UNIVERSIDAD DE LOS ANDES

THESIS

Two-Photon Imaging Using Tunable Spatial Correlations

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A thesis submitted in fulfillment of the requirements for the degree of Physicist

in the

Quantum Optics
Physics Department

May 28, 2018

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.

Signed:

Date:

"I think I can safely say that nobody understands quantum mechanics"

Richard Feynman

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Abstract

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Two-Photon Imaging Using Tunable Spatial Correlations

by Juan VARGAS

Two-photon imaging is a technique for obtaining an image of an object by means of the coincidence counts of two spatially separated detectors, the first realization was reported by Pittman et al.[**?**]. Traditionally we need to face a single camera (detector) to the object we would like to take an image from, but with Two-photon imaging technique we obtain the image by measuring the correlations between light beams. We use a light generated by the Spontaneous Parametric Down Conversion. The popularity of this source of paired photons is strongly related to the relative simplicity of its experimental realisation, and to the variety of quantum features that down converted photons can exhibit.

We focus a 405nm CW laser to a BBO Cristal, this type-II crystal generates pairs of strongly correlated photons in a noncollinear configuration. As seen in [**?**], it is possible to change the spatial correlations by changing the pump waist that hits the crystal. We are interested in observing the effect on the generated images when changing the spatial correlations, these effects have to be understood as resolution of the image and the flips of the images with respect to the original object. The Two-photon imaging have some peculiar features: it is non-local; its imaging resolution differs from that of classical. These features may turn a local 'bucket' sensor into a nonlocal imaging camera with classically unachievable imaging resolution [**?**].

$$\langle I(\vec{r}_i)^{(i,j)}\rangle = \int_{obj} d\vec{r_o}^{(i,j)} |T(\vec{r_o}^{(i,j)})|^2 \delta(\vec{r_o}^{(i,j)} + \frac{\vec{r_i}^{(i,j)}}{m}), \tag{1}$$

$$\langle I(\vec{r_i}^{(i,j)})\rangle = \int_{obj} d\vec{r_o}^{(i,j)} |T(\vec{r_o}^{(i,j)})|^2 \mathrm{somb}^2[\frac{\pi D}{\lambda S_o}|\vec{r_o}^{(i,j)} + \frac{\vec{r_i}^{(i,j)}}{m}|], \tag{2}$$

$$R_{BA}(\vec{r_A}^{(i,j)}) = \int_{obj} d\vec{r_B}^{(i,j)} |T(\vec{r_B}^{(i,j)})|^2 G^{(2)}(\vec{r_B}^{(i,j)}, \vec{r_A}^{(i,j)}), \tag{3}$$

$$\tilde{\Phi}(\vec{q}_B^{(i,j)}, \vec{q}_A^{(i,j)}) = N exp\left[-\frac{1}{2}x^T A x + i b^T x\right]. \tag{4}$$

$$R(\vec{r}_A^{(i,j)}) \propto |\int d^2\vec{r}_B^{(i,j)} T(\vec{r}_B^{(i,j)}) \Phi(\frac{2\pi}{\lambda f}\vec{r}_B^{(i,j)}, \frac{2\pi}{\lambda f}\vec{r}_A^{(i,j)})|^2 \tag{5}$$

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Two-photon imaging es una técnica para obtener una imagen de un objeto mediante el conteo de las coincidencias de dos detectores que se encuentran espacialmente separados, la primera realización fue reportada por Pittman et al.[**?**]. Tradicionalmente necesitamos enfrentar una sola cámara (detector) a el objeto del cual queremos recuperar una imagen, pero con la técnica de Two-photon imaging nosotros obtenemos la imagen midiendo las correlaciones entre rayos de luz. Usamos la luz generada por el proceso de Spontaneous Parametric Down Conversion. La popularidad de esta fuente de pares de fotones esta fuertemente ligada a la relativa simplicidad de su realización experimental, y a la variedad de características cuánticas que los pares producidos pueden exhibir. Nosotros concentramos un laser de onda continua a 405nm a el cristal BBO, este cristal tipo-II genera pares de fotones que están fuertemente correlacionados en una configuración nocolineal. Como visto en [**?**], es posible cambiar las correlaciones espaciales cambiando la cintura del bombeo que llega a el cristal. Estamos interesados en observar el efecto en las imágenes generadas cuando cambiamos la correlación espacial, estos efectos tienes que entenderse como la resolución de la imagen y las rotaciones de las imágenes con respecto a el objeto original. El Two-photon imaging tiene algunas características peculiares: no es local; su resolución difiere a la resolución clásica. Estas características convertirían un sensor bucket en una cámara no local con resolución clásicamente inalcanzable [**?**]

Acknowledgements

My very first thanks must go to my parents, without them and their unconditional support through this years nothing of this would be possible. I also would like to thank my brothers for being always a good example for myself.

The present monograph is the compilation of the efforts of many people, First of all I would like to thank director Alejandra Valencia, for showing me a different perspective about experimental physics and for the many discussions we had where I've learnt a wide set of things. There must be also a special thanks to the Quantum Optics group. To Omar Calderon for sharing the theoretical and experimental skills necessary to have a source light with Tunable spatial correlations. To Daniel Urrego and Johnny Tenorio for instruct me in most of the experimental procedures and to Juan Andrés Urrea for the numerical solutions used in this monograph.

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Appendix A

Two-photon Imaging Using Chaotic Sources

In principle the term "thermal radiation" should refer only to radiation coming from a blackbody in thermal equilibrium at some temperature T. But with this realisation of thermal radiation we have to face some characteristics of true thermal fields. Thermal radiation is also referred as chaotic light, which have extreme short coherence time. This is because a thermal source contains a large number of independent sub-sources, such as the trillions of atoms or molecules.These atomic transitions that can be identical or different act like sub-sources, that emit light into independently and randomly.

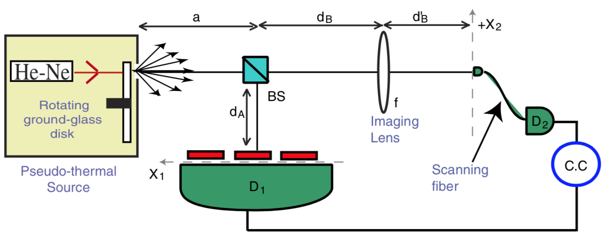

FIGURE A.1: Experimental setup for the Two-photon imaging using thermal light, taken from [?]

The source light in Figure A.1 is the one developed by Martinssen and Spiller[?] which is the most commonly used among the pseudothermal fields. A coherent laser radiation is focused on a rotating ground glass disk, the scattered radiation is chaotic with a Gaussian spectrum. After this, a nonpolarizing beam splitter (BS) splits the radiation in two distinct optical pths, In the reflected arm an object, with transmission function $T(r_1)$, is placed ar a distance d_A from the BSand a bucket detector (D_1) is just behind the object. In the transmitted arm an imaging lens, with focal lenght f, is placed at a distance d_B from the BS, and a multimode optical fiber (D_2) scans the transverse plane at a distance d_B' from the lens. The output pulses from the two single photon counters are sent to an electronic coincidence circuit to measure the rate of coincidence counts.

Once again we expect the joint-detection counting rate between photodetectors D_1 and D_2 to behave like the one described in Eq. 3. But thos rate this coincidence counts is governed by the second-order Glauber correlation function [**?**]:

$$G^{(2)}(\vec{r}_1;\vec{r}_2) \equiv \langle E_1^{(-)}(\vec{r}_1)E_2^{(-)}(\vec{r}_2) \times E_2^{(+)}(\vec{r}_2)E_1^{(+)}(\vec{r}_1)\rangle \tag{A.1}$$

where the $E^{(-)}$ and $E^{(+)}$ are the negative-frequency and the positive-frequency field operators describing the detection events at the locations $\vec{r}_1$ and $\vec{r}_2$. The transverse second-order correlation correlation function for a thermal source is given by [**?**]:

$$G^{(2)}_{thermal}(\vec{r}_1;\vec{r}_2) \propto \sum_{\vec{q}} |g_1(\vec{q},\vec{r}_1)|^2 \sum_{\vec{q}'} |g_2(\vec{q}',\vec{r}_2)|^2 + |\sum_{\vec{q}} g_1^*(\vec{q},\vec{r}_1)g_2(\vec{q},\vec{r}_2)|^2 \tag{A.2}$$

where $\vec{r}_i$ is the transverse position of the detector D_i, $\vec{q}$ and $\vec{q}'$ are the transverse components of the momentum vectors, and $g_i(\vec{q},\vec{r}_i)$ is the Green's function associated with the propagations of the field with transverse momentum $\vec{q}$ from the source, to the position $\vec{r}_i$ at the detection plane defined by the detector D_i. $g_i(\vec{q},\vec{r}_i)$ is defined in a similar way as in Eq. **??**.

It is important to note that there are two main differences with respect to the SPDC case: First the presence of a background noise (first term of Eq. A.2), which does not exist for SPDC. Second, the possibility of writing the second term of Eq. A.2 as a product of the first order correlation functions, $G^{(1)}_{12}G^{(1)}_{21}$, while there is no way to write the biphoton produced by the SPDC as a product of other correlations. Also this term $|\sum_{\vec{q}} g_1^*(\vec{q},\vec{r}_1)g_2(\vec{q},\vec{r}_2)|^2$ Is the interference of intensities of a incoherent statistical assemble of randomly distributed photons.

Following the proces done in [**?**], it can be shown that for any values of distances d_A, d_B and d'_B which obey the equation:

$$\frac{1}{d_B - d_A} + \frac{1}{d'_B} = \frac{1}{f} \tag{A.3}$$

which clearly has the form on a thin-lens equation, defining a point-to-point correspondence between imaging and object plane. Then Eq. A.2 can be simplified as:

$$G^{(2)}_{tot}(\vec{r}_2) \propto N + |T\left(\frac{d_A - d_B}{d'_B}\vec{r}_2\right)|^2 \tag{A.4}$$

where $T(\frac{d_A - d_B}{d'_B}\vec{r}_2)$ is the object transmission function ($T(\vec{r}_1)$) reproduced on the D_2 plane. Thanks to this result we can conclude that a thermal source allows reproducing in coincidence measurements the two-photon image of an object, similarly to the SPDC case, except for a constant background noise, where N is proportional to it.

It is possible to establish an analogy between classical optics and entangled two-photon optics: the two-photon probability amplitude plays in entangled two-photon processes the same role that the complex amplitude of the electric field plays in classical optics [**?**].