Advanced Laboratory Project Report
Towards the measurement of second order correlation function by using a CCD

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Abstract: We investigate methods to retrieve the second order spatial correlation function of light from images taken by an CCD camera. We discuss advantages of EMCCD in comparison with CCD. We apply binarization process to a set of SPDC photon images taken with a CCD camera operating at -3 °C.

I. INTRODUCTION

The 1963 Glauber's series of papers on fundamental problems of optics are a milestone of quantum optics. The article entitled *The Quantum Theory of Optical Coherence* [1] is devoted amply to defining the concept of coherence.

To measure the coherence degree in n-photon coincidence experiments, Glauber introduces an infinite succession of correlation functions, $G^{(n)}$ for arbitrary n

$$G^{(n)}(x_1 \cdots x_n, x_{n+1} \cdots x_{2n}) \\ = \mathsf{tr}\left\{\rho E^{(-)}(x_1) \cdots E^{(-)}(x_n) E^{(+)}(x_{n+1}) \cdots E^{(+)}(x_{2n})\right\} \tag{1}$$

in which ρ is the density operator that represents our knowledge of the state of the field, $E^{(+)}(x_i)$ and $E^{(-)}(x_i)$ are projections of the positive and negative frequency parts of field operators at the coordinate $x_i = (\mathbf{r_i}, t_i)$.

As an special case of equation (1), we have for the photon coincidence rate, a second-order correlation function given by

$$G^{(2)}(\mathbf{r_1}t_1\mathbf{r_2}t_2, \mathbf{r_3}t_3\mathbf{r_4}t_4) \\ = \mathsf{tr}\left\{\rho E^{(-)}(\mathbf{r_1}t_1) E^{(-)}(\mathbf{r_2}t_2) E^{(+)}(\mathbf{r_3}t_3) E^{(+)}(\mathbf{r_4}t_4)\right\}. \tag{2}$$

This second order correlation function is used to characterize different types of light, for example to differentiate classical and non-classical light.

On the other hand, $G^{(n)}$ permit us to characterize high dimensional correlations that are on the grounds of most current quantum technologies. These quantum technologies include quantum information, quantum computing and quantum cryptography.

The traditional way to measure $G^{(2)}$ consists on scanning each detector position what makes the procedure time consuming [2]. In this context, recent development of Electron Multiplying Charge Coupled Device or EMCCD, a device that permits single photon detection by pixel, open possibilities of measuring and exploding high order correlations functions in a more efficient manner.

In this report we present the first steps of a protocol to get second order correlation function by images taken with a CCD. We use a CCD camera operating at -3°C to study background noise features and Spontaneous Parametric Down Conversion [SPDC] signal as a function of exposure time. As a first step in the implementation of such an image analysis method we apply the *binarization process* to SPDC images.

The discussed protocol is applicable to measurements of correlations functions from of EMCCD images [3–5]. In a long term, this capability will allow us to perform transverse momentum-resolved two-photon quantum interference measurements that may have implications for quantum information processing [6].

A. STATE OF THE ART

In this section we will discuss the most recent experimental works that support our investigation. The study of this literature highlight the relevance of using EMCCD cameras as a tool in measuring statistical properties of light and encourage our future work.

It has been shown in recent papers that the use of EMCCD cameras lead to important capabilities in quantum optics and quantum information [3–5].

In 2012 Padgett's work [3] an EMCCD camera is used to measure correlations in both position and momentum across a multi-pixel field of view.

Other application was presented at the 2014 paper of Bondani et.al.[5] in which twin-beam coherence properties are analyzed in both spatial and spectral domains. They used an imaging spectrometer composed by spherical mirrors, grating and EMCCD camera.

Another work in 2018 by Fleischer et. al[4] is devoted to explore a new theory of camera detection that take advantage of parallelization inherent in an array of pixels to calculate a second order spatial correlations.

These examples of today's academic debate demonstrated the high level of interest into apply EMCCD cameras in quantum optics.

B. DETECTION

A CCD camera is a rectangular array of thousands of multi-layer structures called pixels. A pixel is schematically depicted in figure 1. In a pixel light is converting into electrons by means of a photoelectric effect sensor. The performance of the sensor is measured by the quantum efficiency

$$\eta = \frac{\text{Number of impinging photons}}{\text{Number of produced photoelectrons}}$$

A potential well is used to accumulate electrons and a signal proportional to this number of electrons is produced. Fluctuations in the measurement of this signal are called readout noise. As a final step, the output signal is converted into a discrete value between 0 and 255. This set of all these values organized as a matrix is a grayscale image.

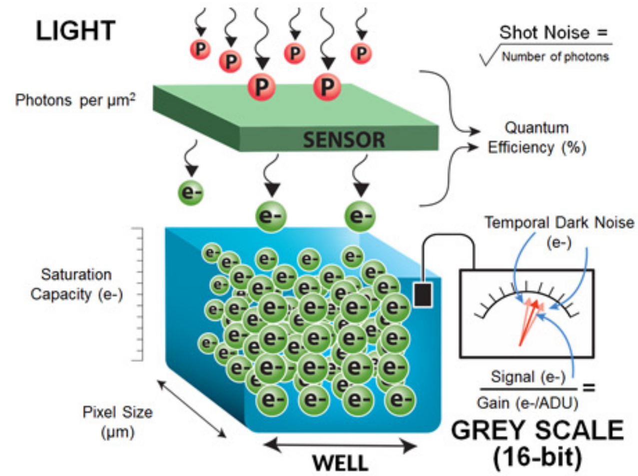

Figure 1: CCD camera. Image from [7].

An EMCCD camera is a CCD in which photo-electrons are multiplied by passing through a gain register before being storage in the potential well. As shown schematically in figure 2 the gain register is composed by a series of layers that double the number of electrons with a certain probability p during their passage.

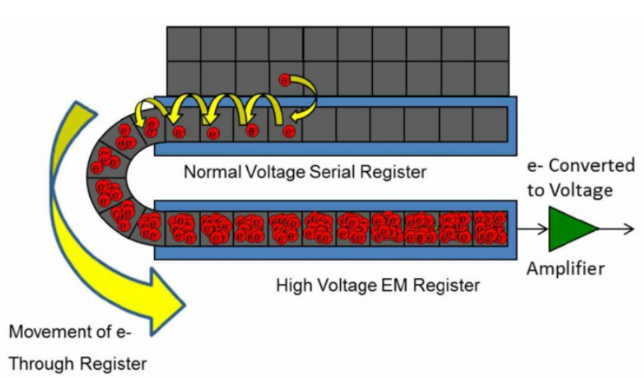

Figure 2: EMCCD camera. Image from [8].

This implies orders of magnitude improving the signal-to-readout-noise ratio. Because of this performance improvement in EMCCD, every pixel behaves like a single photon detector, at low operation temperatures [$\sim -80^o$C].

Thus the EMCCD operates as an spatial array of single photon detectors. Which in principle permits high order correlation functions measurements. Advantages of EMCCD in comparison with CCD can be identified by simple inspection of table I.

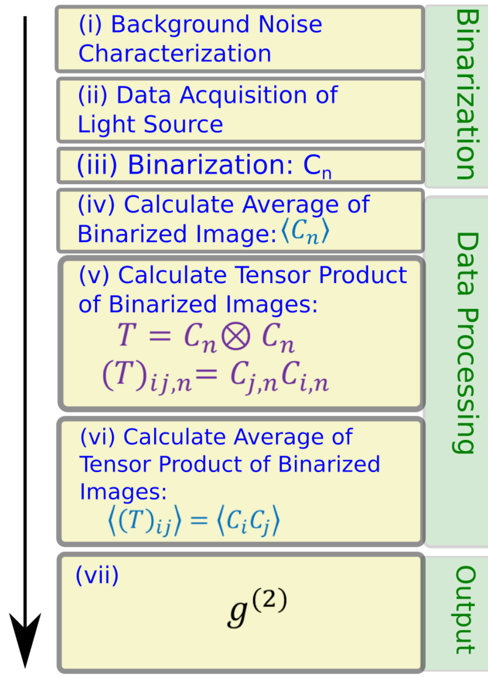

Figure 3: Flow-chart of the algorithm.

C. ALGORITHM

In this section we will present a detailed description of the algorithm proposed by Padgett [3] that permits to calculate the second order correlation function. Flow chart of the algorithm is shown in figure 3.

(i) Background noise characterization: The camera is first characterized by measuring the histogram of the grayscale output of each pixel from many ($\approx 10^6$) frames taken with the shutter closed and laboratory lights turned off. Thus, for every pixel we define a threshold value that determine if there is a detection or not.

(ii) Data acquisition of light source. Many photos, grayscale arrays, of the light source are taken. Every image is recorded as a column matrix $\hat{C}_n$. $\hat{C}_n$ corresponds to the nth grayscale photo and $\hat{C}_{i,n}$ to the value of the ith pixel.

(iii) Binarization. The binarization or thresholding process consist into compare $\hat{C}_{i,n}$ with the threshold: if the value is grater than threshold and zero otherwise. Resulting array is C_n ant its elements $C_{i,n} \in \{0, 1\}$.

(iv)Calculate the average of binarized images. The av-

Table I: Key features of CCD and EMCCD.

	Model	Pixel Array	Pixel Size [μm$\times\mu$m]	Frame Rate [frames s^{-1}]	Quantum Efficiency	Readout Noise [e^-]	Dark Counts [$1e^-$ pixel^{-1} s^{-1}]
EMCCD	897[a]	512×512	16×16	56	$> 90\%$	< 1	0.00025 @-80^oC
	888[a]	1024×1024	13×13	26	$> 90\%$	< 1	0.00030 @-80^oC
CCD	1603ME[b]	1530×1020	9×9	10 ms resolution	$> 80\%$ Peak	< 17 RMS	1

[a] Oxford Instruments: iXON Ultra.
[b] Santa Barbara Instruments.

erage image is given by:

$$\langle C\rangle = \frac{1}{N}\sum_{n=1}^{N} C_n \tag{3}$$

with elements

$$\langle C_i\rangle = \frac{1}{N}\sum_{n=1}^{N} C_{i,n} \tag{4}$$

(v)Calculate the tensor product of binarized images. Tensor product of binarized images is images is given by

$$T_n = C_n \otimes C_n \tag{5}$$

which elements are given by

$$(T)_{ij,n} = C_{j,n}C_{i,n} \tag{6}$$

(vi) Calculate the average of the tensor product of binarized images. The average tensor product of binarized images is given by

$$\langle T_n\rangle = \frac{1}{N}\sum_{n=1}^{N} C_n \otimes C_n \tag{7}$$

with elements

$$\langle (T)_{ij}\rangle = \frac{1}{N}\sum_{n=1}^{N} C_{j,n}C_{i,n} = \langle C_iC_j\rangle \tag{8}$$

(vii) Output. The second order correlation function [4] is proportional to a function

$$g^{(2)} \propto \ln\left(1 + \frac{\langle C_iC_j\rangle - \langle C_i\rangle\langle C_j\rangle}{(1-\langle C_i\rangle)(1-\langle C_j\rangle)}\right) \tag{9}$$

of the values calculated in steps (iv) to (vi).

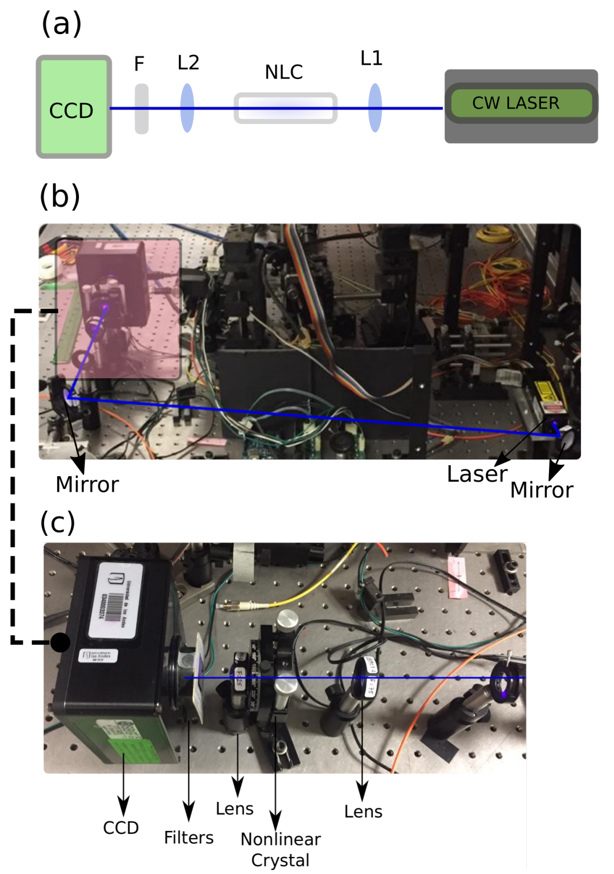

Figure 4: Experimental Setup. (a) Diagram of the experimental setup, (b) panoramic and (c) detailed view of the experimental setup. Blue line corresponds to the laser path.

II. EXPERIMENT

In figure 4(a) is shown the experimental setup. A type-I nonlinear crystal [NLC] is used as a source SPDC photons. This crystal is pumped by a (405±5) nm continuous wave laser.

SPDC photons are filtered out with band-pass filters [F] centered around 810 nm and detected by a Santa Barbara Instruments CCD camera operating at $T = -3^oC$. Lenses are used to focus the pump beam on the crystal [L1] and to collimate SPDC signal before detection [L2].

III. RESULTS AND DISCUSSION

In this section we will show preliminary results for the first three steps of the flow chart shown in figure 3. In section §III A we discuss the features of background noise for different expousure times. In section §III B we present some of the acquired data for SPDC source and in the corresponding binarized images.

A. NOISE CHARACTERIZATION

In order to study dark counts of our detection system we turn off all the light sources in the laboratory and take $N = 10$ photos.

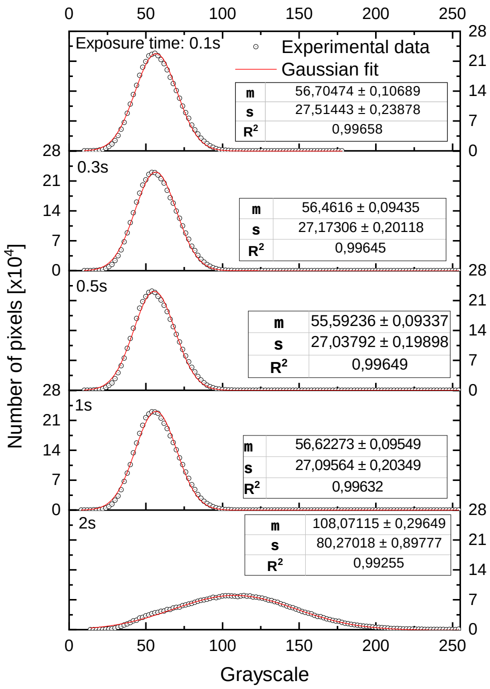

Figure 5: Background noise. Detection histogram for $N = 10$ images taken by using a Santa Barbara CCD camera at -3^o C with lights turn off.

We calculate the average of the images and built the histogram distribution for the grayscale as shown in figure 5 for various exposure times of the CCD camera.

B. DATA ACQUISITION AND BINARIZATION

The SPDC images are shown in figure 6 for different exposure times. After the binarization process we obtain figure 7. Up to now we have implemented the first three steps of the image analysis algorithm, as a perspective we will work into implement the complete algorithm.

the dependence of background noise in function of exposure time. Noise statistics remains unaltered for exposure times between 0.1s and 1.s. We observe the SPDC photons by using a CCD camera operating around -3^{o}C. We

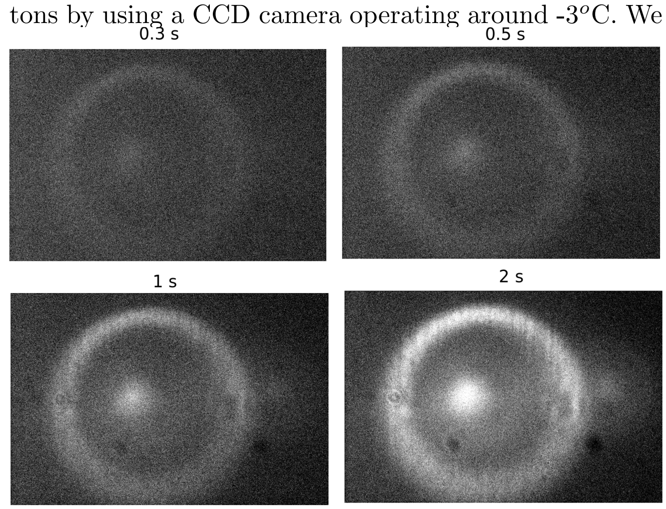

Figure 6: SPDC photons. Different exposure time images of SPDC signal taken by using a Santa Barbara CCD camera at -3^o C.

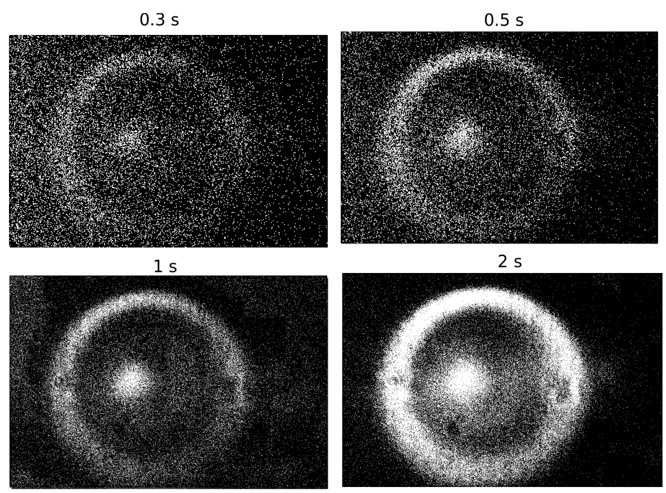

Figure 7: Binarized images of SPDC photons. Different exposure time images of SPDC signal taken by using a Santa Barbara CCD camera at -3^o C.

IV. CONCLUSIONS

We describe an algorithm that permits to calculate correlation functions from a series of images. We study implement the first steps of the algorithm that consists into convert grayscale images to binary.

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