UNIVERSIDAD DE LOS ANDES

THESIS

Two-Photon Imaging Using Tunable Spatial Correlations

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Declaration of Authorship

I, Juan VARGAS, declare that this thesis titled, "Two-Photon Imaging Using Tunable Spatial Correlations" and the work presented in it are my own. I confirm that:

- This work was done wholly or mainly while in candidature for a research degree at this University.
- Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated.
- Where I have consulted the published work of others, this is always clearly attributed.
- Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work.
- I have acknowledged all main sources of help.
- Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself.

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“Nonesenses... later due”

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Abstract

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Two-Photon Imaging Using Tunable Spatial Correlations

by Juan VARGAS

Two-Photon Imaging is a well studied fenomena, where we take advantage of the diferent correlations in wich the light can be related to recontruct the image of certain objects. In this Thesis use diferent spatial correlations of a SPDC light source, where we change this correlations changing the pump waist.

Acknowledgements

The acknowledgments and the people to thank go here, don't forget to include your project advisor… s [1] ss [2] green [3] green here [3] Shih[4]

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List of Abbreviations

LAH	**L**ist **A**bbreviations **H**ere
WSF	**W**hat (it) **S**tands **F**or

Physical Constants

Speed of Light $c_0 = 2.997\,924\,58 \times 10^{8}\,\mathrm{m\,s^{-1}}$ (exact)

List of Symbols

a	distance	m
P	power	W (J s^{-1})
ω	angular frequency	rad

For/Dedicated to/To my…

Chapter 1

Introduction and Background

1.1 Imaging

1.2 Two-Photon Imaging

1.2.1 Two-Photon Imaging using entangled photon pairs

A two-photon optical imaging experiment was perfomed based on the quantum nature of the *signal* and *idler* photons pairs produced in spontaneous parametric down-conversion[7]. An important fact of this experiment is the use of a lens in

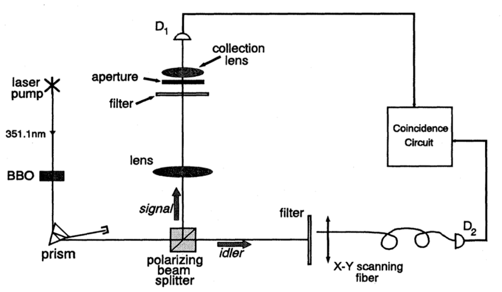

FIGURE 1.1: Cartoon schematic of the experimental setup used by Pittman, Taken from [7]

the signal beam that establishes an image plane with the definitive point-by-point correspondence object(mask) plane.

1.2.2 Can quantum Imaging be classically simulated?

No[8]

1.2.3 Thermal Sources

In [9] they compared ghost Imaging using entanglement versus Classical correlated light. read and information in [10]. [11]

Chapter 2

Theoretical Discussion

2.1 Quantum Imaging

2.2 Light Source

main source of information [12]

2.2.1 Biphoton

$$|\Psi\rangle = \int dq_s dq_i d\Omega_s d\Omega_i x[\Phi(q_s,\Omega_s;q_i,\Omega_i)\hat{a}^\dagger(\Omega_s,q_s)\hat{a}^\dagger(\Omega_i,q_i) + \Phi(q_i,\Omega_i;q_s,\Omega_s)\hat{a}^\dagger(\Omega_s,q_s)\hat{a}^\dagger(\Omega_i,q_i)]\,|0\rangle \tag{2.1}$$

taken like it appears on [1]

Where $\Phi(q_s,\Omega_s;q_i,\Omega_i)$ are the mode fuctions or Biphotons, a fuctions that contain all the information about the correlations. $\hat{a}^\dagger(\Omega_n,q_n)$ the creation of a photon with tranverse momentum q_n and frequency Ω_n

2.2.2 Mode Function

$$\Phi(q_s,\Omega_s;q_i,\Omega_i) \propto E_p(q_p,\Delta_0)B_p(\Omega_p)\mathcal{C}_{spatial}(q_s)\mathcal{C}_{spatial}(q_i)x\mathcal{F}_{frequency}(\Omega_s)\mathcal{F}_{frequency}(\Omega_i)sinc\left(\frac{\Delta_k\mathcal{L}}{2}\right) \tag{2.2}$$

where $B_p(\omega_p^0+\Omega_p)$ and $E_p(q_p)$ are the frequency and transverse momentum distribution of the pump. $\mathcal{C}_{spatial}(q_n)$ spatial filtering. $\mathcal{F}_{frequency}(\Omega_n)$ frequency filter function.

2.2.3 Phase matching conditions

$$\Delta_0 = q_s^y cos\varphi_s + q_i^y cos\varphi_i + k_s sin\varphi_s - k_i sin\varphi_i; \tag{2.3}$$

$$\Delta_k = k_p - k_s cos\varphi_s - k_i cos\varphi_i - q_s^y sin\varphi_s + q_i^y sin\varphi_i + (q_s^x + q_i^x)tan\rho_0 cos\alpha + \Delta_0 tan\rho_0 sin\alpha \tag{2.4}$$

where $k_n = [(\omega_n^0 n_n/c)^2 - |q_n|^2]^{\frac{1}{2}}$ is the longitudinal wavevector inside the crystal. φ_s and φ_i are the propagation directions of the generated photons inside the crystal with respect to the pump direction z and α is the azimuthal angle.

2.2.4 Gaussian approximations

Taking into account the Gaussian nature of the pump, that's $E_p(q_p^x,q_p^y) \approx exp\left[-\frac{w_p^2}{4}(q_p^{x^2}+q_p^{y^2})\right]$.

approximating the sinc function by a Gaussian function with the same width at $\frac{1}{e^2}$ of its maximum, i.e., $sinc(x) \approx exp(-\gamma x^2)$ with γ equal 0.193.

$$\mathcal{F}_{frequency}(\Omega_n) \approx exp\left[-\frac{\Omega_n^2}{4\sigma_n^2}\right] \tag{2.5}$$

$$\tilde{\Phi}(q_s, q_i) = \int d\Omega_s d\Omega_i \mathcal{F}_s(\Omega_s)\mathcal{F}_i(\Omega_i)\Phi(q_s, \Omega_s; q_i, \Omega_i) \tag{2.6}$$

The Biphoton then takes a quadratic form:

$$\tilde{\Phi}(q_s, q_i) = Nexp\left[-\frac{1}{2}x^T Ax + ib^T x\right] \tag{2.7}$$

where N is a normalization constant, x is a 4-dimensional vector defined as $x = (q_s^x, q_s^y, q_i^x, q_i^y)$, A is a 4 x 4 real-valued, symmetric, positive definite matrix and b is a 4- dimensional vector. A and b are defined from the phase-matching conditions of the SPDC process. x^T and b^T denote the transpose of x and b. A and b are functions that depend of all the relevant parameters in the experiment such as the length of the crystal L, pump waist w_p, creation angles inside the crystal φ_n and the width of the spectral filter σ_n.

A way to quantify the degree of spatial correlation we shall define 'correlation parameter':

$$K^\lambda = \frac{C_{si}^\lambda}{\sqrt{C_{ss}^\lambda C_{ii}^\lambda}} \tag{2.8}$$

calculated for each direction ($\lambda = x, y$) from the covariance matrix C^λ with elements $C_{kj}^\lambda = \langle q_k^\lambda q_j^\lambda \rangle - \langle q_k^\lambda \rangle \langle q_j^\lambda \rangle$.

2.2.5 Fresnel Propagator

Fresnel Propagator: $h(r,z) = (-\frac{i}{\lambda z})e^{(i\frac{2\pi z}{\lambda})}\Psi(r,z)$ with $\Psi(r,z) = e^{(i\frac{\pi}{\lambda z})r^2}$. Thin-lens transfer function $L_f(r) = \Psi(r, -f)$

$$G = \int d^2 r_1 \int d^2 r_0 h(r_f - r_1, f) L_f(r_1) h(r_1 - r_0, f) \tag{2.9}$$

The propagation is done by determining the Green function of the optical path by which the beam will travel. The biphoton function in terms of transverse momenta $\Phi_1(q_s, q_i)$ after traveling through two arbitrary optical paths can be expressed in terms of the corresponding Green functions and the initial biphoton function $\Phi(q_s, q_i)$ as:

$$\Phi_1(q_s, q_i) = G_s(q_s, r_1)G_i(q_i, r_2)\Phi(q_s, q_i) \tag{2.10}$$

$$\Phi_1(r_1, r_2) = \int d^2 q_s d^2 q_i \Phi_1(q_s, q_i) \tag{2.11}$$

Taking advantage of the 2-F system as a Fourier-Transform to reduce the amount of calculations. Solving 2.9 over r_0 and r_1 we have:

$$G(q, r_f) = Ce^{\frac{i\pi}{\lambda f}r_f^2} e^{\frac{i\lambda f}{4\pi}q^2} \delta(q - \frac{2\pi}{\lambda f} r_f) \tag{2.12}$$

where C is a complex constant that depends only on $\lambda = 2\pi c$ and f. Then we can define the Green Functions for each path:

$$G_1(q_s, r_1) = G(q_s, r_1) x T(r_1) \tag{2.13}$$

$$G_2(q_i, r_2) = G(q_i, r_2) \tag{2.14}$$

Where $T(r_1)$ is the transfer function of the object.

Gathering all the previous results we can obtain $\Phi_1(r_1, r_2) = C^2 T(r_1)\Phi(\frac{2\pi}{\lambda f}r_1, \frac{2\pi}{\lambda f}r_2)$, which describes the biphoton at the planes of the object and the scanning detector. It shows that the biphoton at the 2F plane in terms of r_1 and r_2 has the same form as the biphoton at the output face of the crystal with the relationship $q = \frac{2\pi}{\lambda f}r$. This allows to computationally simulate the biphoton at the 2-F plane by using Eq 2.7 without the need to computationally simulate its propagation through the 2-F system.

We are collecting all the light that interacts with the object by the means of a bucket detector, this from the mathematical point of view leave us with: $\Phi_1(r_2) = C^2 \int d^2 r_1 T(r_1)\Phi(\frac{2\pi}{\lambda f}r_1, \frac{2\pi}{\lambda f}r_2)$ The coincidence counts that will be measured by the Detectors will be proportional to the magnitude square of the resulting biphoton function $\Phi_1(r_2)$.

$$S(r_2) \propto |\int d^2 r_1 T(r_1)\Phi(\frac{2\pi}{\lambda f}r_1, \frac{2\pi}{\lambda f}r_2)|^2 \tag{2.15}$$

For non-ideal forms of $\Phi(q_s, q_i)$ we have the relation between $\Phi(q) \rightarrow \Phi(r)$ for a 2F system, Hence: $\Phi(r) = \frac{1}{\sqrt{det(\Sigma)(2\pi)^4}} e^{-\frac{1}{2}r^T\Sigma^{-1}r} e^{ibr}$

$$\Sigma = \begin{bmatrix} \sigma_{sx}^2 & Cov(x_s, y_s) & Cov(x_s, x_i) & Cov(x_s, y_i) \\ Cov(y_s, x_s) & \sigma_{sy}^2 & Cov(y_s, x_i) & Cov(y_s, y_i) \\ Cov(y_i, x_s) & Cov(x_i, y_s) & \sigma_{iy}^2 & Cov(x_i, y_i) \\ Cov(y_i, x_s) & Cov(y_i, y_s) & Cov(y_i, x_i) & \sigma_{iy}^2 \end{bmatrix}$$

2.3 Fourier Optics

2.4 Spatial Correlations

2.5 Measurement

Paper about stadistics of the messuarement[13]

Chapter 3

Experimental Setup

3.1 SPDC Setup

3.1.1 Diode Laser

The light source used in this experiment is a Diode Laser that delivers a continuous wave(CW) at $\lambda = 406, 101nm$ and $\Delta\lambda = 4nm$. The laser model No. DL 405-200 delivers light at 200 mW with a beam diameter of 1.5 mm and a beam Divergence 1.2 mrad. IN HERE I MAY TALK ABOU THE M FACTOR, QUALITY PARAMETER OF GAUSIAN BEAMS M^2

FIGURE 3.1: Image of the Diode Laser and it's control module, Taken from [5]

3.1.2 Mirror

picture

FIGURE 3.2: Mirror and the cavity mount

3.1.3 Spatial Filter

A laser beam can be characterized by measuring its spatial intensity profile at points perpendicular to its direction of propagation. The spatial intensity profile is the variation of intensity as a function of distance from the center of the beam, in a plane perpendicular to its direction of propagation. In the Figure 3.3(top part) we se see

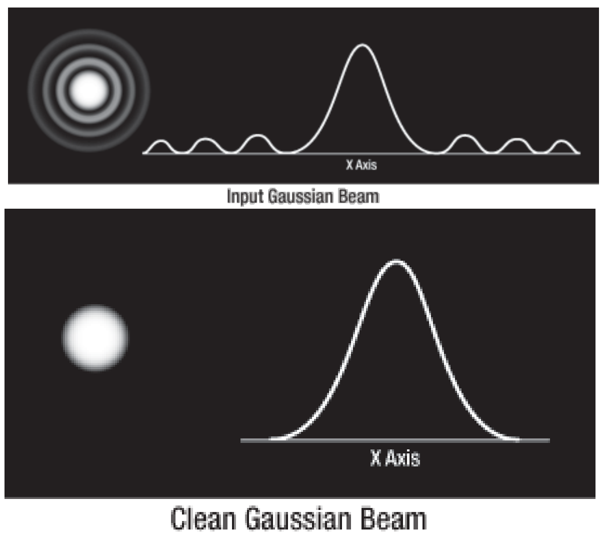

FIGURE 3.3: The spatial intensity profile before and after the spatial filtering process , Taken from [6]

the input gaussian beam and how its intensity fluctuates around the x axis. The output desired beam after going through the spatial filter is shown at the bottom of the Figure 3.3. The simplest arrangement to achieve this output spatial intensity profile is show in the Figure 3.4, where at the end we have a beam which intensity strength falls off transversely following a bell-shaped curve that's symmetrical around the central axis. Taking a closer look at the Figure 3.3(top part) we may recognise a

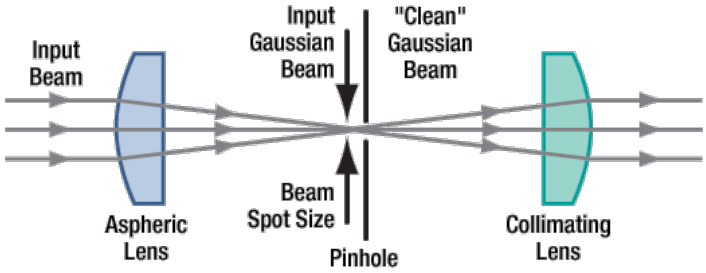

FIGURE 3.4: Basic elements of a Spatial Filter. In our experiment we use a Aspheric Lens of $f = 30mm$(LA1805-A), a pinhole of $50\mu m$ and a collimating lens of $f = 60mm$(LA1134-A). Taken from [6]

diffraction pattern, but when we measure this spatial profile directly from the diode laser, we find out that it doesn't follow that behaviour, on the contrary it follows a more random spatial profile. This ramdom spatial profile is a result of the randomnes in the quantum emissions and absorptions that are happening at the exited atoms at the diode laser[14].

In order to have this spatial intensity profile at the input of my lens arrangement, Figure 3.4, we put a circular aperture with the help of a pair of irises, Figure 3.5, before the $f = 30.0mm$ lens and after the $f = 60.0mm$ lens.

FIGURE 3.5: This helps to form circular apertures of variable radius

3.1.4 Waist Lens

A Gaussian beam hits a lens....To control the pump waist we can put a lens in the propagation direction with certain focal lenght f. This lens will define a zone around the distance f called *Focus depth*[14] , where in the middle we find the narrowest point of the beam, Figure 3.6. The radius of this zone is:

$$W_0 = \frac{\lambda f}{\pi W_B} \tag{3.1}$$

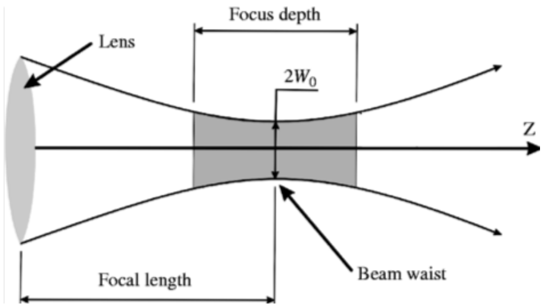

FIGURE 3.6: Lens' effect on a Gaussian beam

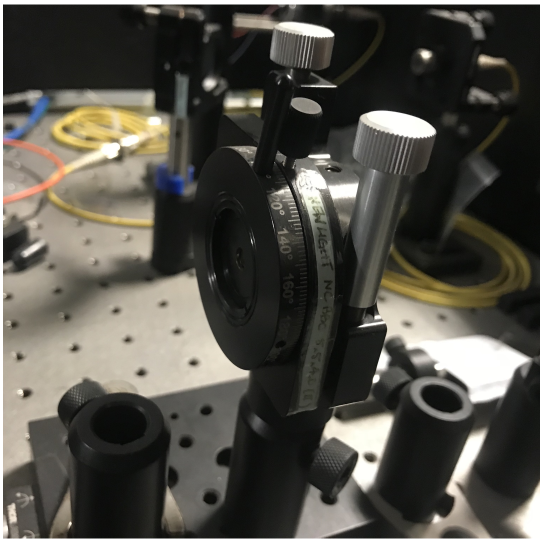

FIGURE 3.7: Actual BBO crystal used in experiment

Where W_B is the initial waist beam.
If we want to focus the beam at a fixed distance F, using this method to control the pump waist is not practical. Every different lens we would use will make this waist W_0 at a differents distances f. It is necessary to find a *Waist lens* that make us a waist W_0 at a transverse plane located in a fixed position F from the *Waist Lens*. This special lens consists in an arrangment of two lenses, a positive and negative one respectively, separated a distance d_0 from each other. SOURCE WHERE THEY EXPLAIN HOW TO USE A POSITIVE AND NEGATIVE ASK OMAR!!!

3.1.5 BBO(Beta Barium Borate) Crystal

The nonlinear optical media used in this experiment is a BBO(Beta Barium Borate) crystal, this crystal is $5x5x4mm$.

The crystal is mounted is such way that the input and output plane are fixed, Figure 3.7.

3.2 Spatial Correlations Measurement Setup

From this point we will talk about a pair of entangled photon pairs, that will come from the output plane of the BBO crystal, for historical reasons we will label this pairs as *signal* and *idler*.

3.2.1 Lens (Fourier Plane)

To define the $2f$ system we use a lens(LA1708) of $f = 200.0mm$ in front of each *signal* and *idler*. This lens is placed at a distance f from the output plane.

3.2.2 Polariser

In order to be able to filter certain polarisation direction we used a pair of Polarisers(WP25M-UB), which consist in a circular surface than only transmit the light that comes in a specific direction. other directions are reflected

3.2.3 Interferometer Filter

In this situation we are interested in the correlations in the space variables, hence we would like to filter al this time variables. To do this filtering we used a spectral filter(FB810-10) that only transmits the light that comes with $\lambda = 810 \pm 2nm$.

3.2.4 Pin Hole(Arduino)

MORE DETAILS, HOW MANY ARDUINOS, coupling lens refernece ETC ...

3.2.5 Single Photon Counting Module(SPCM)

To detect photons we a self-contained module that detects single photons of light over the $400nm$ to $1069nm$ wavelength range. The module used (SPCM-AQRH-13) uses a unique silicon avalanche photodiode (SLiK) with a detection efficiency of more than 65%[15]. Light is transmitted through a optic fiber from the pin hole detector to the SPCM. The result signal coming from the SPCM are pulses that represents one photon detections.

FIGURE 3.8: Single Photon Counting Module

3.2.6 Field-programmable gate array(FPGA)

Both *signal* and *idler* pulses from the respective SPCM goes to the same FPGA(ZestSC1). This Field-programmable gate array is programmed to count the photon coincidences, this means that the FPGA is fast enough to detect and separate pulses from photons that are time-separated.

3.2.7 Computer(Data Analysis)

labview is used to control the detection module, where is delivers a list of the detection, graph are made with any program language able to handle the data.

3.3 Two-Photon Imaging Setup

For the Two-photon imaging process we no longer have spatial information about the *signal* photon after it interacts with the mask

3.3.1 Mask

This is an obstruction that is placed in the *signal* path with certain shape, it could be a mask with the shape of a letter or any other geometry. This is the object of which we want to construct an image.

3.3.2 Folding Mirror

In order to change de path followed by the *signal* photon, we use a Folding mirror, Figure 3.9. This mirror can be in the *signal* path or not.

FIGURE 3.9: Foldind Mirror, it is in the position for measuring the correlations

3.3.3 Bucket Detector

This detector consist in a coupling lens that collects all the light that goes through the mask, In contrast to the other detections made in this experiment, the Bucket detector loses track of any spatial information of the *signal* photon. Another big difference is that this Bucket detector uses a multimode optic fiber to take the light to the SPCM.

Chapter 4

Results

4.1 Experimental Correlations

4.1.1 $w_p =?$

4.2 Two-Photon Images

4.2.1 mask1

4.2.2 mask2

4.2.3 mask3

Chapter 5

Discussions and Conclusion

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