Experimental Verification of Heralded Single Photon Generation by Second Order Degree of Coherence

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ABSTRACT— This paper describes the second-order coherence degree of photons produced in SPDC. First, the nonlinear BBO crystal generates the twin correlated signal and idler photons in the experimental setup. Then, g^2 (0) is obtained experimentally via Hanbury Brown-Twiss set-up for investigation of the light source nature. The results show this value is less than 1 which verifies the generated photons are in the heralded single photon (HSP) regime.

KEYWORDS: Spontaneous parametric down-conversion, Heralded Single Photon, Second-order degree of coherence.

I. INTRODUCTION

While the classical wave behaviors of light, such as interference and diffraction, have been observed in laboratories for many years [1], the explicit observation of the quantum nature of light (photons) is much more difficult. For example, well-known phenomena such as the photoelectric effect and Compton scattering show the presence of photons [2, 3]

From the quantum mechanics point of view, light has a wave-particle duality nature. In this article, an experiment is presented that clearly shows the quantum nature of light. This experiment is the experimental confirmation of the existence of particles called photons, which cannot be explained using the classical theory of light. One of these experiments was done by Grangier and his colleagues [4, 5]. The basic idea is that if a single photon meets a beam splitter, it can be detected only in the transmission port or the reflection port, not both ports. In other words, there are no photons in the transmission and reflection ports at the same time.

The frequency-entangled photon pairs can be generated by Spontaneous Parametric Down-Conversion (SPDC) using a nonlinear crystal [6-11]. The SPDC is a three-wave mixing process where a photon in a medium with $\chi^{(2)}$ nonlinearity can be down-converted into two photons under the constraint of energy and momentum conservation, commonly referred to as phase matching. The entangled photons generated by the SPDC process are correlated in energy, time, and momentum. This correlation is intimately related to energy uncertainty and emission time. For SPDC photon pairs, if we discard all the signal photons and only measure the emission of idler photons, thermal-state statistics is expected [12, 13]. Their energy is in the quantum regime and the biphoton waveforms exhibit non-classical behavior. Detection of one of the entangled photons announces the presence of its partner, which is called heralded single photons (HSP) [14, 15]. By removing the spatial and spectral correlations of the entanglement photons, one can obtain the HSP [16, 17]. Spatial and spectral filters are simple to implement experimentally, while is decreased the number of photons available. The proof of concept for a scheme to generate on-demand single photons via actively multiplexing several heralded photons probabilistically produced from pulsed SPDCs has been demonstrated [14].

Furthermore, to ensure that the source is operating in the single-photon regime, the heralded second-order correlation function $g^2(0)$ is measured by adding a 50/50 beam splitter into the signal arm [18]. In this article, an experiment has been designed, which is used to calculate a function called the degree of second-order coherence $g^2(0)$. So, the classical or quantum nature of the light source and operating in the single photon regime can be determined via $g^2(0)$. If the light source follows the classical theory, it will be $g^2(0) \geq 1$. According to the theory of quantum mechanics, the use of a non-classical light source violates this inequality and $g^2(0)$ less than one will be obtained. The relation is also established for ideal single photon sources as $g^{(2)}(0) = 0$.

II. THEORY

The theory behind the SPDC has been widely studied. It is based on the nonlinear interaction of some particular [17]

$$\left|\Psi_{PDC}\right\rangle = \left|0\right\rangle_s \left|0\right\rangle_i + \gamma \int d\omega_1 d\omega_2 f(\omega_1, \omega_2) \left|\omega_1\right\rangle_s \left|\omega_2\right\rangle_i, \qquad (1)$$

where s and i denote the signal and the idler photons, respectively. $f(\omega_1, \omega_2)$ is the joint spectral function (JSF) of the photon pairs representing the probability distribution associated with the signal and the idler frequencies. The JSF characterizes the two photons' state which depends on the phase-matching properties of the crystal and the spatial shape of the pump (including the degree of focusing). $|\gamma|^2$ is proportional to the rate of the photon-pair generation and characterizing the nonlinear interaction strength as $\gamma \propto \chi^{(2)} E_p E_s E_i$ where $\chi^{(2)}$ is proportional to the original tensor product susceptibility [19].

The states of the idler and signal are denoted by $\left|\omega_2\right\rangle_i$ and $\left|\omega_2\right\rangle_s$, respectively where $a^\dagger$ and $b^\dagger$ are the annihilation operators on the idler and the signal, respectively.

The JSF as a function of the signal and the idler frequencies are depicted in Fig. 1. The signal and the idler frequencies are related to the pump frequency as $\omega_p = \omega_s + \omega_i$. Here, the pump spectral amplitude is described by a Gaussian function centered at frequency ω_p, and the joint amplitude of the photon pairs is considered as [20].

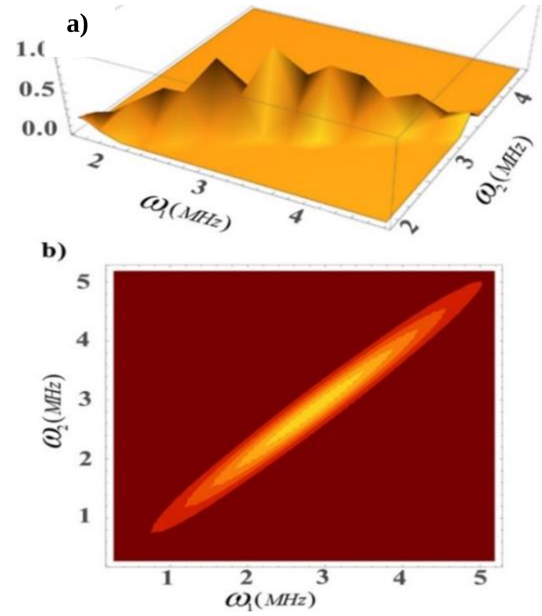

Fig. 1. The joint spectral function in free as a function of the signal (ω_1) and the idler (ω_2) frequencies (Hz): (a) 3D (b) 2D representations

$$f(\omega_i, \omega_s) = \frac{2}{\sqrt{\pi \sigma_1 \sigma_2}} e^{-\left(\frac{\omega_s - \omega_i}{\sigma_1}\right)^2} e^{-\left(\frac{\omega_s + \omega_i - 2\omega_p}{\sigma_2}\right)^2}, \qquad (2)$$

where σ_1 and σ_2 are the normalized bandwidth of the signal and idler frequencies, respectively.

In classical physics, electromagnetic waves are fully described by Maxwell's equations. For such a field, the correlation between the transmitted I_T intensity and the reflected I_R from the beam splitter is described by a second-order (temporal) degree of coherence $g^{(2)}_{T,R}(\tau)$, which is a function of the time delay between intensity measurements [20].

$$g^2_{T,R}(\tau) = \frac{\left\langle I_T(t+\tau) I_R(t) \right\rangle}{\left\langle I_T(t+\tau) \right\rangle \left\langle I_R(t) \right\rangle}, \qquad (3)$$

If the light source intensity is constant, that is, if its statistics do not change in time, the brackets can be interpreted as ensemble averages rather than temporal averages. The above relation represents the second-order degree of coherence because it involves the correlation between intensities, while the first-order degree of coherence describes the correlation between fields.

Assuming a 50/50 beam splitter where transmitted, reflected and input intensities are related as $I_T(t) = I_R(t) = \frac{1}{2} I_t(t)$. From Eq. 1 for simultaneous intensity measurement, τ=0, we will have [2]:

$$g_{T,R}^{2}(0) = \frac{\left\langle \left[I_I(t) \right]^2 \right\rangle}{\left\langle I_I(t) \right\rangle^2}, \tag{4}$$

From the Cauchy–Schwarz inequality, $\left\langle I_I(t) \right\rangle^2 \le \left\langle \left[I_I(t) \right]^2 \right\rangle$, it can be proved that and the conclusion can be drawn [2]:

$$g_{T,R}^{2}(0) \ge 1, \tag{5}$$

This result was obtained using classical wave theory. In Eq. 2, equality 1 is achieved when the input field is completely stable and without fluctuations (assuming an input field in a coherent state, one finds $g_{T,R}^{(2)}(0)$=1), and an input field in a thermal state (which is an incoherent mixture) one can find $g_{T,R}^{(2)}(0) > 1$. Such a field is said to be bunched.

In quantum theory, quantum mechanical operators are used to calculate the correlation between the output fields from the light splitter and the equation $g_{T,R}^{(2)}(\tau)$ is rewritten as follows [2]:

$$g_{T,R}^{2}(0) = \frac{\left\langle : \hat{n}_T \hat{n}_R : \right\rangle}{\left\langle \hat{n}_T \right\rangle \left\langle \hat{n}_R \right\rangle}, \tag{6}$$

The intensity operator is proportional to the photon number operator for the field $\hat{n} = \hat{a}^\dagger \hat{a}$, where $\hat{a}^\dagger$ and $\hat{a}$ are creation and annihilation operators. Using the below relationships [3]:

$$g_{T,R}^{2}(0) = \frac{\left\langle \hat{a}_T^\dagger \hat{a}_R^\dagger \hat{a}_R \hat{a}_T \right\rangle}{\left\langle \hat{a}_T^\dagger \hat{a}_T \right\rangle \left\langle \hat{a}_R^\dagger \hat{a}_R \right\rangle}, \tag{7}$$

where $\hat{a}_R = \frac{1}{\sqrt{2}} \left(\hat{a}_I + \hat{a}_V \right)$ and $\hat{a}_T = \frac{1}{\sqrt{2}} \left(\hat{a}_I - \hat{a}_V \right)$ are the output field operators after the beam splitter. Also, $\hat{a}_I$ and $\hat{a}_V$ are the incident field operators before the beam splitter. $g_{T,R}^{2}(\tau)$ can be rewritten as [2]:

$$g^{2}(0) = \frac{\left\langle \hat{n}_I (\hat{n}_I - 1) \right\rangle}{\left\langle \hat{n}_I \right\rangle^2}, \tag{8}$$

III. EXPERIMENTAL SETUP

The SPDC is used to produce correlated photon pairs, through which, by applying the non-collinear Type-I degenerate SPDC from a (5×5×0.5) mm BBO crystal pumped using 405 nm focused light (*f*=5 cm) from a CW diode laser with 120 mW power. The signal and idler photon pairs with a wavelength of 810 nm are produced. Before the crystal, the laser beam passes through a spatial filter, half-wave plate and two broadband (380-420 nm) high-reflective mirrors. The extra light especially 405 nm in the detectors is removed by the filters (with bandwidth 5 nm and 12 nm transmission centered at 810 nm). The transmitted entangled photons are focused on a four-channel single photon counting module (SPCM) (Excelitas:SPCMAQ4C; dark counts 351, 483, 156, and 146 cps (count per second) for channels A, B, C, and D, respectively, time resolution 600 ps, dead-time 50 ns and quantum efficiency about 28 at 810 nm) which is connected to a coincidence counting unit (using Altera-DE2 FPGA board with 7.1 ns coincidence window and adjustable acquisition time greater than 0.1 s) to detect the photon rate in the coincidences. To obtain the experimental efficiency of detectors we use $\eta_s = \frac{N_{cc}}{N_i}$ and $\eta_i = \frac{N_{cc}}{N_s}$ [4], where N_s, N_i and N_{cc} are the photon counts in the signal, idler arms, and the coincidence count rate, respectively. The detectors efficiency obtained as 25.7%±3.2%, 26.4%±2.2%, 26.1%±5.2% and 24.2%±3.4 which they are in agreements with the reported company value.

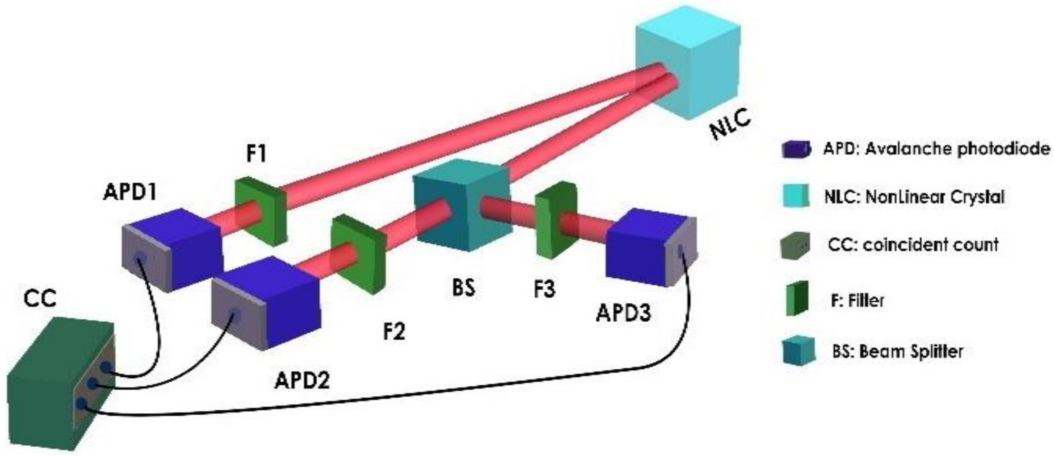

Fig. 2. Schematic arrangement of the laboratory related to measuring the degree of second-order coherence of photons produced by the SPDC process.

Since the two output arms of the SPDC process have some kind of quantum correlation, so each photon is in the energy superposition state and the total energy is fixed. Thus, measuring a photon in one arm guarantees the presence of a photon in the other arm. This source is called a heralded single photon source. The two output photons called twin photons even though their energies are not necessarily equal.

To ensure the source is operating in the HSP regime and quantify the operating parameter of the HSPs, the statistical properties of the generated photon pairs in the SPDC can be investigated in terms of the second-order coherence using three detectors. The second-order coherence degree is commonly evaluated with a Hanbury-Brown-Twiss (HBT) interferometer operating at the single-photon level or using two detectors placed at the outputs of a (50:50) beam splitter. The idler photon meets the detector 1 and the signal photon hits a beam splitter. Photon detection in detector 1 acts as a gate which announces the presence of a signal photon in the beam splitter.

Our source regularly produces singles count rates in the idler beams of 360 k cps, and total coincidence rates between the two arms of the beam splitter and idler beams of 30 k cps where the count rate of two arms of the beam splitter are 207 k cps and 117 k cps.

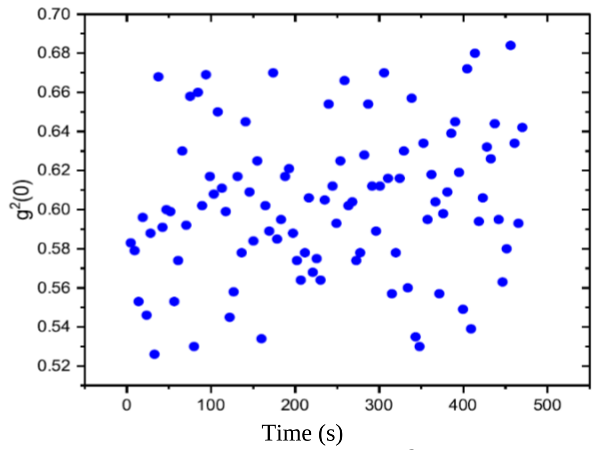

Fig. 3. The measured value of $g^2(0)$ in time.

In Fig. 2 the photon correlation set up in the HBT experiment is shown The signal photon that hits the beam splitter is either transferred to the passing detector2 or reflected to the detector3.

If N_1 is the number of photons that arrives the detector 1 in the acquisition time, N_{12} is the number of photons which arrives detectors 1 and 2 simultaneously (similarly defined as N_{13}), and N_{123} is the number of photons arrives three detectors simultaneously. Grangier and his colleagues showed that the classical optical field in the beam splitter must satisfy the following inequality [21]:

$$g^2_{Her}(0) = \frac{N_{123}N_1}{N_{12}N_{13}} \geq 1 . \quad (9)$$

The measurement of $g^2_{Her}(0)$ less than 1 indicates the light source is in the single photon regime and the biphoton nonclassical behavior [9].

It is noted that some corrections must be considered in our experiments. Apart from corrections from the optical path, corrections from dark count, accidental coincidence and dead time of detectors should be remarked. We decrease the dark counts from the raw data and consider the accidental coincidence and the dead time in our corrections, see Ref. [3].

The dead time of detectors, τ_{dead}, is correction that should be considered by substituting γN_i instead of N_i where, $\gamma = 1-(N_j \tau_{dead})/T$ is the dead time correction factor and $N_j (j = s, i)$ is photon count in the signal or idler arms. The γ-factor is evaluated around 0.9. The dead time of detector is around 50 ns.

Figure 3 shows the second order coherence function $g^2_{Her}(0)$ at the different time. The standard deviation value of these results is 0.057. The results show that the light source is not compatible with the classical wave theory.

The accidental coincidence, the average number of photons arrives the detectors in the coincidence interval purely by happenstance without any correlation, should be considered in the pair photon generation $\left(N_{acc} = \Delta t \dfrac{N_s N_i}{T}\right)$, where, Δt is the coincidence window (7.1 ns), and T is the acquisition time (0.3 ns). This value must be subtracted from the total number of the recorded coincidences to evaluate the degree of the entanglement. This leads to the modified (expected) value for $g^2_{Her}(0)$.

Here, $g^2_{Her}(0)$ with the effect of the contributions from the dark counts and all other noises of the photons and the accidental coincidence can be evaluated about 0.117 and the standard deviation is 0.027. The experimental value of $g^2_{Her}(0)$ is less than 1, which confirms the existence of a heralded single photon source [2, 22, 23]. This means one photon announces the arrival of the other. We compared our results to others. For example $g^2_{Her}(0)$ in our experiment is in agreement with those in [4], which $g^2_{Her}(0)$ is 0.0177+0.0026 [3].

IV. CONCLUSION

In this article, at first, a heralded single photon has been generated in the nonlinear process of spontaneous parametric down-conversion (SPDC). In this process the annihilation of a pump photon is accompanied by creation of two correlated photons. Then the degree of second-order coherence of the output photons has been obtained in the HBT experiment. The single-photon generation results are consistent with the quantum mechanical description of a field impinging on a beam splitter in a single-photon state. The results indicate the modified $g^2_{Her}(0)$ has a value smaller than1. This experimental result verifies the photons are in the quantum HSPs regime.

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REFERENCES

[1] R.W. Lucky, "Automatic equalization for digital communication," Bell Syst. Tech. J., Vol. 44, pp. 547–588, 1965.

[2] H. Sobhani, M. Khodabande, J.S. Nezamabadi, A. Dadahkhani, and S. Sarshar, "Generation and detection of optical vortices superposition by using interferometer setups," Laser Phys., Vol. 31, pp. 105202 (1-5), 2021.

[3] M. Beck, *Quantum mechanics: theory and experiment*, Oxford University Press, pp. 60-85, 2012.

[4] J.J. Thorn, M.S. Neel, V.W. Donato, G.S. Bergreen, R.E. Davies, and M. Beck, "Observing the quantum behavior of light in an undergraduate laboratory," Am. J. Phys., Vol. 72, pp. 1210-1219, 2004.

[5] G. Brida, M. Genovese, and C. Novero, "An application of two-photon entangled states to quantum metrology," J. Mod. Opt., Vol. 47, pp. 2099-2104, 2000.

[6] P. Grangier, G. Roger, and A. Aspect, "Experimental evidence for a photon anticorrelation effect on a beam splitter: a new light on single-photon interferences," SPIE milestone series, EuroPhys. Lett., Vol. 1, pp. 173-179, 1986.

[7] A. Motazedifard, S. A. Madani, and N.S. Vayaghan, "Measurement of entropy and quantum coherence properties of two type-I entangled photonic qubits," Opt. Quantum Electron., Vol. 53, pp. 1-26, 2021.

[8] A. Motazedifard, S.A. Madani, J.J. Dashkasan, and N.S. Vayaghan, "Nonlocal realism tests and quantum state tomography in Sagnac-based type-II polarization-entanglement SPDC-source," Heliyon, Vol. 7, pp. e07384 (1-8), 2021.

[9] A. Motazedifard and S.A. Madani, "High-precision quantum transmittometry of DNA and methylene-blue using a frequency-entangled twin-photon beam in type-I SPDC," OSA Continuum, Vol. 4, pp. 1049-1069, 2021.

[10] C. Couteau, "Spontaneous parametric down-conversion," Contemp. Phys., Vol. 59, pp. 1-15, 2018.

[11] Y. Peng, Y. Qiao, T. Xiang, and X. Chen, "Manipulation of the spontaneous parametric down-conversion process in space and frequency domains via wavefront shaping," Opt. Lett., Vol. 43, pp. 3985-3988, 2018.

[12] P.S. Kuo, T. Gerrits, V. Verma, S.W. Nam, O. Slattery, L. Ma, and X. Tang, "Characterization of type-II spontaneous parametric down-conversion in domain-engineered PPLN," Adv. Opt. Photonics Quantum Computing, Memory, Commun., Vol. 9762, pp. 108-116, 2016.

[13] X. Guo, C.L. Zou, C. Schuck, H. Jung , R. Cheng, and H.X. Tang, "Parametric down-conversion photon-pair source on a nanophotonic chip," Sci. Appl., Vol. 6, pp. e16249 (1-8), 2017.

[14] B. Blauensteiner, I. Herbauts, S. Bettelli, A. Poppe, and H. Hübel, "Photon bunching in parametric down-conversion with continuous-wave excitation," Phys. Rev. A, Vol. 79, pp. 063846 (1-6), 2009.

[15] X.S. Ma, S. Zotter, J. Kofler, T. Jennewein, and A. Zeilinger, "Experimental generation of single photons via active multiplexing," Phys. Rev. A, Vol. 73, pp. 043814 (1-8), 2011.

[16] Li, Jiamin, Su . Jie, Cui. Liang, Xie. Tianqi, Z. Y. Ou, and Li, Xiaoying "Generation of pure-state single photons with high heralding efficiency by using a three-stage nonlinear interferometer," Appl. Phys. Lett., Vol. 116, pp. 204002 (1-6), 2020.

[17] J. Flórez, O. Calderón, , A. Valencia, and C.I. Osorio, "Correlation control for pure and efficiently generated heralded single photons," Phys. Rev. A, Vol. 91, pp. 013819 (1-7), 2015.

[18] H. Lotfipour, H. Sobhani, and M. Khodabandeh, "Quantum diagnosis of cancer with heralded single photons," Laser Phys. Lett., Vol. 19, pp. 105603 (1-6), 2022.

[19] K. Guo, E.N. Christensen, J.B. Christensen, J.G. Koefoed, D. Bacco, Y. Ding, H. Ou, and K. Rottwitt, "High coincidence-to-accidental ratio continuous-wave photon-pair generation in a grating-coupled silicon strip waveguide," Appl. Phys. Express, Vol. 10, pp. 062801 (1-5), 2017.

[20] Z.-Y.J. Ou, *Multi-photon quantum interference*, Springer, Vol. 43, 2007.

[21] K. Zielnicki, K. Garay-Palmett, D. Cruz-Delgado, H. Cruz-Ramirez, M.F. O'Boyle, B. Fang, V.O. Lorenz, A.B. U'Ren, and P.G. Kwiat, "Joint spectral characterization of photon-pair sources," J. Mod. Opt., Vol. 65, pp. 1141-1160, 2018.

[22] N. Lal, A. Banerji, A. Biswas, A. Anwar, and R.P. Singh, "Single photon sources with different spatial modes," arXiv preprint arXiv:1905.01089 (1-7), 2019.

[23] B.J. Pearson and D.P. Jackson, "A hands-on introduction to single photons and quantum mechanics for undergraduates," Am. J. Phys., Vol. 78, pp. 471-484, 2010.

[24] E. Bocquillon, C. Couteau, M. Razavi, R. Laflamme, and G. Weihs, "Coherence measures for heralded single-photon sources," Phys. Rev. A, Vol.79, pp. 035801(1-4), 2009.

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