Simple direct measurement of nonclassical joint signal-idler photon-number statistics and correlation area of twin photon beams

Ondřej Haderka§, Jan Peřina, Jr., and Martin Hamar
Joint Laboratory of Optics of Palacký University and Institute of Physics of Academy of Sciences of the Czech Republic, Av. 17. listopadu 50A, 772 00 Olomouc, Czech Republic

Abstract. The measurement of joint signal-idler photon-number distribution of a field obtained from spontaneous parametric downconversion using an intensified CCD camera is presented. It is shown that a classicality criterion is violated directly by the measured data. Characteristic dimensions of the area of correlation are determined in the same experimental setup.

PACS numbers: 42.65.Lm, 42.50Dv, 42-50.Ar, 42.50.Xa

Submitted to: J. Opt. B: Quantum Semiclass. Opt.

§ To whom correspondence should be addressed (haderka@sloup.upol.cz)
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1. Introduction

In recent years an enormous number of applications of correlated photon pairs obtained by the process of spontaneous parametric down-conversion has emerged. Such photon pairs are quantum correlated in various quantities including photon number, position, momentum, energy, polarization, angular orbital momentum etc. These correlations are responsible for highly nonclassical properties of the generated light fields that enabled to successfully test the fundamental rules of quantum theory (see, e.g., [1] for a review) as well as to co-found a whole new field of quantum communications. Quantum key distribution (see, e.g., [2] for a review), teleportation [3], dense coding [4], or entanglement-swapping [3, 5], among others, are now well established methods that make use of nonclassical correlations between the signal and idler photons.

While the process of spontaneous parametric down-conversion (SPDC) itself has been thoroughly studied for many years [6, 7, 8], still new approaches to the characterization of the correlations are being developed. The first experiments to obtain correlated photon pairs used bulk nonlinear crystals pumped by cw ion lasers [9] (omitting pioneering approach based on resonant fluorescence [10]). Since efficiency of the process is quite low, the mean number of pairs per detection interval has always been much lower than one. Despite the fact that the real photon-number distribution of photon pairs is Poissonian (Bose-Einstein) in multi-mode case (single-mode case), the output state could be described as a superposition of vacuum and one-pair state due to a low mean photon number. The idea of using SPDC for a probabilistic source of single-photon states [11] emerged from this form of the output state. Availability of ultrafast tunable pulsed lasers was welcomed by the researchers as it enabled to produce down-converted pairs synchronized in time and also with the detection equipment, as well as to achieve considerably higher mean photon numbers in a time window given by a pump-pulse duration time. Also development of new materials featuring several orders of magnitude higher nonlinear efficiencies [12] in comparison with bulk crystals contributed in the same direction. Nowadays even SPDC sources pumped by laser diodes are available [13].

On the other hand, the analysis of photon-number statistics of the down-converted fields is not a simple task because traditional detectors offer only single-photon sensitivity — photomultipliers or avalanche photodiodes do not usually yield an information about the number of photons detected in a detection interval owing to a large noise introduced in the signal amplification process. They work just as trigger detectors announcing an impingement of some light quanta. Recently there has been devoted a great deal of interest to overcome this limitation. Two main classes of approaches in construction of photon-number resolving devices have been developed.

The first class relies on getting the amplification process under better control. This is possible using special detection structures cooled down to low temperatures. Two approaches seem currently the most promising. A visible light photon-counter (VLPC) [14] can resolve small photon numbers in the visible light range with a very high quantum efficiency at temperatures of 6-7K but it shows a quite high dark-count noise. A superconducting transition-edge sensor micro-calorimeter [15] on the other hand has a low noise and covers a wider spectral range but its quantum efficiency is currently lower. It also requires sub-1K temperatures. While development of these devices undergoes a rapid progress they are still quite demanding in operation.

The second class of devices is based on a beam division and it makes use of the fact that photons in the state to be analyzed behave independently on a beam-
splitter. When the number of paths offered to a photon is much larger than the number of all photons, each photon takes a different route with a high probability and can be detected alone with a trigger detector. The total number of trigger detections then yields an information about the number of photons [16]. While many-detector devices are impractical, several configurations using only one or two trigger detectors have been devised and constructed [17, 18, 19, 20, 21, 22] utilizing fiber delay-loops to translate different spatial paths into a time-multiplexed signal. Still, the number of photons to be analyzed by these devices is limited by the available number of time-multiplexed channels to rather low photon numbers. In our previous publication [23] we have used a different device for the measurement of photon-number statistics of photon pairs — an intensified CCD camera (iCCD). iCCD can be seen as a massively multichannel device where each pixel serves as a trigger detector with single-photon sensitivity. Since the total detection efficiency in our previous experiment was quite low, we have used reconstruction methods based on an expectation-maximization algorithm to get the field emerging from the process of SPDC and to show its nonclassical character (a new non-classicality criterion has been introduced).

In this paper we show that with an improved detection efficiency the classicality criterion is violated even directly by the measured data. In addition, we employ the spatial resolution provided by the iCCD to measure directly the area of correlation of the twin photon beams. We note that an iCCD camera has been used for the measurement of spatial correlations in SPDC in a different experimental configuration previously [24] and scientific CCD cameras have been applied for the analysis of strong down-converted fields in [25, 26]. Measurement of the photon-number statistics in a summed signal-idler collinear beam has also been accomplished using a VLPC detector [27].

2. Experimental setup

To measure the joint signal-idler photon-number distribution, we use a simple experimental setup. Photon pairs are generated by a type-I SPDC process in a 5 mm long LiIO\(_3\) bulk nonlinear crystal. Using 400 nm pumping, wavelength-degenerate pairs are generated at a cone-layer with a vertex angle of 31 deg behind the crystal (see Figure 1).

In our experimental arrangement, we let one part of the cone layer to impinge directly on the photocathode of the iCCD camera while the opposite part of the cone layer is reflected on a mirror placed very close to the crystal to minimize path difference. The width of the cone layer is determined by filtering both beams using a 20 nm (FWHM) wide interference filter, thus accepting slightly nondegenerate pairs as well. Two additional edge filters (high-pass above 750 nm) are used to remove the majority of laboratory stray light, scattered pump beam and fluorescence from the crystal.

The pump beam is obtained as second-harmonic of a femtosecond train of pulses from an amplified Ti:sapphire laser (Coherent Mira/RegA). The pulses are 200 fs long and their repetition rate is determined by the amplifier and set to 11 kHz in our case. Their second-harmonic is produced in a 2-mm long BBO crystal and pulses of energy up to 1.3 \(\mu\)J are obtained. This is sufficient to generate several thousands of pairs to all spatial modes accepted by the interference filter; we therefore attenuate the pumping beam using a variable attenuator.

In the software of the camera, three regions of interest are defined, two for the
Figure 1. Degenerate ($\Lambda_s = \Lambda_i$) photon pairs occur at opposite points of a cone layer behind the crystal. There is a certain spread in the position (given by $\Delta \theta_i, \Delta \phi_i$) occupied by an idler photon being correlated with a signal photon detected at $\theta_s, \phi_s$. This spread depends on a number of quantities including pump pulse width, duration, spectrum, beam shape and crystal properties.

Figure 2. Scheme of the experiment. The iCCD camera is placed further from the crystal in reality than in the scheme. The inset shows an accumulated image from the iCCD camera after the exposure of 240,000 frames. Signal and idler strips and a third one that serves for monitoring the noise level (see inset in Figure 2). Frames of the camera are transferred one-by-one to a PC that performs image processing based on double thresholding and centroid-finding and counts photon detections in all three detection strips. The maximum overall quantum efficiency of the iCCD camera has been found to be about 14%. Total detection efficiency including filters, mirror, and crystal output face has been estimated to reach approximately 7%.
3. A direct measurement of the nonclassical character of joint signal-idler photon-number distribution

In our previous publication [23] we have shown that even though the marginal signal (idler) distributions are almost Poissonian, as it should be for a multimode SPDC, the joint signal-idler photon-number distribution \( f(c_S, c_I) \) shows correlations in photon numbers. These correlations have been observed (i) by comparing the measured \( f(c_S, c_I) \) with that one obtained as a direct product of the marginal distributions (as if they were independent) and (ii) by computing the correlation coefficient \( C_p \),

\[
C_p = \frac{\langle \Delta n_S \Delta n_I \rangle}{\sqrt{\langle (\Delta n_S)^2 \rangle \langle (\Delta n_I)^2 \rangle}}, \quad \Delta n_i = n_i - \langle n_i \rangle, \quad i = S, I,
\]

that reached the value of 0.0435 ± 0.008. We have also introduced the following inequality:

\[
p(n_S, n_I) \leq \frac{n_S^n}{n_S!} \exp(-n_S) \frac{n_I^{n_I}}{n_I!} \exp(-n_I),
\]

that must be fulfilled by any photon-number distribution \( p(n_S, n_I) \) originating in a classical field [28, 29]. This classicality criterion can be readily obtained starting from a photodetection equation [30] for \( p(n_S, n_I) \) and assuming a nonnegative distribution function of integrated intensities. Mainly due to a low detection efficiency we were not able to show a violation of this inequality by the measured photon-number distribution \( f(c_S, c_I) \). We have shown, however, that the reconstructed photon-number distribution \( p(n_S, n_I) \) at the output plane of the crystal shows the maximum violation of the criterion (2) by 49.2 standard deviations.

With the improvement of detection efficiency we can demonstrate violation of the criterion in Eq. (2) directly using the measured data. Figure 3 shows the difference between the measured joint signal-idler photon-number distribution \( f(n_S, n_I) \) and the calculated joint signal-idler photon-number distribution given by a direct product of the signal and idler marginal distributions. We can see in Fig. 3 that elements lying on
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Figure 4. Definition of the area of correlation in the detection plane of the iCCD camera.

a diagonal or near the diagonal are enhanced whereas those lying far from the diagonal are suppressed. This is a direct experimental manifestation of the fact that signal and idler photons are generated in pairs. The correlation coefficient $C_p$ computed from the measured data shown in Figure 3 is $C_p = 0.051 \pm 0.005$. This value being higher than that in our previous publication reflects an improved detection efficiency. In Figure 3, we plot the measured joint signal-idler photon-number distribution together with a contour line around the point $n_s = 8, n_i = 9$ where the criterion expressed in Eq. (2) is violated by 2.8 standard deviations. A larger deviation can be obtained if a longer measurement sequence is used and instabilities of the measurement setup and fluctuations of the pump intensity are lowered.

4. A direct measurement of spatial correlations

As already pointed out in Introduction, the benefit of the iCCD detector lies not only in its ability to be used as a photon-number resolving detector but also in the fact that it provides a spatial information about a detection event. In the geometry of our experiment, the signal $(\Theta_s, \Phi_s)$ and idler $(\Theta_i, \Phi_i)$ output angles approximately translate to horizontal and vertical coordinates in the iCCD detection plane $(x_s, y_s, -x_i, y_i)$; the minus sign in the idler strip comes due to a horizontal inversion of the strip after reflection on the mirror (see Figure 4). Provided that the distance of the camera from the crystal is large enough, the error introduced by this transition from polar to rectangular coordinates is negligible compared to the size of the detector macropixel (several pixels of the iCCD can be grouped together into one macropixel in the hardware of the camera to speed-up the image readout).

Since the total detection efficiency is quite low, we often detect only one member of a photon pair (see Figure 4). We do not want to make a priori assumptions about the dimensions of the area of correlation and so we take into account all possible combinations of detection events in the signal and idler strips. For example, if there is $n_s$ ($n_i$) detections in the signal (idler) strip in a particular frame, we plot the total of $n_s n_i$ points in Figs. 5a(c) at coordinates $[(\Phi_s(i), \Phi_s(j))$ ($[\Theta_s(i), \Theta_s(j)])$, $i = 1, ..., n_s$, $j = 1, ..., n_i$, each with a weight of $1/(n_s n_i)$. The plots are then accumulated along all the frames in one measurement sequence. The resulting plots as shown in Figs. 5a,c then clearly reveal correlations in the positions of detection events.
in both coordinates. In both cases we can see a diagonal coming from upper left to lower right corner of the plot. The width of a diagonal corresponds to the dimension of the area of correlation in the corresponding coordinate. We can see cross-section of the diagonal in Figs. 5b,d. From Gaussian fits to the measured data we can determine both radial dimension \((7.3 \pm 0.5 \text{ mrad, FWHM})\) and angular dimension \((10.1 \pm 0.4 \text{ mrad, FWHM})\) of the area of correlation. Since characteristics of the pump beam are not known with a sufficient precision at present, a quantitative comparison of the measured dimensions of the area of correlation with a theoretical model of SPDC cannot be done.

We note that measurement of spatial correlations is much less sensitive to instability of the pump intensity so that larger sequences of camera frames can be processed within one measurement.
5. Conclusions

By improving the detection efficiency of an iCCD camera with respect to our previous results \[23\] we have obtained experimental data that directly violate the criterion of classicality for a joint signal-idler photon-number distribution introduced in \[23\]. In addition, radial and angular dimensions of the area of correlation have been experimentally determined.

Acknowledgement

The authors acknowledge support by the projects 6198959213 of the Ministry of Education of the Czech Republic and 202/05/0498 of the Grant Agency of the Czech Republic.

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