

Using Spatial Correlations of SPDC Sources for Increasing the Signal to Noise Ratio in Images

A I Ruíz, R Caudillo, V M Velázquez and E Barrios

Facultad de Ciencias, Universidad Nacional Autónoma de México, Ciudad Universitaria, D.F. 04510, México

E-mail: e.barrios@ciencias.unam.mx

Abstract. We experimentally show that, by using spatial correlations of photon pairs produced by Spontaneous Parametric Down-Conversion, it is possible to increase the Signal to Noise Ratio in images of objects illuminated with those photons; in comparison, objects illuminated with light from a laser present a minor ratio. Our simple experimental set-up was capable to produce an average improvement in signal to noise ratio of 11dB of Parametric Down-Converted light over laser light. This simple method can be easily implemented for obtaining high contrast images of faint objects and for transmitting information with low noise.

1. Introduction

A main problem in receiving low intensity signals is the detectors noise level. It takes relevance when the signal amplitude is on the order of the detectors electronic noise because it leads to a practical limit for the detection of weak signals [1]. An example of this is the detection of optical signals at the level of photon counting. Avalanche Photodiodes (APDs) have the capacity for counting photons [2, 3]; however, they suffer from a background noise (Dark Counts), which is random in nature, is present even when there is no light impinging on the detector and typically is on the order of hundreds of counts per second. This type of noise could be removed from our measuring device if we could have knowledge (or a reference) of how it is produced and behaves. However, this turns highly difficult to do because this noise is random (lack of predictable behavior) and if the signal is weaker than the background noise. This problem can be circumvented, to a certain degree, by using the correlations produced by non-linear materials, which can give us a reference to identify the photons (signal) of interest instead of removing the noise. There have been experiments showing the effectiveness of this idea [4–7]; however, they require particular and time consuming experimental conditions [5, 6]. In this work we show how this can be simplified and still obtain a good capability for reducing the noise in a signal.

2. Spontaneous parametric down conversion

The theory behind Spontaneous Parametric Down Conversion (SPDC) has been widely studied and is based on the nonlinear interaction of some particular materials with an intense electromagnetic field [8] to produce pairs of photons with certain properties. In SPDC, a pump photon (with frequency ω_p) is annihilated to generate two new photons called signal and idler (with frequencies ω_s and ω_i respectively) according to energy and momentum conservation (phase



matching condition):

$$\omega_p = \omega_s + \omega_l, \quad \vec{k}_p = \vec{k}_s + \vec{k}_l. \quad (1)$$

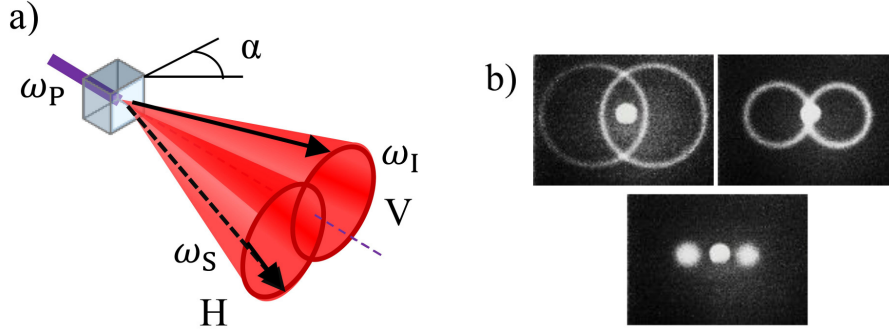


Figure 1. a) Type II SPDC geometry. Conical distributions had orthogonal polarizations; each photon of a pair is in one of the two cones. b) Transversal view of the cones for horizontal angular phase matching conditions of $\alpha = 0^\circ, 2^\circ, 4^\circ 10''$. The central spot is reminiscent of the pump beam.

In the degenerated case both photons have the same frequency ($\omega/2 = \omega_s = \omega_l$). Under Type II phase matching photons have orthogonal polarizations, horizontal photons form one cone while vertical ones form another (Figure 1a)). By changing the phase matching conditions it is possible to modify the geometry of the cones [5, 8] (Figure 1b)). Due to momentum conservation, each pair of photons is produced in times and directions correlated between them according to equation (1). By placing two detectors in an anti-symmetric way, one in each cone, it will be possible to detect the simultaneous arrival of the photons of a pair (Coincidence) [9, 10], any other not anti-symmetrical position will not produce coincidences because it does not conserve momentum. This phenomenon can be interpreted as a spatial correlation. In contrast, classical light sources (lasers) will not present this correlation because the origin of each photon is not correlated with any other photon. Experimentally the degree of spatial correlation between a pair of spatial regions can be relatively quantified through the number of coincidences, where a great number of coincidences will imply a great correlation degree [10]. Then, if we use an SPDC source to transmit a signal through coincidences, we can reduce the amount of noise in its detection, because the correlations will help us to discriminate the signal from noise and because the random noise will not produce coincidences.

3. Signal to noise ratio

To quantify the advantage of SPDC light over the classical sources we use a simple Signal to Noise Ratio (SNR) measurement. This quantity is of great importance to quantify the performance of a receiver in a communication system. The SNR compares the power level of a signal with the power level of the noise in the receiver:

$$SNR_{dB} = 10 \log_{10} \left(\frac{P_{Signal}}{P_{Noise}} \right) = P_{Signal,dB} - P_{Noise,dB}, \quad (2)$$

where the greater the difference of the signal and noise power levels, the better the performance of the system. In our case, the power of our signal (or noise) will be given by the measured number of photons or coincidences (or dark counts): $P_{Signal} = N_{Signal}$ ($P_{Noise} = N_{Noise}$).

We calculated the SNR for two types of signals (light): a laser source, where the power of the signal will be proportional to the number of photons or coincidences detected, and an SPDC

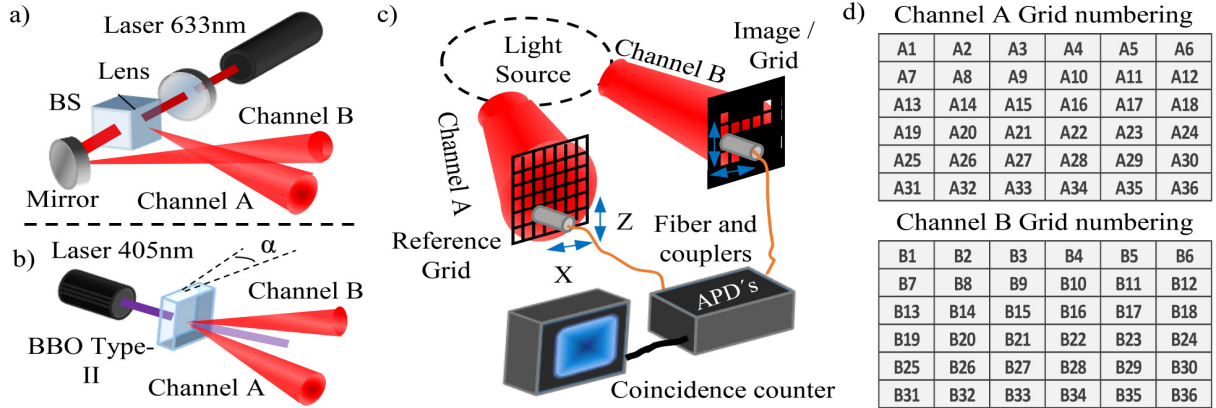


Figure 2. Set-ups for measuring spatial correlations and SNR. a) Laser light source. The beam is expanded and divided in two by a Beam Splitter (BS), the cones area cover the grids. b) SPDC source. The pairs of correlated photons are distributed in two cones (A y B). c) Detection. Composed by reference grids, the image (for noise reduction), XZ moving fiber collectors with 1mm^2 aperture, two APDs for detection and a coincidence counter. d) Grids numberings.

source, were the signal power will be given by the number of coincidences. The noise power will be given by the number of dark counts in the case of the laser, and by the number of dark (false) coincidences measured between no correlated regions or when there is no light measured, for the case of the SPDC source. It can be expected that for the SPDC source the number of coincidences (and the SNR ratio) will be greater than for the laser source, as long as we measure coincidences.

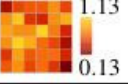
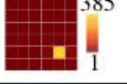
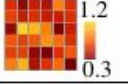
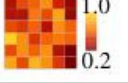
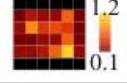
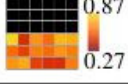
4. Experimental set-up

The experiment is divided in two sections. In the first, we quantified the degree of spatial correlation and the SNR through coincidences (or counts) for both, laser and SPDC sources. In the second part we analyzed an image illuminated with this two types of sources and quantify the SNR by using counts or coincidences.

For the laser source, we used a 633nm laser attenuated to an average of 9000 photons per second. The beam is expanded with a lens and divided in two with a beam-splitter to generate a pair of cones of light with the same dimensions of that of the SPDC cones (Figure 2a)). For the SPDC source, a 405nm laser is used to pump a BBO crystal type-II at an incident angle of $\alpha = 4^\circ 10''$ in the horizontal plane, in order to produce completely separated and solid 810nm light cones (Figure 2b)). In either case, each cone is denoted Channel A and Channel B.

The detection system is common to both sources (Figure 2c)). Photons are collected by a single mode fiber with a fiber coupler which has a 1mm circular aperture. This fibers are mounted on XZ displacers that allow collecting light from different spatial regions. For reference, in front of these light collectors we placed two numbered grids to divide the transversal area of each cone in sub-areas of 1mm^2 (Figure 2d)). The fibers are connected to a pair of Avalanche Photodiodes (APD), which generate an electrical pulse for each photon collected. This pulses are received by a pulse counting card which also counts the number of coincidences (simultaneous arrival of photons) within a measuring window of 5ns.

In the first experiment we measured the number of photon counts in each channel at different positions and the number of coincidences between them. Collector in Channel A was placed in a particular grid position (pixel) while collector in Channel B was swept through all B grid. This procedure is done for both types of sources. To measure the SNR of the coincidences, the signal power will be the number of coincidences and the noise power the average of the background

Table 1. Spatial Correlation Graphs ^a				Table 2. SNR Image Analysis Graphs ^a		
Laser source		SPDC source		Case	Avg. counts or coin.	Avg. SNR
Conditions	Avg. Coinc.	Conditions	Avg. Coinc.			
Ch A: {A8} Ch B: {B1-B36}	 1.13 0.13	Ch A: {A8} Ch B: {B1-B36}	 385 1	Laser photon counts.	 6300 640	9.16dB
Ch A: {A29} Ch B: {B1-B36}	 1.2 0.3	Ch A: {A29} Ch B: {B1-B36}	 292 0.3	SPDC photon counts.	 10200 600	11.3dB
Ch A: {A26} Ch B: {B1-B36}	 1.0 0.2	Ch A: {A26} Ch B: {B1-B36}	 218 0.3	Laser Coinc. Counts.	 1.2 0.1	7.32dB
Ch A: {A11} Ch B: {B19-B36}	 0.87 0.27	Ch A: {A11} Ch B: {B19-B36}	 510 0.33	SPDC Coinc. Counts.	 330 1.7	22.3dB
^a Black elements means no measurement performed.				^a Black elements, no measurement.		

noise.

In the second experiment we showed how SDPC spatial correlations can improve the SNR of an image as long as the correlation analysis is performed in an Anti-symmetrical way to take into account the photon momentum conservation of the SPDC. For this purpose, we placed in Channel B an image (aligned with the grid) and performed simultaneous sweeps through both grids in the following order (A1,B36), (A2,B35), (A36,B1). From the obtained counts or coincidence data, the SNR of the image can be calculated using equation (2), for both laser light or with SPDC light.

5. Results

5.1. Spatial Correlation

For the laser source no spatial correlations were found. The very low number of coincidences are fortuitous and can be assumed as a background noise for coincidences. We got an average $SNR_{Coin.laser}$ of $-285dB$. Meaning that we cannot distinguish any signal from the noise.

For the SPDC source, we found a great number of coincidences between anti-symmetrical regions in the light cones, giving an average $SNR_{Coin.SPDC}$ of $23.22dB$. Table 1 summarizes this correlations for different pairs of regions. As it can be seen, the SPDC correlation is greater than for the laser.

5.2. SNR reduction

To prove that SPDC light allows us to increase the SNR factor in an image due to spatial correlations, in Table 2 we present a comparison for the SNR obtained using a laser (or SPDC light without coincidences) against the SNR obtained using a laser or SPDC source through coincidences. In cases where there is no coincidence reference, the average SNR is similar for both the laser and the SPDC; when coincidences are used to reproduce the image, we obtained an average of 22.31dB for the SPDC and 7.32dB for the laser. In addition, it can be noticed that due to the momentum conservation, the image reconstructed through coincidences is rotated by 180° .

6. Conclusions

Our results show that, when using an SPDC sources, the production of pairs of photons according to momentum conservation generates a clear anti-symmetrical spatial correlation signal between the channels pixels above the APD noise, while for a laser source this correlation is non-existent. By taking advantage of this spatial correlations we were able to improve the SNR of an image illuminated with an SPDC source by an average of 11dB, which is translated in higher image contrast; on the contrary, when we used a laser source for illumination, the lack of correlation produces an average decrease on the SNR of image of 1.84dB, which can be interpreted as a loss on information. The increase in SNR by using an SPDC source for illumination can be very useful for applications where the object is faint or it requires low intensities of illumination in order to avoid damage [6].

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