable for transmission in an optical telecommunication fiber, and the heralding photons have a wavelength of 810 nm, suitable for efficient detection. To characterize the source we use the second-order autocorrelation function, which we derive formulas for in terms of singles rates, coincidence rates, and coupling parameters, assuming that the original photon distribution is Poissonian. In this way we are able to determine the autocorrelation function at zero time-delay without needing to perform a Hanbury-Brown and Twiss correlation experiment \[22\], which is not a straightforward task for a heralded and gated source \[9\].

The paper is organized as follows. In Sec. II we take a theoretical viewpoint and investigate the prospects for generating heralded single photons using the photon-pairs created by a CW laser in a nonlinear crystal. In Sec. III we describe the principal setup of the source and define the coupling parameters. We also show how these parameters are determined from the detected and derived photon rates. Section IV discusses the autocorrelation function and other measures to quantify the source in terms of system parameters. The result of the experiment is presented in Sec. V and we round off with some conclusions and discussion in Sec. VI.

![FIG. 1: Outline of a heralded single photon source. The autocorrelation function \( g^{(2)}(\tau) \) can be measured using a Hanbury-Brown and Twiss experiment \[22\] measuring the second-order cross-correlation function using two detectors \((D_1, D_2)\) behind a beamsplitter, see Fig. 1. The true and continuous autocorrelation function is found in the limit of infinitely short detector gate-periods, \( \Delta t_{\text{gate}} \to 0 \), for different time-delays \( \tau = t_1 - t_2 \), assuming a wide sense stationary and ergodic source of light. In terms of probabilities of photon counts, the autocorrelation function is given by

\[
\mathcal{g}^{(2)}(\tau) = \frac{2P_{m\geq2}(\tau)}{P_{m\geq1}(\tau)},
\]

where \( P_{m\geq k} \) is the probability to find \( k \) or more photons within the detector gate-period. The factor 2 in Eq. (1) origins from the fact that the probabilities are normalized to attain the maximum value of unity, which is not the case when \( g^{(2)}(\tau) \) is written in the standard form using the intensity of the light.

Using a single detector, \( D_1 \), it is clear that as \( \tau \to 0 \), the probability for a photon in the idler will be large conditioned on a photon in the signal, and that the probability of an empty gate is very small, or even zero, if the probability that the idler photon makes it from the source to the detector is unity. If also the gate-period, \( \Delta t_{\text{gate}} \), is made short, the probability of two or more photons
within the gate becomes small as a result of the Poisson distribution in the number of photons arriving. Hence, by gating in the temporal mode we hereby sub-select events to effectively change the original statistics. To quantify, we are interested in the autocorrelation function of the idler for \( \tau = 0 \),

\[
g^{(2)}(0) = \frac{2P_{m \geq 2}}{P^2_{m \geq 1}}. \quad (2)
\]

It is a well-known fact that for \( g^{(2)}(0) < 1 \) and \( g^{(2)}(\tau \neq 0) > g^{(2)}(0) \) we have antibunching, hence sub-Poisson statistics, and for \( g^{(2)}(0) > 1 \) and \( g^{(2)}(\tau \neq 0) < g^{(2)}(0) \) we have bunching, hence super-Poisson statistics.

We would like to characterize our source using this quantity, which is zero for perfect antibunching. Thus, we need to know the probabilities \( P_{m \geq 2} \) and \( P_{m \geq 1} \), which can be determined by assuming that the original distribution is Poisson (a valid assumption as long as \( \Delta t_c \ll \Delta t_{\text{gate}} \) as will be discussed later), and by measuring the mean rate of accidental photons per gate-period, \( b = \Delta t_{\text{gate}} \bar{R} \), where \( \bar{R} \) is the singles rate of accidental photons in counts per second. The rate of accidental photons, \( \bar{R} \), is simply the difference between the total rate and the rate of truly correlated photons. We make the assumption that on time scales longer than the coherence time of the photons they can be viewed as being independent, so that the correlated photons and the accidental photons obey different photon number distributions. (Please note that we use the term “original photon number distribution” for the distribution before heralding. This “original distribution” is then altered by the conditional gating resulting in the photon number distribution of the HSPS.) The probability for at least \( k \) photons to be present in the gate is given by

\[
P_{m \geq k} = P_{m \geq 1}^{\text{cor}} P_{n \geq k-1}^{\text{acc}} + (1 - P_{m \geq 1}^{\text{cor}}) P_{n \geq k}^{\text{acc}} \quad (3)
\]

where \( P_{m \geq 1}^{\text{cor}} \) is the probability that the “true” twin photon is present, and \( P_{n \geq k}^{\text{acc}} \) is the probability that at least \( k \) accidental photons are present. The former probability is unity for a perfect system, and the latter probability is given by

\[
P_{n \geq k}^{\text{acc}} = 1 - \sum_{j=0}^{k-1} e^{-b} b^j / j!, \quad (4)
\]

originating from the original Poisson distribution. Note that in Eq. (4) we do not care if we herald a truly correlated pair or an accidental, which can happen for lower than unity coupling efficiencies and transmission factors into the fibers. In Fig. 2 we have plotted Eq. (2) for different values of the parameter \( b_0 = \Delta t_{\text{gate}} R_0 \) (bottom x-axis), where \( R_0 \) is the heralding rate. The parameter \( b_0 \) is related to \( b \) of Eq. (4) via \( b = \Delta t_{\text{gate}} \bar{R} = \Delta t_{\text{gate}} (\bar{R} - P_{m \geq 1}^{\text{cor}} R_0) = \frac{b_0}{b_0 - b_{\text{cor}}} - P_{m \geq 1}^{\text{cor}} b_0 \), where the total rate \( \bar{R} \) is assumed to be the same for both signal and idler. It is clear from the graph that the statistics of the heralded photons can be either sub- or super-Poissonian. The statistics is Poissonian for an intermediate value \( b_0 = 0.55 \) for \( P_{m \geq 1}^{\text{cor}} = 1 \), and \( b_0 = 0.42 \) for \( P_{m \geq 1}^{\text{cor}} = 0.5 \), given as two examples. Sufficiently large values of \( b_0 \) will always give “bunched” light in the sense that there will always be more than one photon present within the gate-period. For two uncorrelated events that are each Poisson distributed, the \( g^{(2)}(0) \) value follows instead the dashed line implying that such a source remains Poissonian for short gate-periods or low photon flux, as opposed to a HSPS. The expression for \( g^{(2)}(0) \) for a CW pumped HSPS with \( P_{m \geq 1}^{\text{cor}} = 1 \) becomes

\[
g^{(2)}(0) = 2[1 - e^{-b}]. \quad (5)
\]

In order to compare the CW and the pulsed case, \( g^{(2)}(0) \) is also plotted as a function of the heralding rate \( R_0 \) (top x-axis). The solid line then shows \( g^{(2)}(0) \) for a CW source with a fixed gate-period \( \Delta t_{\text{gate}} = 10 \) ns, and the dash-dotted line is for a pulsed source with pulse repetition rate of \( 1/\Delta t_{\text{gate}} = 100 \) MHz. As seen, \( g^{(2)}(0) \) is higher for a pulsed source than for a CW source in the sub-Poisson region, making it more suitable to use a CW pump than a pulsed for HSPS. However, this is for the ideal case of perfect coupling efficiencies with \( P_{m \geq 1}^{\text{cor}} = 1 \), but in any real experimental situation the two choices are practically equivalent as will be discussed later. It should be noted that the plotted result is for a pulsed...
source with an original thermal photon number distribution. The original distribution will be thermal as long as the coherence time of the emission is longer than the duration of a pump pulse, $\Delta t > \Delta t_p$, since there is then a single coherent SPDC process present. This situation is rather easily achieved by short-pulsed lasers and narrow bandpass filters for the emission, or alternatively, with long downconversion crystals to increase the coherence length. If $\Delta t_c < \Delta t_p$ but $\Delta t_c > \Delta t_{\text{gate}}$, we still have the same situation, but now with the gate-period as the limiting factor, selecting photons originating from a single process. However, this situation is rather unrealistic using pulsed lasers, since it requires $\Delta t_{\text{gate}} \ll \Delta t_p$. If instead $\Delta t_c \ll \Delta t_p$ and $\Delta t_c \ll \Delta t_{\text{gate}}$, there will be a large collection of processes, all individually with a thermal distribution. Hence, even for a pulsed source it is possible to have a Poisson original distribution, but here we only consider the thermal case when discussing pulsed sources. Correspondingly, for a CW source a thermal distribution is obtained when the coherence time is longer than the gate-period, $\Delta t_c > \Delta t_{\text{gate}}$, since then the photons within a gate originate from a single coherent SPDC process. However, here we only consider the case when $\Delta t_c \ll \Delta t_{\text{gate}}$, resulting in a large collection of SPDC processes collectively giving a Poisson distribution.

For an ideal single photon source, the overall mean photon number per gate-period, $\langle n \rangle = b + P_{\text{cor}}$, equals unity, which means that $b = 0$ and $P_{\text{cor}} = 1$, i.e. there are no accidental photons present and there is perfect correlation between signal and idler. In addition, the variance $(\Delta n^2)$ of the mean photon number should be zero, as quantified by $g^{(2)}(0) = 1 + \frac{(\Delta n^2)-\langle n \rangle}{\langle n \rangle^2}$, which motivates why $g^{(2)}(0)$ is a good qualitative measure of HSPS, if related to the parameter $b$.

Moreover, the probability for getting exactly $n$ photons within the gate can also be expressed by the above probabilities as

$$P(n) = P_{m \geq n} - P_{m \geq n+1}. \quad (6)$$

The probability $P(1)$ equals the parameter $\mu^{\text{her}}$ commonly used to characterize sources of single photons, i.e. the probability that exactly one single photon is heralded (ignoring if its a twin or an accidental for a non-perfect system).

III. COUPLING EFFICIENCIES AND PHOTON RATES

There are several different coupling efficiencies of interest in photon-pair sources. In this section we will define them and discuss their mutual relations in detail. For a schematic illustration of the different quantities see Fig. 3. All the coupling efficiencies are related to the bandwidth $\Delta \lambda$ of the light. The motivation for this is that the photons emitted from SPDC has in general a very wide bandwidth, and are preferably filtered before detection, either by bandpass filters $\Delta \lambda_{\text{BP}}$ or by the spectral filtering performed by the single-mode fibers $\Delta \lambda_{\text{SM}}$, such that $\Delta \lambda \leq \min(\Delta \lambda_{\text{BP}}, \Delta \lambda_{\text{SM}})$. The single-mode fiber filtering is an effect of the correlation between each wavevector’s spatial direction and frequency as determined by the phase-matching in the SPDC process. By normalizing to the bandwidth of interest we solely investigate how well photons within that bandwidth are collected into the fibers. Hence, as a natural consequence, with no spatial filtering the “coupling” is perfect, as, e.g., in the case of a free-space detector or a multimode fiber (essentially), with a frequency filter in front.

With this in mind, we denote the total number of photon-pairs generated within a given bandwidth $\Delta \lambda$, with $\Omega_p$, and normalize it to 1. This set will of course differ in size in the sense of absolute numbers of photon pairs, depending on the bandwidth of the chosen filter. The single coupling efficiencies for the signal, $\gamma_s$, and idler, $\gamma_i$, are the fraction of $\Omega_p$ that is coupled into the single-mode fibers, i.e. the probability to have a photon in the fiber which was emitted within the filter bandwidth $\Delta \lambda$. A high single coupling efficiency leads to a high photon rate, but does not guarantee a good quality heralded single-photon source. For that, a high pair coupling efficiency $\gamma_c$, and high conditional coincidences $\mu_{\text{ij}}$ and $\mu_{\text{is}}$ are required. The pair coupling efficiency denotes the amount of pairs where both photons are coupled into the two fibers, i.e. the degree of overlap between the two sets $\gamma_s$ and $\gamma_i$ in Fig. 3. It is important to note that in general $\gamma_c \neq \gamma_s \gamma_i$, and instead of only optimizing the single coupling efficiencies it is crucial to maximize the overlap, i.e. to couple the matching modes of the signal and idler into the fibers, in order to obtain a high pair coupling efficiency. The conditional coincidence is the probability to have a photon in the fiber given that the partner photon of the pair is in its fiber.

All of these coupling efficiencies can be determined from the measured photon rates and parameters of the experimental setup such as losses and detector efficien-
cies. Referring to Fig. 4 we denote by $R_p$ the total photon pair rate generated within the given bandwidth $\Delta \lambda$. The photon rates inside the single-mode fibers are $R_s$ and $R_i$ for the signal and idler respectively. They are related to the single coupling efficiencies by

$$\gamma_s = \frac{R_s}{\zeta \delta_s R_p}, \quad \gamma_i = \frac{R_i}{\delta_i R_p}, \quad (7)$$

where $\delta_s$ and $\delta_i$ are the total transmission factors for the signal and idler, resulting from the filter transmissions and reflection losses of all components between the crystal and the detectors. Thus, $\delta_s = \delta_i = 1$ corresponds to an ideal system with no losses present other than the fiber coupling. By weighting the coupling efficiencies by the transmission factors we obtain measures that solely describe how well the coupling into the fibers is performed. The factor $\zeta \leq 1$ compensates for the possibly unmatched bandwidths of the interference filters of the signal and idler. When $\zeta = 1$ the filter bandwidths match (the relation between signal and idler for our choice of wavelengths is $\Delta \lambda_s \zeta \approx 3.66 \times \Delta \lambda_i$) while $\zeta < 1$ represents a narrower filter used for the signal than for the idler.

At the end of the fibers we have single photon detectors with quantum efficiencies $\eta_s$ and $\eta_i$. The signal detector measure the single photon rate $r_s$. These detections serve as the trigger signal to the other detector. However, it is routed via a delay/pulse generator which in turn provides the gate-pulses for the idler detector. We call the gate-pulse rate the heralding rate, denoted $R_0$. This signal announces the presence of the heralded single photon. In principle $R_0$ should equal $r_s$, but in practice $R_0$ is lower because of the dead-time of the delay/pulse generator used. A heralding pulse gates the idler detector for a time $\Delta t_{gate}$ during which the idler photon is expected to arrive at the detector. From the idler detector we then obtain the measured heralded photon rate $r_i$. We also measure the accidental rate $r_1$ at the idler detector, i.e. the single photon rate at random gating, to provide the mean accidental photon number. Also dark count rates, $r^d_s$ and $r^d_i$, are measured for the two detectors, while after-pulsing effects of the 1550 nm detector are removed by an electrical hold-off circuit (10 $\mu$s).

In order to determine $R_p$, the photon rate for the signal is measured using a multimode fiber. This detected rate is denoted $r_p$, and $R_p$ is then found as

$$R_p = \frac{r_p \delta_p^{\text{corr}} - r^d_s}{\eta_s \zeta \delta_s}, \quad (8)$$

where $\delta_p^{\text{corr}}$ is the correction factor at rate $r_p$ for the signal detector, when compensating the detected rate for the Poissonian distribution of the arrivals of the photons (including the dead-time of the detector). The photon rate for the signal inside the single-mode fiber, $R_s$, is obtained in a similar way:

$$R_s = \frac{r_s \delta_s^{\text{corr}} - r^d_s}{\eta_s}, \quad (9)$$

The idler fiber photon rate, $R_i$, is calculated from the measured rate of accidental coincidences, $r_1$, i.e. the rate when the idler detector is randomly gated, using $r_1 = R_0 P_{\text{acc}}^{\text{click}}$, where

$$P_{\text{click}} = 1 - (1 - P_{\text{light}})(1 - P_{\text{dark}}), \quad (10)$$

is the probability of a detector-click during one gate-period caused by light or by dark count probabilities. Assuming a Poisson photon statistics within the gate, justified by a gate-period $\Delta t_{gate}$ much larger than the coherence time $\Delta t_c$ of the downconverted light, we have $P_{\text{light}} = 1 - \exp (-\eta_i \Delta t_{gate} R_i)$ and $P_{\text{dark}} = \Delta t_{gate} r^d_i / R_0$, leading to

$$R_i = \frac{1}{\eta_i \Delta t_{gate}} \ln \left( \frac{1 - r^d_i / R_0}{1 - r_1 / R_0} \right). \quad (11)$$

The pair coupling efficiency $\gamma_c$ is defined via the rate of correlated pairs inside the fibers $R_c$. This rate describes the amount of $R_p$ where both the photons of a pair have coupled into their respective fiber, giving

$$\gamma_c = \frac{R_c}{\zeta \delta_s \delta_i R_p}, \quad (12)$$

The correlated pair rate $R_c$ is determined from the measured heralded count rate $r_c = R_0 P_{\text{corr}}^{\text{click}}$, where

$$P_{\text{click}}^{\text{corr}} = 1 - (1 - P_{\text{corr}}^{\text{light}})(1 - P_{\text{acc}}^{\text{light}})(1 - P_{\text{dark}}), \quad (13)$$

once again is the probability of a detector-click during one gate, with $P_{\text{corr}}^{\text{light}} = \eta_i R_c / R_s$ as the probability to detect the "true" twin photon, and $P_{\text{acc}}^{\text{light}} = 1 - \exp (-\eta_i \Delta t_{gate} (R_i - R_c R_0 / R_s))$ as the probability to detect an accidental photon. The last minus term in the exponential excludes those events which are
counted as true coincidences. In terms of photon rates we obtain an implicit expression for $R_c$:

$$\frac{r_c}{R_0} = 1 - \left(1 - \frac{R_c}{R_s}\right) \left(1 - \frac{r_{id}}{R_0}\right) e^{-\eta \Delta t_{gate}(R_i - R_c/R_s)},$$  

(14)

which can be solved numerically.

Having determined all the photon rates, we can calculate the different coupling efficiencies from Eq. (7), Eq. (12), and

$$\mu_{ij} = \frac{R_c}{R_s}, \quad \mu_{i|j} = \frac{R_c}{R_i},$$  

(15)

altogether describing how well the fiber coupling is optimized in the experiment. Note that $P_{cor}$ introduced in Sec. III equals $\mu_{ij}$. The conditional coincidences in Eq. (15) are the probabilities of having the “true” twin photon present, a property which is important when using downconversion sources to create entanglement. For a HSPS however, the significant quantity is $\mu_{her} = P(1)$; the probability to herald exactly one photon, as determined by Eq. 9. This procedure to determine rates and coupling efficiencies is not only relevant for heralded single-photon sources, but is applicable to other fiber-coupled downconversion sources as well [16, 23].

IV. HERALDED SINGLE- AND MULTIPHOTON PROBABILITIES

As discussed in Sec. III, the characterizing quantities for a heralded single-photon source are the probabilities of the photon statistics. We will in this section relate these probabilities to the various photon rates and coupling efficiencies presented in Sec. III.

To obtain the $g^{(2)}(0)$-value for the source we need to determine the probabilities $P_{m \geq 1}$ and $P_{m \geq 2}$ according to Eq. (2). Using Eqs. (3) and (4), expressed in terms of photon rates these probabilities are found to be

$$P_{m \geq 1} = 1 - \left(1 - \frac{R_c}{R_s}\right) e^{-b},$$  

(16)

$$P_{m \geq 2} = 1 - \left[1 + \left(1 - \frac{R_c}{R_s}\right) b\right] e^{-b},$$  

(17)

where $b = \Delta t_{gate}(R_i - R_c/R_s)$. Inserting this into the expression for $g^{(2)}(0)$, Eq. (2), we obtain

$$g^{(2)}(0) = \frac{2\left[1 + \left(1 - \frac{R_c}{R_s}\right) b\right] e^{-b}}{\left[1 - \left(1 - \frac{R_c}{R_s}\right) e^{-b}\right]^2}. $$  

(18)

A good approximation for small $b$ is

$$g^{(2)}(0) \approx 2(1 - e^{-bR_s/R_c}) \approx \frac{2bR_s}{R_c}.$$  

(19)

for a non-ideal source with $P_{cor} = R_c/R_s$, in contrast to Eq. (20), for which $P_{cor} = 1$. Rewriting $g^{(2)}(0)$ using the coupling efficiencies in Eq. (7) and Eq. (12) we get

$$g^{(2)}(0) \approx 2\Delta t_{gate}\left(\frac{\gamma_s\gamma_i}{\gamma_c} R_p - R_0\right).$$  

(20)

For an ideal antibunched source $g^{(2)}(0) = 0$, so we want the value to be as small as possible. As seen from Eq. (20), $g^{(2)}(0)$ can be made smaller by decreasing the number of generated photon pairs $R_p$, i.e. by simply lowering the pump power. However, for a single photon source to be useful for applications, high photon rates are in general desirable, so this does not seem like a sensible way to improve the performance of the source. We also conclude that a decrease of the single coupling efficiencies, $\gamma_s$ and $\gamma_i$, and an increase of the pair coupling, $\gamma_c$, both lower $g^{(2)}(0)$. Since $\gamma_c \leq \min(\gamma_s, \gamma_i)$, the optimum is to have all three equal, but as small as possible. Again however, this leads to undesirably low photon rates. Decreasing the gate-period $\Delta t_{gate}$ is also a possibility, and this seems like a more natural way to enhance the performance since it essentially does not affect the photon rates. Yet, $\Delta t_{gate}$ must still be kept much longer than the coherence time of the downconverted photons in order to keep the above analysis valid by maintaining the original photon number statistics to be Poissonian.

Using Eq. (9), Eq. (16) and Eq. (17) we find the expression for $\mu_{her} = P(1)$ to be

$$\mu_{her} = \left(1 - \frac{R_c}{R_s}\right) b + \frac{R_s}{R_c} e^{-b}. $$  

(21)

V. EXPERIMENTAL RESULTS

The experimental setup of the source is shown in Fig. 5. A CW laser at a wavelength of 532 nm pumps a 4.5 mm long periodically poled KTiOPO4 (PPKTP) bulk crystal. The crystal is poled with a period of 9.6 mm to assure collinear phase-matching for a signal and idler.
at 810 nm and 1550 nm, respectively. The pump’s polarization is controlled by a polarizing beam splitter, a half wave plate, and a quarter wave plate, before focusing the light onto the crystal with an achromatic doublet ($f_p = 50 \text{ mm}$). Directly after the crystal the pump light is blocked by a bandstop filter. The signal and idler emission are refocused by an achromatic doublet ($f_{si} = 30 \text{ mm}$) before split by a dichroic mirror, then collimated by two additional lenses ($f_s = 60 \text{ mm}$, $f_i = 40 \text{ mm}$), and finally focused into single-mode fiber by aspherical lenses ($f = 11 \text{ mm}$) following the predictions in [16]. In front of the signal fiber-coupler a Schott-RG715 filter is placed to block any remaining pump light, together with an interference filter with 2 nm bandwidth centered at 810 nm (all bandwidths are full-width half-maximum, FWHM). For the idler it suffices with a Schott-RG1000 filter to block the last residue of the pump, giving an estimated single-mode bandwidth of 15 nm for the accidental photons (set by the spatial filtering of the idler single-mode fiber) and 7 nm for the coincidence photons (set by the interference filter of the signal). The detectors used are a Si-based APD (PerkinElmer SPCM-AQR-14) for the 810 nm light with a quantum efficiency $\eta_s = 60\%$, and a homemade InGaAs-APD (Epitaxx) module for the 1550 nm light with $\eta_i = 18\%$. The detection of a 810 nm photon triggers the digital delay generator (DG535 from SRS), which, in turn, generates a gate-pulse for the 1550 nm detector.

We measured the singles- and heralded photon rates for different pump powers by varying it using neutral density filters. As expected, both singles, heralded, and accidental counts increase with the pump power, see Fig. 4. The pump power 1.2 mW was chosen for the subsequent measurements. Histograms of the heralded rate for different delays of the gate-signal can be seen in Fig. 7. The gate delay was moved within a 12 ns window for the two cases of gate-periods, $\Delta t_{\text{gate}}$, of 2 ns and 4 ns. We can observe that the heralded photons are well localized in time in both cases. The total number of heralded photons are lower for the 2 ns gate-period than for the 4 ns gate-period due to the finite rise time of the gate-pulse, and a lower excess gate voltage for shorter gate-periods, causing a decrease in the detector quantum efficiency.

We have optimized the fiber coupling with the goal of obtaining an as high conditional coincidence as possible, which did not correspond to the highest possible single coupling efficiencies. The resulting detected single counts rate for the signal was $r_s = 218 \times 10^3 \text{ s}^{-1}$ with the multimode fiber, and $r_s = 88 \times 10^3 \text{ s}^{-1}$ with the single-mode fiber. The latter rate resulted in a heralding rate $R_0 = 81 \times 10^3 \text{ s}^{-1}$, and a detected heralded rate $r_c = 7200 \text{ s}^{-1}$ for a gate-period $\Delta t_{\text{gate}} = 10 \text{ ns}$. Accidental coincidences, i.e. coincidences measured with random gating, was $r_l = 130 \text{ s}^{-1}$. The dark count for the signal detector was $r_d^s = 90 \text{ s}^{-1}$ and for the idler detector $r_d^i = 40 \text{ s}^{-1}$ at gate-rate $R_0$. The overall transmission factors in the signal and idler arm were $\delta_s = 54\%$ and $\delta_i = 63\%$, as determined by sending strong laser light at the corresponding frequency through the setup and measuring the loss. The 2 nm interference filter for the signal and no interference filter for the idler give $\zeta = 0.5$. With these measured photon rates and setup parameters the actual photon rates were calculated using the expressions in Sec. III obtaining a generated photon-pair rate $R_p = 1340 \times 10^3 \text{ s}^{-1}$, photon rates inside the single-mode fibers $R_s = 147 \times 10^3 \text{ s}^{-1}$, and $R_i = 615 \times 10^3 \text{ s}^{-1}$, and correlated pair rate inside the fibers $R_c = 71 \times 10^3 \text{ s}^{-1}$. This resulted in single coupling efficiencies $\gamma_s = 40\%$ and $\gamma_i = 71\%$, pair coupling efficiency $\gamma_c = 31\%$, and conditional coincidences $\mu_{ij}^c = 48\%$ and $\mu_{ji}^c = 12\%$.

With the calculated photon rates the heralded photon statistics was determined, see Fig. 8. The probability to have zero photons present within the gate-period was $P(0) = 0.514 \pm 0.003$, and the probability to have exactly one photon present was $P(1) = 0.483 \pm 0.003$. 

![FIG. 6: (Color online) The singles rate of signal and idler, both in free-running mode (left axis). The idler’s rate in counts per second is derived from randomly gated mode, with a gate-period $\Delta t_{\text{gate}} = 10 \text{ ns}$, at a rate $R_i$. The right axis shows the total gated heralded rate $r_c$ and the derived accidental coincidence rate $r_{\text{acc}}$. Errors are all within the size of the data points in the graph.](image)

![FIG. 7: The rate of gated heralded photons, $r_c$, for different delays of the gate-signal at a heralding rate $R_0 = 65 \times 10^3 \text{ s}^{-1}$. The gate-period, $\Delta t_{\text{gate}}$, was in the left histogram 2 ns and in the right 4 ns.](image)
The probabilities for higher number of photons drop off rapidly, with $P_{m \geq 1} = 0.486 \pm 0.003$, and $P_{m \geq 2} = 0.0028 \pm 0.00002$, giving $g^{(2)}(0) = 0.0235 \pm 0.0005$. For the different pump powers in Fig. 6 $g^{(2)}(0)$ was also calculated, showing a growth with pump power via the $b_0$ parameter, see Fig. 9 in agreement with Eq. (20). We see that $g^{(2)}(0)$ decreases faster with decreasing $b_0$ for the ideal case (solid line), where $P^{\text{cor}} = 1$, than for the non-ideal case. The non-ideal CW case will in fact approach the pulsed case (illustrated by the lower dashed line in Fig. 2), making them practically equivalent in a real experimental situation. Indeed, the observation we have made is that the more advantageous behavior of the ideal CW case (in terms of correlation statistics) is cancelled as soon as the coupling efficiencies decrease even slightly below unity, thus rapidly reducing the CW case to the pulsed case.

VI. CONCLUSIONS AND DISCUSSION

In this paper we have made an analysis of an asynchronous heralded single-photon source in terms of photon rates, gate-periods, coupling efficiencies etc. We have determined the photon number statistics and found it to be highly sub-Poissonian. We have also calculated the autocorrelation $g^{(2)}(\tau = 0)$, and concluded that it is not a fully satisfactory measure for HSPS, since it can, for example, be improved by simply lowering the overall photon rate as also noted by [4]. Still, from a different aspect, we have noted that the autocorrelation at $\tau = 0$ is proportional to the variance of the mean photon number for a source both with or without losses, turning $g^{(2)}(0)$ into a rather good measure if related to the mean accidental photon number per gate $b$, which is affected by the rate and the gate-period.

When comparing synchronous and asynchronous HSPS, i.e. sources with pulsed and CW pump lasers, regarding photon number statistics, one finds that both setups can in principle give either thermal or Poissonian original distributions. For most practical cases, a CW source gives a Poisson distribution, while a pulsed source gives a thermal distribution. By selecting temporal modes (events) from the original distributions by conditional gating, the photon number distribution can be further altered to show sub-Poisson statistics, effectively decreasing both the probability of a falsely heralded single photon, and suppressing the probability of multiphoton events. Depending on the original photon number distribution, the autocorrelation shows different behaviors, giving in the ideal case of perfect coupling efficiencies a better result for the Poisson distribution. However, in a real experimental situation the two cases are practically equivalent. In our experiment there is a probability of false heralding events of 52%, but in contrast to weak coherent pulses it is primarily of an experimental challenge to lower the fraction of such events by increasing the coupling efficiencies or the transmission factors, and of no fundamental problem.

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