Experimental implementation of a single-photon source based on SPDC

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An experimental setup towards a single-photon light source is reported. Using the characteristics of type-II colinear spontaneous parametric down conversion, the presented setup achieves a trigger-signal mechanism with count rates of up to 6,000 photons per second at a common wavelength of 818 nm. As such, a thorough description of the implementation of optical apparatus like lenses and crystals is made in order to reproduce the mentioned light source. The final setup achieved a value of $g^{(2)}(0) = 0.17 \pm 0.06$.

I. INTRODUCTION AND STATE OF THE ART

A single-photon source (SPS) is by definition a source of single, indivisible light quanta. These sources have ambitious applications such as quantum cryptography [1] and detector calibration [2]. The problem with these light sources is their limited possibilities of production even with sophisticated technology. Moreover, two approaches to generate a SPS are useful for production and investigation purposes [3]. On one hand, the first approach type commonly found is called *on-demand*, where the user may set the production of a single-photon as the experiment needs it. On the other hand, a heralding approach accounts for sources that sporadically and spontaneously produce a single photon but the mechanism generates a secondary signal that announces that a photon was produced successfully.

Heralded single-photon sources are usually implemented using the process denominated as Spontaneous Parametric Down-Conversion (SPDC)[4]. In this process, an incident photon with frequency ω_p is destroyed to create a pair of photons conventionally called signal and idler. Furthermore, the energy and momentum of the system must be conserved during SPDC. The conservation laws associated to SPDC are called phase matching conditions and are given by

$$\hbar\omega_p = \hbar\omega_s + \hbar\omega_i \tag{1}$$
$$\bar{k}_p = \bar{k}_s + \bar{k}_i \,, \tag{2}$$

where the subscript p denotes the pump (incident) photon, and the generated photons are denoted as s, the signal photon and i, the idler photon. In this case, equation (1) addresses the energy conservation in terms of the frequency of the photons and equation (2) is the corresponding momentum conservation relation in terms of the momentum $\vec{k}$. As the phase matching conditions are fulfilled, the signal and idler photons are spatially and temporally correlated, which means that the probability of finding the idler photon in a given time and spatial mode depends on the modes of the signal photon.

Operationally, the way to achieve SPDC is by using a nonlinear crystal. Depending on the crystal and its orientation, different types of SPDC arise. For this SPS, SPDC type II is used. In this kind of SPDC the pair of photons have orthogonal polarization [5]. Moreover, type II SPDC produce a certain spatial distribution for the signal and idler photons as it is shown in figure 1.

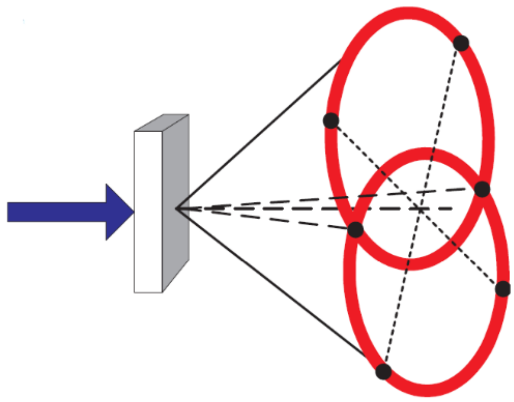

Figure 1. Light rings characteristic of Type-II SPDC. The circles are conformed of orthogonally polarized photons that follow equations 1 and 2. Taken from [5].

As mentioned, the pair of photons are also correlated in time. Therefore, it is possible to use SPDC to generate a heralded SPS. This correlation of the pair production of photons is characterized by a time difference near to femtoseconds [6], which means that the pair of photons are produced and detected in a very short time period. Due to this short window, it is possible to use one photon of the pair to herald or announce the presence of its correlated partner. Hence, in a detection system, if one photon is detected, the detection of its partner should be in a very short time difference . It is customary to call the photon that heralds the *trigger* photon and the announced photon as the heralded

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single-photon.

Thereafter, the way of identifying a heralded single photon is by measuring the second order correlation function $g^{(2)}(\tau)$ [7]. This function describes the intensity correlation of the source of light. It is measured by detecting in two locations and two instants with a time difference τ. Specifically, the $g^{(2)}(\tau)$ function is given by

$$g^2(\tau) = \frac{\langle \hat{E}_s^\dagger(t+\tau)\hat{E}_i^\dagger(t)\hat{E}_i(t)\hat{E}_s^\dagger(t+\tau)\rangle}{\langle \hat{E}_s^\dagger(t+\tau)\hat{E}_s(t+\tau)\rangle\langle \hat{E}_i^\dagger(t)\hat{E}_i(t)\rangle}, \quad (3)$$

where $\hat{E}_s$ and $\hat{E}_i$ are the positive frequency field operators. One can demonstrate that the $g^2(\tau)$ is proportional to the probability of measuring a coincidence between the signal and idler photon in a time difference τ, denoted as $P_{s,i}(\tau)$. Then, when $g^2(\tau)$ function is measuring correlated pairs of photons it is expected to get a bunched function [8]. On the other hand, the $g^2(\tau)$ can be extended for the heralded single-photon. In this case, it is convenient to study the $g^2(\tau)$ function in terms of the probability of having a coincidence in a time difference $\tau = 0$. Therefore, using an extra detector as trigger, the second order correlation function at $\tau = 0$ is conditioned to the trigger detection as follows:

$$g^{(2)}(0) = \frac{P_{A,B,C}(0)}{P_{A,B}(0)P_{A,C}(0)}, \quad (4)$$

where $P_{A,B,C}(0)$ is the number of threefold coincidence detections, and $P_{A,B}(0)$ and $P_{A,C}(0)$ are the probabilities of coincidence detection between detector-A and detectors B and C, respectively [7]. In this case, it is expected to have a $g^{(2)}(0) < 1$ since there cannot be 3 fold coincidences at $\tau = 0$ [4]. Even when theoretically this result should be zero, experimentally the delay time and response rates in the photon detector counters do not permit this ideal behaviour.

In this experimental report, an experimental setup is proposed and implemented, where a trigger photon dictates the existence of its photon pair that may be used on further experiments. The proposed setup uses SPDC to generate pairs. The $g^{(2)}$ function is measured for pairs in order to make an step towards the measurement of the $g^{(2)}$ of a heralded single-photon.

II. EXPERIMENTAL SETUP

In this section, the setup is presented in two different modules. In first place, the setup used in the preparation and measurement of correlated photon pairs is addressed. In second place, a modification in the detection system is presented in order to get the $g^{(2)}$ function of a heralded single-photon.

With the purpose of obtaining a replicable SPDC process, it is necessary to use a well characterized pump. Therefore, the wavelength and the spatial distribution of the pump are measured and adjusted. In this case, a laser diode with a maximum power of 150mW is used as pump. The laser diode has a temperature and current driver that allows to obtain a desired wavelength. For the experiment, it is used an operation current of 100mA, where the wavelength is centered at 409 nm at 14°C. On the other hand, an spatial filter is used to correct the spatial distribution of the pump that arrives into the BBO crystal. With this spatial filter, it is possible to create a well defined Gaussian beam as pump using a pinhole and two lenses (L1 and L2) shown in figures 2 and 3. Once the spatial distribution of the light is well defined, the mirrors M3 and M4 are in charge of carrying light in a straight path to the BBO crystal. After the spatial filter, the polarization state of the pump is set vertically using a polarizer (POL). Then, the pump beam arrives to the BBO crystal with 11mW. Finally, the SPDC process is achieved using a BBO crystal set to produce co-linear type II SPDC.

A. Two-photon $g^{(2)}$ function

Before measuring the $g^{(2)}$ of a single-photon source, it is necessary to ensure that the generation of the time correlated photon-pairs is successful. Therefore, a setup used to measure the $g^{(2)}$ function of the correlated pairs is presented in figure 2. In this figure, the pump beam after the BBO crystal is removed using two long pass filters with cut-off frequencies of 450 nm and 750 nm (FELH). Afterwards a polarizing beam splitter (PBS) is used to split the correlated photons with different polarization states. The light coming from the PBS is collected into a multimode fiber (MM) with the help of a fiber port collimator (FPC). Finally, the single photon counter modules (SPCM) produce a TTL signal when a photon arrives into the detector. All the electronic signals produced by the SPCM are registered in time using a time to digital converter (quTAU). With this setup it is expected to find a time correlation between the photons that arrive into the SPCM1 and SPCM2.

B. Heralded single-photon $g^{(2)}$ function

Once the $g^{(2)}$ function for the pair of photons is measured, it is possible to make a modification in the setup shown in figure 2 to obtain $g^{(2)}$ function for the heralded single-photon. The modification consist of adding a 50/50 beam splitter (BS) after the PBS as it is shown in figure 3. In this figure a band pass filter of 810±10 nm (FBP) is also added. With this band pass filter, only

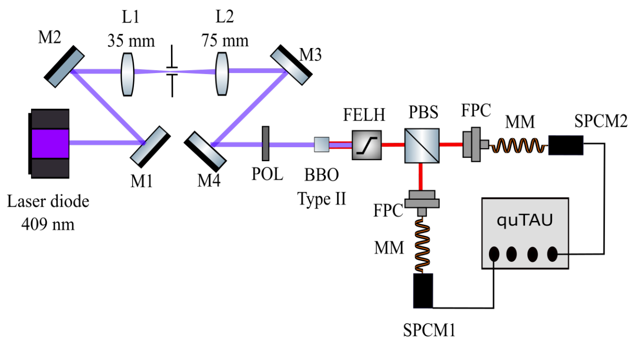

Figure 2. Final functional setup to measure the $g^{(2)}$ function of the correlated pairs. The correlated pairs are separated with the PBS and the resulting rays are directed to two independent SPCM.

the photons with a wavelengths between 800-820 nm can reach the detectors.In this setup, it is expected that there will be no coincidences between SPCM3 and SPCM2 when there is a detection in SPCM1.

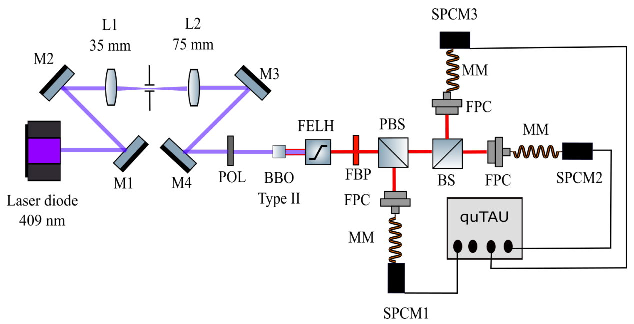

Figure 3. Complete experimental setup used for heralding single-photon validation step. An additional BS is placed after the PBS and the resulting rays are directed towards two independent SPCM.

III. RESULTS AND DISCUSSION

Throughout the implementation of the setup described in previous sections, validation steps had to be made to ensure the final functionality of the SPS. As such, the experiment had to be constantly measured, realigned and, therefore, validated. The initial validation process consists of constantly checking the alignment of the light source with the use of five reference pinholes. Besides this process, throughout the experiment four different preliminary results were achieved that ensured the final functionality of the SPS.

A. Light beam profile

Each step of the setup process presents itself with a measurable result. Initially, the first preliminary result obtained was the measurement of the light profile. The objective of this step was using the four mirrors and the L1 and L2 lenses to obtain a Gaussian profile of the pump beam. In figure 4 the achieved profile is presented.

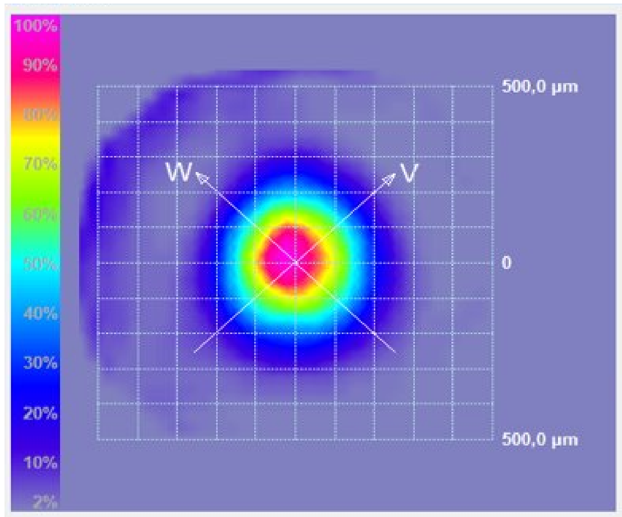

Figure 4. Pump beam with Gaussian-like profile in both W and V directions. Figure obtained using a BeamMaster module and software. Additionally, the diameter of the beam at the 80% maximum intensity frontier varies by 1% among the axis and by 3.6% at the 50% intensity frontier. In particular, the beam has a width of 600 μm at 20% maximum intensity.

B. SPDC confirmation and alignment

After the pump beam was aligned and led towards the non linear crystal, a CCD camera was placed in the path. This step is crucial to align the crystal into a type-II colinear setting. One of the key characteristics of BBO crystals is that their orientation dictates what type of SPDC is produced. Consequently, the crystal must be rotated to obtain type-II SPDC. When the crystal setting is correct, the two generated rings of opposite polarization photons must intersect at a single point. In figure 5 the optimal setting obtained is presented.

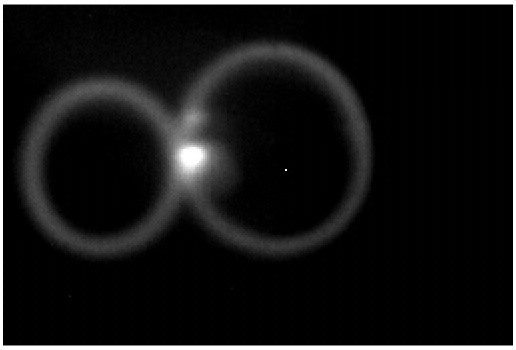

Figure 5. SPDC circles that resemble the ones observed in figure 1. The crystal is set so the circles intersect at a single point populated by pairs of entangled photons. One circle is bigger due to the camera placement.

C. Two fold correlation

The first of the validation steps involved the generation of $g^{(2)}(\tau)$ correlation functions for the setup shown in figure 2. Using this setup and taking advantage of the capabilities of the quTAU module, the $g^{(2)}$ correlation function between the two SPCM was generated using ≈500000 single photon counts per second in each SPCM and a 10% coincidence rate. Consequently, figure 6 was built with an acquisition time of 3 seconds.

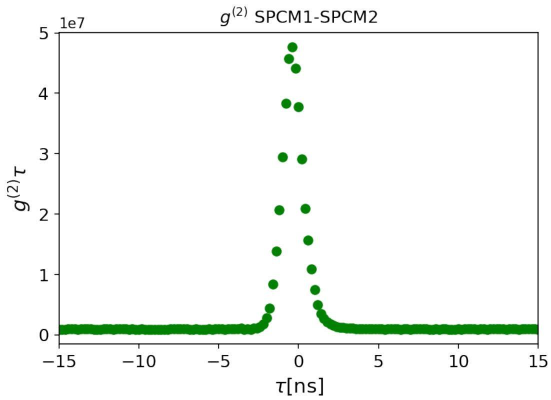

Figure 6. $g^{(2)}$ correlation function between SPCM1 and SPCM2 (figure 2). The peak in the middle of the figure indicates a high correlation between measurements at both sites. This is the expected behaviour as pairs generated through SPDC are expected to reach the counters at the same time (disregarding electronic delay).

D. Three fold correlation

Likewise, the second of the validation steps involved the generation of the two independent $g^{(2)}$ functions that show the correlation of SPCM2 and SPCM3 with SPCM1 (see figure 3). In this case, there were ≈20000 single counts per second in the SPCM1, ≈6000 singles counts per second in the other detectors and ≈30 coincidences per second between the SPCM1-SPCM2 and SPCM1-SPCM3. Accordingly, figure 7 shows both of the mentioned correlation functions constructed with an acquisition period of 8 seconds. As expected, both graphs show a peak close to the 0 delay-time mark.

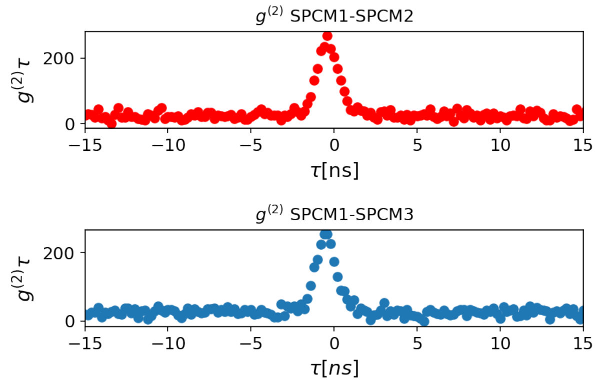

Figure 7. $g^{(2)}$ correlation function between SPCM1-SPCM2 and SPCM1-SPCM3 (figure 3). The peak in the middle of both figures indicates that the production of pairs is performed correctly in the three detector system used.

In order to measure the three-fold correlation function $g^{(2)(\tau)}$ a computational algorithm was developed using python3. For further information see [9]. In order to generate the mentioned function with this program, a higher count rate must be achieved. However, the value of $g^{(2)}(0)$ can be obtained. With a bin of 0.72 ns, the three fold correlation function at $\tau = 0$ was calculated using equation (4), obtaining a value of $g^{(2)}(0) = 0.17 \pm 0.06$. This value falls into the accepted theoretical values that indicate the anticorrelation between SPCM2 and SPCM3. Moreover, as the photons interacting with the BS (see figure 3) are indivisible, there should never be a coincidence in both detectors at the same time, therefore, it is possible to claim experimentally the existence of photons given that $g^{(2)}(0) < 1$. This value is not zero due to the electronic lag, detection efficiency and dark counts present in the SPCM.

IV. CONCLUSIONS

In this report, we implemented a heralding single-photon source to be used in subsequent experiments. Additionally, throughout the implementation of the setup a set of thorough validation processes were made which are crucial to ensure the functionality of the source. In particular, the quality achieved of the alignment of the optics, profiling of the pump beam, SPDC preparation and the generation of $g^{(2)}$ correlation functions were done to an experimental level for use in investigation or calibration. The SPS presented is capable of producing up to 6,000 heralded photons per second with a wavelength of 818 nm. It was found a $g^2(0)$ value of 0.17 ± 0.06 for the single photon source.

For future implementations, to further characterize the source used, a numerical approach should be developed to generate the $g^{(2)}(\tau)$ correlation function between SPCM2 and SPCM3. To achieve this, a higher rate of photon-pairs should be used in order to obtain more significant count rates in the three SPCM. Nevertheless, the setup is replicable and functional for use, for example, in the future characterization of the electronic devices used as well as in other projects.

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