Characterization of Entangled Photon Pairs Produced by a PPKTP Crystal

Antonio Linares Sancho, Mayerlin Nuñez Portela
Universidad de los Andes

The Periodically Poled Potassium Tytanil Phosphate (PPKTP) is a type of non linear crystal that serves as a source of production of entangled pairs of photons. The produced pair of photons, known as the signal and idler photons, possess unique characteristics within their entanglement that allow the production of new technologies such as quantum cryptography and quantum teleportation. The creation of the signal and idler photons occur through a process named Spontaneous Parametric Down Conversion (SPDC), which occurs when the pump laser beam penetrates a non linear medium. SPDC follows conservation of momentum and energy, thus imposing phase matching conditions on the generated photon pairs. These conditions result in specific space and frequency correlations of the photons. The aim of this project is to characterize the entangled photon pairs in their frequency spectrum, known as the Joint Spectrum.

I. INTRODUCTION

The interaction of a laser light source with a second order nonlinear crystal (with high second order electric susceptibility) produces entangled pairs of photons of lower energies via the process of Spontaneous Parametric Down Conversion (SPDC)[3, 4]. These photons have been the source and protagonists of developments of quantum computing, quantum cryptography, quantum communications and others [7, 8, 12, 17].

To introduce the behavior of non linear crystals, consider the general definition of the polarization vector

$$\vec{P} = \chi^{(1)}\vec{E} + \chi^{(2)}\vec{E}\vec{E} + \chi^{(3)}\vec{E}\vec{E}\vec{E} + ... \tag{1}$$

where $\chi^{(n)}$ represent the n^{th} order electric susceptibility and $\vec{E}$ the interacting electric field. For a second order non linear crystal, the $\chi^{(2)}$ is not negligible, so the polarization of the particles in the crystal is no longer linear with the interacting electric field, allowing for SPDC process to take place. With that said, the production of entangled photons, or SPDC, will occur when a laser beam penetrates a second order nonlinear crystal and the beam photons, known as the Pump photons, interact with the crystalline molecules to generate two lower frequency photons known as the signal and idler photons [6].

With the pump, signal and idler photons traveling through the crystal at different frequencies, it is expected that the index of refraction experienced by each wave is different. Also, accounting for the possibility that the photons have different polarization due to birefringence in the crystal, the paths they take through the crystal will depend on this parameter. This means that the index of refraction shall depend on the frequency and polarization of each photon, meaning that there is no obligation for them to be affected by the same index of refraction. This implies that the phase accumulated by each photon in the crystal can be different [6].

For the photons to be seen it is relevant that constructive interference takes place. That is, that the overall difference in phase is of multiples of 2π. This is known as phase matching. With birefringence, it's possible to make this happen by adjusting the angle of incidence. In the case where every photon is identically polarized, the effect of birefringence is negligible, making the phase matching conditions unattainable by angle tuning. The crystal to be studied at the laboratory has no birefringence. The SPDC that takes place within makes signal and idler photons with the same polarization as the Pump photon. In this scenario, the phase matching conditions must be attained by temperature tuning. This consists in modifying the temperature of the crystal so that the length is such that the accumulated phase between the entangled photons allows for constructive interference to happen.

The requirement that phase matching takes place poses restrictions on the angle at which the signal photon is emitted θ_s.

$$\theta_s = \theta_s(\omega_p, \omega_s, \omega_i, T) \tag{2}$$

From the definition of θ_s the analytical characterization of the PPKTP source is performed. This gives the experimental approach two different objectives: the characterization of the spacial profile and the relationship between the wavelengths of the produced photon pairs, known joint spectrum. The remaining objective, which is to be accomplished before the joint spectrum, is the temporal correlation between the signal and idler photons.

II. THEORETICAL BACKGROUND

The SPDC pocess follows conservation of momentum and conservation of energy, conditions that are expressed as

$$\omega_P = \omega_s + \omega_i \tag{3}$$

and

$$\Delta_k = \vec{k_p} - \vec{k_s} - \vec{k_i} = 0 \tag{4}$$

.

[3, 4, 6, 9, 15].

In the case of a PPKTP crystal, the poling period induces an extra $\vec{k_g}$ vector that fixes the mismatch [9], making equation (4) take the form of

$$\Delta_k = \vec{k_p} - \vec{k_s} - \vec{k_i} - \vec{k_g} = 0 \quad (5)$$

. An analysis of equation (5) on the longitudinal axis of the crystal and the transversal plane of the crystal yields an expression for the angle of emission of the signal photon, denoted θ_s, which is the angle between the wave vectors $\vec{k_p}$ and $\vec{k_s}$ and depends on the temperature of the crystal and the wavelength of the pump photon [2, 9, 10]. With some algebra, it's possible to isolate θ_s from Eq. (5) as

$$\theta_s(T, \omega_p, \omega_s, \omega_i) = \sqrt{\frac{2n_i\omega_i}{n_s\omega_s}[1 + \frac{\frac{2\pi c}{\Lambda} + n_p\omega_p}{n_i\omega_i + n_s\omega_s}]} \quad (6)$$

Since the refractive index depends on the wavelength of the traveling wave, θ_s has explicit and implicit dependence on the frequencies of the pump, signal and idler photons. Also, since the index of refraction and the poling period of the PPKTP crystal depend on temperature, θ_s has implicit dependence on the temperature of the crystal.

From Eq. (6) it is possible to obtain a relationship between θ_s and the temperature of the crystal for a degenerate case of λ_s and λ_i. This relationship is shown in Fig. 1.

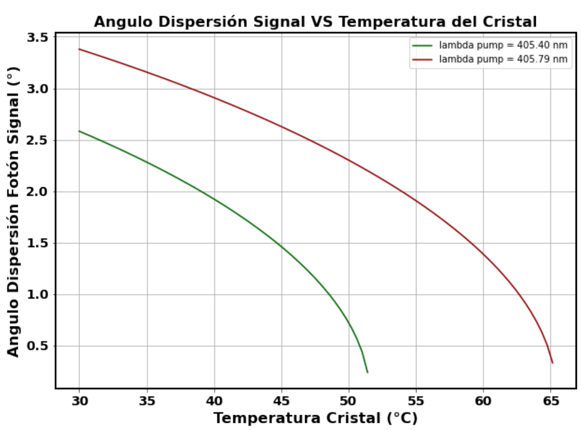

Figura 1. θ_s vs Temperature for two different λ_p: $\lambda_p = 404{,}8$ nm and $\lambda_p = 405{,}1$ nm, with λ_p being the value in vacuum

It is evident that θ_s does not reach 0 °. For that to happen, the crystal must be heated up until it reaches the threshold temperature T_h, which is when the entangled photon pairs become collinear. Consequently, the signal and idler photons become non degenerate with the crystal temperature above T_h. Because of this, it is of interest to understand the difference between the signal and idler wavelength $\Delta\lambda$ as the temperature increases beyond T_f. For a pump wavelength of $\lambda_p = 405{,}26$ nm, such relationship is shown by Fig. 2

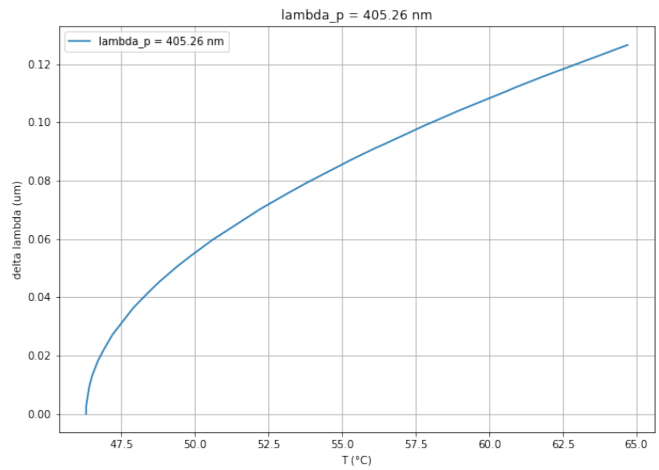

Figura 2. $\Delta\lambda$ VS Temperature for $\lambda_P = 405{,}26$ nm at temperatures above threshold.

Analytically, in order to see high values of $\Delta\lambda$, the temperature of the crystal must be increased. Clearly, it is expected to see different combinations of λ_s and λ_i for different configurations of $l\lambda_p$ and temperature of the crystal. The values of λ_s and λ_i that the signal and idler photons may have simultaneously are expressed by the joint spectrum.

The joint spectrum may be calculated with time dependent perturbation theory. The relevant integrals yield the conservation of momentum and conservation of energy conditions [11, 13, 15]. From there, the joint spectrum is obtained as

$$JS(\omega_s, \omega_i) = |e^{\frac{\Delta k(\omega_s,\omega_i)L}{2}} sinc(\frac{\Delta k(\omega_s, \omega_i)L}{2})|^2 \quad (7)$$

which corresponds to the probability of finding a pair of signal and idler photons at any particular combination of λ_s and λ_i. Visually, equation (7) is represented by Fig. 3.

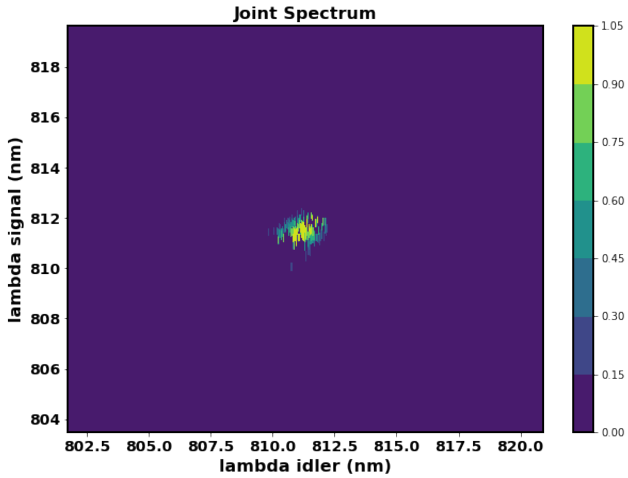

Figura 3. Analytical joint spectrum of the signal and idler photons.

III. EXPERIMENTAL SETUP

As mentioned previously, the goal of this project is to characterize the entangled photon pairs produced by a PPKTP crystal. This means that we will attempt to measure the spatial profile of entangled photon pairs created, the time correlation between the signal and idler photons, and their corresponding joint spectrum. Since SPDC consists in the absorption of a pump photon to produce two entangled photons, the experimental setup will require an adequate pump light beam to optimize the second order non linear interaction within our PPKTP crystal. Then, once the optimal pump beam is obtained for our specific PPKTP crystal, the spatial profile, time correlation, and joint spectrum of the entangled photon pairs will be measured. Consequently, the experimental setup is divided into three different parts: the pump light beam, the PPKTP crystal, and the characterization.

A. Pump Light Beam

The creation of entangled photon pairs within a PPKTP crystal requires that the pump photons respect three conditions. First of all, they must be single frequency because even though SPDC can still occur with different pump wavelengths, the lack of a unique wavelength within the pump beam will invalidate any information from the data obtained. Specifically, the wavelength of the pump light beam will play the role of either independent variable or controlled variable in the experiment, reason for which it must be well defined at one precise value for an entire set of data. Second of all, since a set of data requires a unique frequency among the pump photons, the pump light source must provide a stable single frequency beam for a relatively long period of time. Finally, the pump light beam must behave as a Gaussian beam so that it takes the form of a plane wave at the focus because this allows optimal second order non linear interaction within the crystal [1, 5, 14].

With the requirements stated, the proper light source for the experiment is a Light Amplification by Stimulated Emission Radiation (LASER) because of its potential of providing a stable single frequency Gaussian beam. Specifically, the LASER to be used is diode $Thorlabs\ DL5146-101S$, which radiates at 405 nm with maximum power of 40 mW. Although it is said to radiate at 405 nm, the actual wavelength will vary according to the current and temperature at which the diode is working. At the laboratory the wavelength is then tuned with a current and a temperature controller of the diode.

Now, in order to fulfill the requirements of the pump light beam, the experimental setup to be implemented consists of three sub-setups: the external cavity LASER diode Littrow Configuration, the alignment setup, and the Spatial Filter. The Littrow Configuration makes the pump light source a single frequency source of high frequency stability. The alignment setup is implemented to ensure that the light beam travels through the desired path. The Spatial Filter makes the spacial profile of the light beam more Gaussian-like by removing noise from the light source and allowing the manipulation of the spatial profile with different lenses.

1. *External Cavity LASER Diode Littrow Configuration*

The goal of this setup is to provide higher stability in single frequency modes to the LASER diode. This is achieved by placing a diffraction grating ($Thorlabs\ GH25-24V$), which has 2400 lines per mm, in front of the LASER beam. The function of the grating is to generate feedback, which means to return a portion of light back to the LASER diode to create an external cavity and make the light source more single frequency. To maximize the feedback, the grating is placed at a critical angle with respect to the propagation vector of the pump beam. The current controller allows the measurement of the feedback, making it possible to find the optimal angle of the grating. The Littrow configuration may be appreciated in Fig. 4

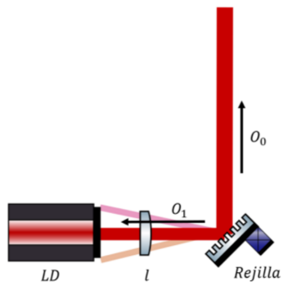

Figura 4. Littrow configuration setup design. Image taken from [9].

2. *Alignment Setup*

The main goal of this setup is to guide the LASER beam through a convenient path. It is desired that the light beam travels perfectly through the spatial filter, which, depending on the lenses used, may be as long as 10 cm. This means that the light beam must be aligned so that it is perfectly parallel to the path of the spatial filter. In order to perform such alignment, a mirror of high reflectivity of blue light $Thorlabs\ BB1-E02$ (E02) and a Dichroic Mirror $EKSMA\ HR/HT$ 405/810 (DM) is used. The DM serves the same alignment task as another $BB1-E02$, while it also allows some infrared light within the source to be removed from the experiment [16]. The alignment consists in making sure that the light passes through two consecutive, yet far apart from each other, holes known as iris, which are placed at the exact same height. The guidance of the light beam through both iris is done by adjusting the horizontal and vertical directions of the beam in each of both mirrors. The optimization of this process is made by measuring and maximizing the power that is allowed to go through each iris. The idea is that if the iris are well apart from each other and maximum power is allowed to go through each iris, then the light beam is traveling parallel to the line that joins both iris. Once the path is well defined, the spatial filter may be implemented. Figure 5 illustrates the setup described.

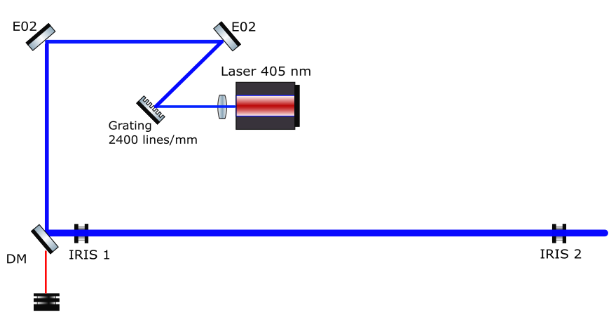

Figura 5. Alignment setup

3. *Spacial Filter*

Once the light beam is perfectly aligned, the spatial filter may be placed. This setup consists in focusing all of the pump light into a pinhole of 25 μm diameter. To do that, lens $Thorlabs\ LA1027-A$ with focal length of 35 mm (F35) is placed right after the DM. At the focus of the F35 lens is placed the 25 μm diameter pinhole. After the pinhole the light is set to diverge, reason for which it is focused to lens $Thorlabs\ LB1471-A$ with focal length of 50 mm (F50). The setup and function of the spatial filter may be observed in Fig. 6.

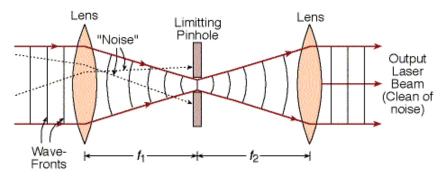

Figura 6. spatial filter. First lens focuses light into pinhole to clean the pump bean from noise. Second lens is used to focus light beam into the posterior setup.

Naturally, the incoming light beam has an elliptical spacial profile. After the spatial filter the light comes out with a circular profile and a Gaussian intensity. Such change may be visualized in Fig. 7, where the left image corresponds to the spacial profile of the original LASER beam and the right image represents the LASER beam after the spacial filter.

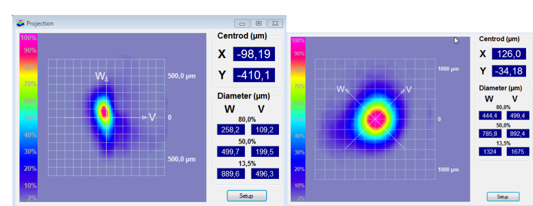

Figura 7. spatial profile of pump beam at a distance of $65cm$ from source. Left: before spatial filter. Right: after spatial filter.

Although the spacial filter makes the light beam very convenient spatially, it does reduce the power of the pump beam. In theory, the loss of light corresponds to 60 percent of the original, however, it was seen that the implemented spacial filter removed 77 percent of the incoming light beam.

Now, given that lenses may be subject to small imperfections, the spatial filter ruins the perfect alignment. This means that two other E02 mirrors will be placed to perfectly align the beam through the PPKTP crystal. This process is conceptually identical to the one illustrated in Fig. 5.

B. PPKTP Setup

Now that an optimal light beam has been created, the setup of the PPKTP crystal may be implemented. The goal is to make sure that a stable single frequency light beam is interacting with the molecules in the PPKTP crystal. Although the first part of the setup provides a stable single frequency LASER beam, it is possible that at any moment the single frequency characteristic ends. For this reason, this part of the setup must allow continuous knowledge of the pump wavelength and whether it is single frequency or not. Simultaneously, to optimize the second order non linear interaction of the pump LASER beam with the PPKTP crystal, the proper study of the spacial profile of the pump beam must be made.

To guarantee a continuous knowledge of the state of the pump LASER beam, a microscope glass (MG) is placed right before the PPKTP crystal. This will reflect around 10 % of the light into a Single Mode Fiber *Thorlabs* $FT030-Y$ (SMF), which guides the pump beam to the wavelength meter (*High Finesse* $WS/6-200$).

Regarding the spatial profile of the pump beam, the PPKTP crystal at the laboratory has dimensions of 15 mm $\times$ 2 mm $\times$ 1 mm. The crystal is placed inside an oven that allows temperature tuning of the material. This oven is 40 mm long. Now, to maximize entangled photon pair production, the LASER beam must behave as a plane wave inside the crystal. Since the spatial filter provided a clean Gaussian beam, the pump wave is set to behave as a plane wave at the focus. The length of the region at which the light beam remains a plane wave is known as the Rayleigh Range [1, 5, 14]. It is then pertinent that the light beam has waist less than 1 mm throughout a Rayleigh Range greater than 40 mm long so that no photon is allowed to hit with the borders of the crystal or the oven. To achieve such conditions, the second lens of the spatial filter is moved either closer or further away from the pinhole until the desired waist and Rayleigh range are observed. After this was executed, the observed spacial profile at the focus is illustrated by Fig. 8. The obtained waist has a value of 147,2 μm with a Rayleigh range of 5,0 $\pm$ 0,5 cm.

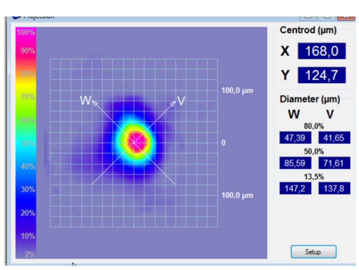

Figura 8. spatial profile of pump beam at the focus. The waist measured is of 147,2 μm

With the proper spatial profile of the pump wave, the oven with the PPKTP is placed anywhere within the Raleigh Range. The overall setup until the PPKTP crystal is illustrated in Fig. 9

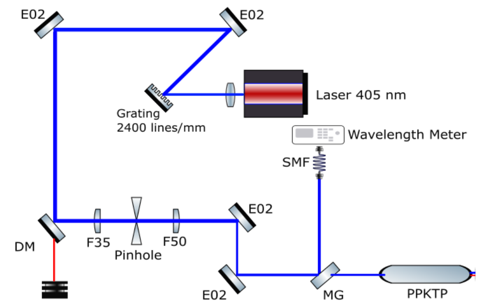

Figura 9. Main Setup

C. Characterization

1. *Spacial Correlation*

With a setup that optimizes the entangled photon pair production, it is now possible to describe the actual characterization in space, time, and frequency of the signal and idler photons. As seen in Ch. **??**, the spacial profile of the entangled photon pairs will be circular. These rings are visualized with the use of a CCD Camera with long-pass filters *Thorlabs* $FEL750$ to neutralize the remaining pump photons. These rings depend on the temperature of the crystal. Such dependence can be appreciated with Fig. 10, where the left image shows the spacial profile of the photon pairs produced with the crystal at a temperature of 34 °C and the right image represents the ring produced at a temperature of 42 °C. Both rings in Fig. 10 were created with a pump wavelength of $\lambda_P = 405{,}4712$ nm.

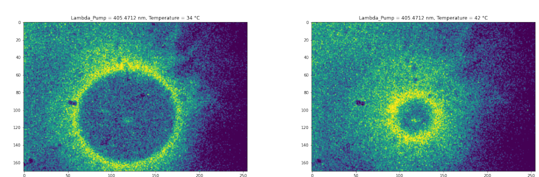

Figura 10. Spatial Profile of produced photon pairs with $\lambda_P = 405{,}4712$ nm. Left: temperature of the crystal at 34 °C. Right: temperature of the crystal at 42 °C

From the rings it is possible to obtain the angle of propagation of the signal photon.

2. *Temporal Correlation*

Once the crystal is producing entangled photon pairs through SPDC, the next step is to measure the time correlation of the photon pairs. In order to do so, the photons will be separated with the use of a beam splitter and coupled to identical multi.mode fibers to separate Single Photon Counters. The photon detectors are connected to the FPGA, which determines the time difference between the counts received by the detectors. This procedure requires to solve two main problems: the photon pairs must be aligned and collimated to ensure that as they travel through space they don't get further away from each other, and the blue pump photons that were not absorbed must be removed.

First, in order to collimate the photon pairs, a lens $Thorlabs\ L1027 - B$ is placed in front of the PPKTP crystal. The CCD Camera is used to study how the rings grow as they travel through space. The goal is to place the lens in a position where the rings will not diverge as the CCD Camera is placed further away. After this is accomplished, one iris is placed right after the lens, while the other is placed right before the beam splitter. The distance between the lens and the beam splitter should be as long as the available space allows. The idea behind the iris is that they are placed exactly where the rings are, so that a similar aligning procedure as that described in the previous part of the setup can take place. After the photons have been collimated, the beam splitter is set and two paths of equal length are designed. For each path, two infrared reflecting mirrors $Throlabs\ BB1 - E03$ are used for proper alignment. Each path ends at a lens with focal length of 11 mm to couple the photons to identical multi-mode fibers, which guide each photon into single photon counters. The photon detectors are electronically connected to the Qu-Tau, which is a tool used to detect time difference in the arrival of the signal and idler photons. Finally, the undesired light is filtered with two long-pass filters $Thorlabs\ FEL$ 750. Figure 11 illustrates the described setup.

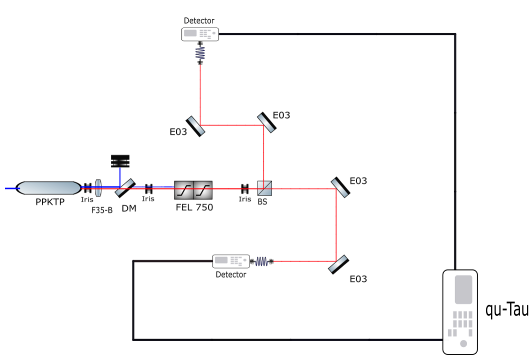

Figura 11. Temporal correlations experimental setup to study the time delay between the signal and idler photons.

The corresponding data regarding time correlations obtained is visualized in Fig. 12, which illustrates a Start-Stop histogram. The start-stop histogram is a graph with number of coincidences in the y axis and time delay between the signal and idler photons in the x axis. It tells us how many coincidences were detected at any given time delay.

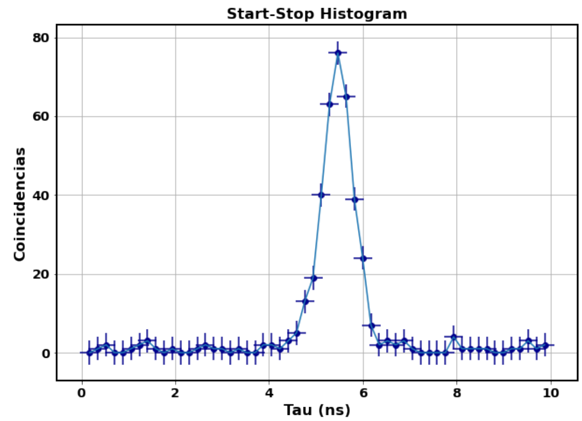

Figura 12. Temporal Correlations measured. The peak indicates that the produced photon pairs have temporal correlation and that their specific time delay is centered at around 5,5 ns

3. *Frequency Correlation: Joint Spectrum*

Now that the spatial and temporal correlations have been measured, we proceed to adjust the setup to facilitate the measurement of the joint spectrum. For this, its important to recall the meaning of a joint spectrum. As studied in Ch. **??**, the joint spectrum is the square of a probability density function known as the joint spectral amplitude. To measure the probability of finding a pair of photons at any combination of λ_s and λ_i, the experimental setup for this measurement must be able to count the number of pairs that have wavelengths λ_s and λ_i and plot that count as an intensity. To achieve the measurement, we will use two monochromators, one for the signal photons and the other for the idler photons. To explain the setup it is important to understand the functioning of the monochromators.

A monochromator makes use of dispersion in order to filter every photon that is not at a specific wavelength value. The way it does this is by allowing all light that enters through an entering opening to go through a prism where the incident photons get dispersed. Given that the angle at which each photon is dispersed depends on its wavelength, it is possible to place the prism in such a way that only one specific and desired wavelength is dispersed in the direction of the exit opening. The previous description is appreciated in Fig. 13

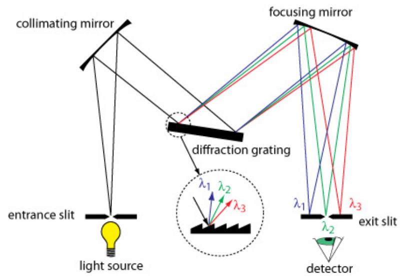

Figura 13. Illustration of the functioning of a monochromator. Incident light with multiple frequencies gets dispersed by a grating of 800 lines/mm so that a desired wavelength is not filtered out. The grating may be rotated to measure any wavelength within the specified domain. Image taken from `https://asdlib.org/imageandvideoexchangeforum/wavelength-selection-using-a-monochromator/`

With two monochromators, the idea is to fix one monochromator to measure a specific wavelength while the other loops over a specified range of wavelengths. After the loop is done, the first monochromator is fixed at the next wavelength value and the second repeats the loop. This takes place until both monochromators have measured every wavelength within the chosen range, or, in other words, until every possible combination of λ_s and λ_i is covered. In our experiment, due to the conservation of energy, the possible wavelength value of the entangled photon pairs will be centered at 810 nm for a 405 nm pump LASER beam. This means that the range of wavelengths for our measurement of the joint spectrum may be chosen so that the central wavelength is 810 nm. The measurement that is intended is to count the number of entangled pairs of photons that were detected at each specific combination. For example, when the signal and idler monochromators takes the values of 805,6 nm and 808 nm respectively, the corresponding measurement is the amount of coincidences that have a signal photon with wavelength of 805,6 nm and an idler photon with wavelength of 808 nm. The joint spectrum will then follow by plotting the number of coincidences of each (λ_s, λ_i) coordinate as an intensity.

To minimize the error in the measurements, the monochromators must be calibrated. This consists in making sure that both of them are allowing the measurement of the wavelength that was specified by the user. In order to do this, an argon calibration source is used. This tool, provided by Ocean Optics, sends light emitted by excited argon through a multi-mode fiber. Since the argon emission spectrum with the intensity of each emitted wavelength is well known, sending the argon light through the monochromators will allow us to know if they are making proper wavelength measurements. For illustration, consider the image in Fig. 14, which refers to the analytical spectrum of the emitted light by Argon

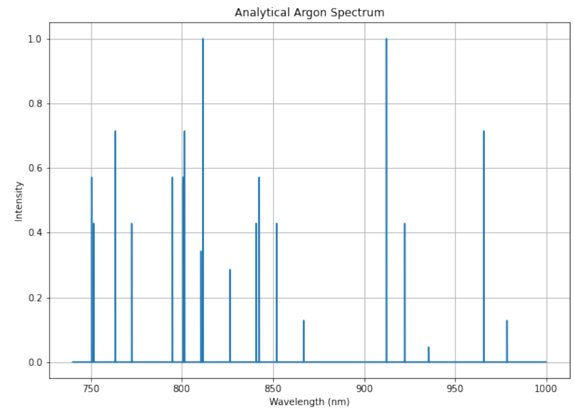

Figura 14. Analytical Argon spectrum

The spectrum of Argon, as measured by the monochromators at the laboratory are seen in Fig. 15.

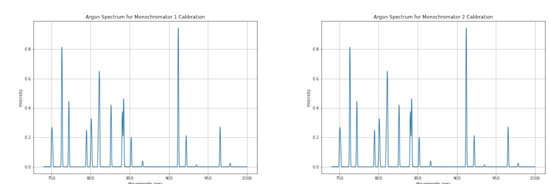

Figura 15. Argon spectrum as measured by both monochromators at the laboratory. Left: spectrum measured by monochromator 1. Right: spectrum measured by monochromator 2.

To implement the measurement of the joint spectrum experimentally, a similar setup as the time correlation setup will be assembled. However, instead of sending the created photons directly into the single photon counters, the signal and idler photons will go to the monochromators. From there, the photons are sent through a multimode fiber to the single photon counters. The single photon counters are connected to the FPGA, which is an alternate tool to the QuTau to measure time correlations. Then, if the FPGA detects a coincidence of two photons, one count is added to the coordinate corresponding to the λ_s and λ_i value in the joint spectrum.

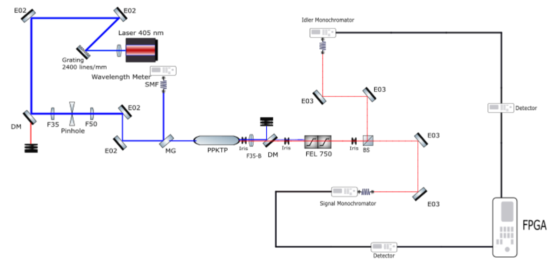

Figura 16. Joint Spectrum setup. signal and idler photons are sent to monochromators, where only specific values of wavelength pass through and into multi-mode fibers for the single photon counters. A count of coincidences at λ_s and λ_i takes place and is plotted as an intensity in the joint spectrum

Intuitively, since the joint spectrum depends on coincidences, and since the amount of coincidences depends on the rate at which the PPKTP generates entangled photon pairs, then the longer the measurement is programmed to be, the more coincidences may occur per combination of λ_s and λ_i. The time taken to count coincidences per each combination of λ_s and λ_i may be fixed with the FPGA. The specific values depend on the stability of the pump beam.

IV. RESULTS

The conservation of momentum restriction over the entangled photon pairs result in a circular spacial profile like represented by Fig. 10. From these rings, an experimental analysis of the relationship between Θ_s and the temperature o the crystal can be made with the use of simple geometric tools.

From the experimental setup one knows the distance from the center of the crystal to the camera. One also has knowledge of the length of the crystal. A potential triangle is obtained with a line joining the crystal and the camera and with the radius of the measured rings. The radius may be obtained using the camera's software, which informs the x and y coordinate of any pixel in the image. Knowing the x coordinates, one may get the diameter of the circle by subtracting the x value of two pixels in opposite ends of the circle. In the camera, one pixel corresponds to 9 μm in distance, making the radius accessible in cm. The triangle looks like the one in Fig. 17

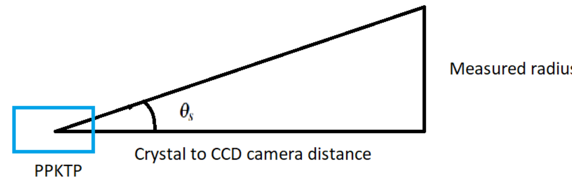

Figura 17. Triangle formed by pump wave and signal wave. The radius of the ring is measured in pixels and converted to distance. In the CCD Camera, one pixel corresponds to 9 μm.

In the experiment, the distance between the crystal and the camera was measured to be 3,0 cm. Since the exact position of the screen inside the camera is unknown, an error of 0,5 cm is accounted for. With the crystal being 1,5 mm long, and assuming that the SPDC process took place in the middle of the crystal in average, the horizontal component of the triangle in Fig. 17 takes the value of 3,75 $\pm$ 0,5 cm. Regarding the radius, since SPDC was assumed to take place in the middle of the crystal, the diameter of the rings were measured according to the pixel in the middle of the circumference. This pixel is selected with an error of 5 pixels to each side, meaning that any measured diameter will be x $\pm$ 10 pixels long. From there the radius is obtained. If the distance between the camera and the crystal is D and the radius is R, then $\theta_s = \arctan \frac{R}{D}$.

In the experiment, the value for λ_p was 405,4712 nm. For temperatures of 39 °C, 43 °C, and 45 °C the spacial profile of the entangled photon pairs was measured. The obtained results may be appreciated in Fig. 18, 19, and 20 respectively.

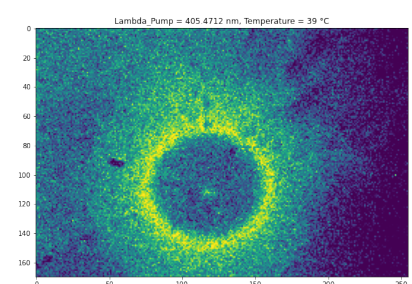

Figura 18. $\lambda_p = 405{,}4712\ nm$. Ring measured with the crystal at 39 $°C$

Clearly, as the temperature of the crystal increases, the radius of the rings plotted by the camera decreases. A value of θ_s is obtained for each image and is graphed with respect to the temperature of the crystal alongside the analytical curve. Such graph is seen in Fig. 21.

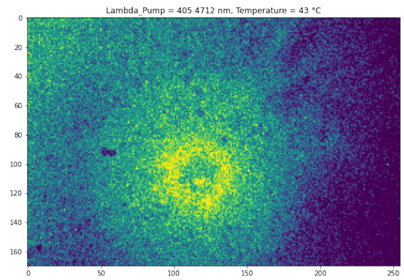

Figura 19. $\lambda_p = 405{,}4712\ nm$. Ring measured with the crystal at 43 $^\circ C$

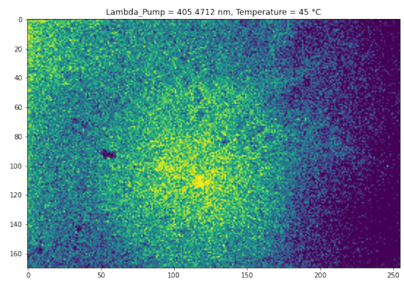

Figura 20. $\lambda_p = 405{,}4712\ nm$. Ring measured with the crystal at 45 $^\circ C$

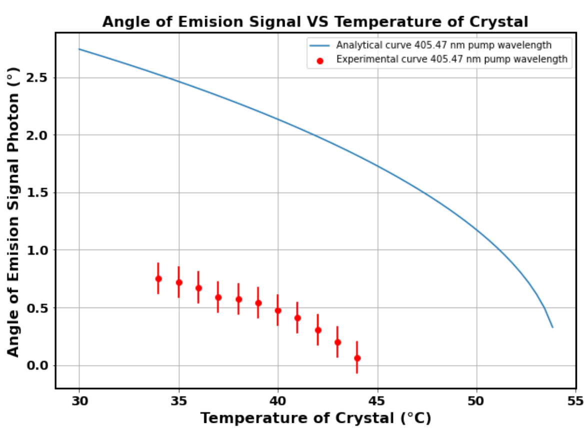

Figura 21. θ_s vs temperature of the crystal. The blue curve represents the expected behaviour of θ_s with respect to the temperature of the crystal according to theory. The red scattered curve represents the experimental values for θ_s measured at different temperatures.

The experimental behaviour of θ_s as the crystal is heated up has a similar form of that expressed by the theory. However, the experimental curve is shifted by roughly 10 °C with respect to the analytical curve. This error in the measurement may be due to a possible lack of calibration in the wavelength meter.

V. TEMPORAL CORRELATION

From the time correlation setup in Fig. 11 the number of coincidences at different time delays between the signal and idler photons may be measured. A start stop histogram was obtained for entangled photon pairs at a pump wavelength of 405,4712 nm and a crystal temperature of 43 °C. The corresponding graph is shown in Fig. 22

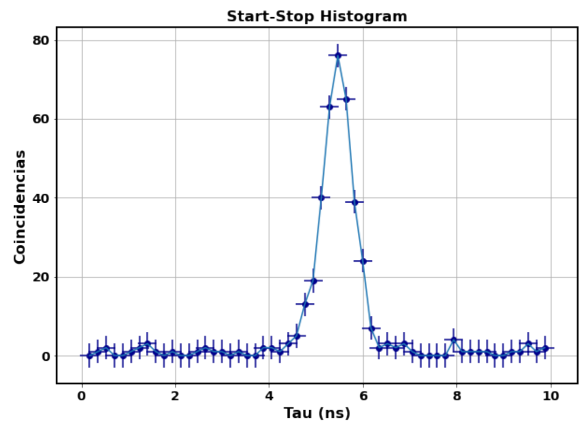

Figura 22. Start stop histogram centered at 5,5 nm.

In theory, the entangled photon pairs are created simultaneously, meaning that their relative time delay should be at 0 ns. In the experiment performed, the delay is centered at 5,5 nm due to possible differences in length of the paths travelled by each photon or a setting in the software. However, the existence of a peak indicates that the photon pairs created by the PPKTP crystal are entangled, otherwise no correlation would be seen in the start stop histogram.

VI. JOINT SPECTRUM

During the measurement of the joint spectrum it was observed that, when using the $FEL750$, the only light that would come out of the monochromators was pure noise. The data shown by the single photon counters did not change if the light from the experiment was entirely blocked. For this reason, the solution to use neutral density filters instead of the long-pass filters was implemented. This was supported by the idea that the monochromators would not allow any unwanted blue light into the detectors when measuring infrared signal and idler photons.

A. With Neutral Density Filters

The available stable pump wavelength was $\lambda_p = 405{,}2106$ nm. At this pump wavelength the threshold temperature takes value of 29 °C. Two measurements of the joint spectrum were made: one at threshold temperature and the other beyond threshold temperature. This was done to visualize the change in the signal and idler spectrum as they are allowed into a more non degenerate case.

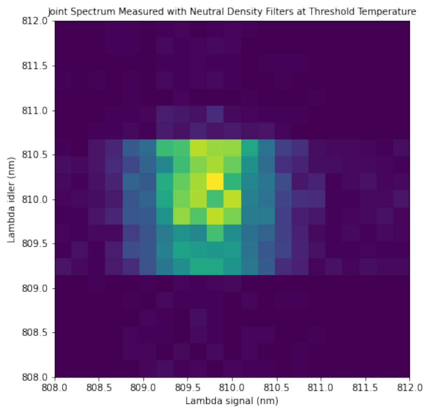

Figura 23. Measurements of the joint spectrum made with Neutral density filters and crystal at 29 $^\circ C$, which corresponds to threshold temperature for the used λ_p.

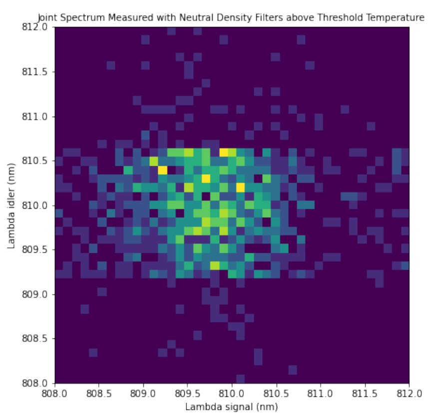

Figura 24. Measurements of the joint spectrum made with Neutral density filters and crystal at 40 $^\circ C$, which corresponds to threshold temperature for the used λ_p.

It was seen that the entangled photon pairs exist with high intensity at the degenerate region, which was expected for temperatures below and not far above the threshold temperature, as seen in Ch. **??**. Figure **??** shows that this was obtained for the measurement at the threshold temperature. However, it was also expected to see that the intensity of photon pairs with non degenerate values of λ_s and λ_i take non zero values. According to Fig. **??**, this was not observed, since both graphs behave similarly in the non degenerate regions. Since this result is far from the analytical joint spectrum, the lack of long-pass filters may be the problem. It is suspected that, even though the monochromators are set to measure in the infrared spectrum, they are still able to measure second modes within the pump beam, allowing measurements of infrared light that is not related to the photon pairs created.

VII. CONCLUSIONS

The results obtained in the experiment for the spacial profile and time correlations do agree with the theaory. Although the relationship between λ_p and the temperature of the crystal is shifted from the analytical curve, the behaviour is similar. On the other hand, the result obtained for the joint spectrum does not agree with the one reported by the theory. Although the time correlation between the photons produced in the experiment does exist, the information is lost as they travel through the monochromators. This is concluded because the analytical value of signal wavelength is not being detected after the monochromators. Regardless, the measured joint spectrum turned out to be a false alarm. This is simply due to the fact that the long pass filters do not neutralize the entangled photon pairs and should not be an obstacle in the measurement.

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