SPECTRAL PROPERTIES OF AN EFFICIENT ENTANGLED PHOTON SOURCE BASED ON BULK PPKTP

Daniel Pérez Gumà

Supervised by Dr. Valerio Pruneri, (ICFO)

Presented on date 1st September 2011

Registered at

Escola Tècnica Superior d'Enginyeria de Telecomunicació de Barcelona
Spectral properties of an efficient entangled photon source based on bulk PPKTP

Daniel Pérez Gumà
ICFO - Institut de Ciències Fotòniques, Mediterranean Technology Park, 08860 Castelldefels (Barcelona), Spain
E-mail: daniel.perez.guma@gmail.com

Abstract. The main objective of this thesis is to study and characterize the spectral properties of spontaneous parametric down conversion (SPDC) generated in bulk periodically poled potassium titanyl phosphate (PPKTP). The work carried out is an essential step towards the implementation of a high brightness photon-pair source for long distance quantum key distribution (QKD) experiments in a free-space environment.

Keywords. Quantum key distribution, spontaneous parametric down conversion, PPKTP

1. Introduction and motivation

Nowadays society needs for fast and secure communications is undeniable. Up to the present time communication and cryptography techniques are being used taking advantage of our knowledge about the realm of classical physics. In this context classical electrodynamics is the solid ground in which all current communication systems are based: wifi local area networks, mobile communications, optical networks, bluetooth, etc... However, quantum physics has become an intensively studied research field over the last century. It turns out some scientific and technological breakthroughs suggest that current classical cryptography could be defeated by near-future quantum systems. This is the reason why the scientific community is pursuing the creation of quantum communication systems.

1.1. The end of classical cryptography

Classical cryptography suffers from two main flaws: either the security of a protocol is not unconditional (i.e. 100% secure) or the key exchange between the parties is very unpractical.

The first issue is usually related to public-key systems, where the security of the key is based on what is called a one way function. One-way functions are mathematical operations that are very easy to compute in one way, but very difficult to reverse.
An example of this technique is the widely used RSA protocol where the security is based on the difficulty of finding the prime factors of large integers. Finding the prime factors of a number using a classical computer is a problem that has exponentially growing complexity with respect to the key length. However, it has been demonstrated that there exists at least one routine (Shor’s algorithm) implementable in a quantum computer that can solve this one-way function in polynomial time. Therefore, the path towards quantum computation renders classical public-key systems.

The second issue is usually related to secret-key systems. In this case the security of the data is based on the assumption that only the two parties involved know the key. This is very unpractical because one entity might want to exchange information securely with many parties, therefore needing many different keys. Moreover, only the face-to-face key exchange would be 100% secure, which is expensive and time consuming.

QKD can solve the problems mentioned before. Thanks to the laws of quantum mechanics, the security of the keys is assured and their creation is remotely negotiated. Quantum protocols are based on the exchange of quantum particles between the two parties namely Alice and Bob. A series of measurements of the states of such particles by Alice and Bob enable the creation of the secure key [2].

1.2. Outline of the project

In section 2 the design of the entangled photon source is described. The numerical model and its main parameters are commented as well. In section 3 the experimental set-up is shown and discussed. Finally in section 4 the results obtained in the laboratory are analyzed and compared with the numerical model.

2. Theory

Currently, SPDC is the most widely used physical process to create entangled photon pairs. This phenomenon is purely quantum, taking place at the particle level. SPDC can be understood as a spontaneous decay of one photon traveling in a nonlinear optical medium into a pair of lower energy photons called signal and idler. The process is allowed only when energy and momentum are conserved. The energy conservation can be expressed in terms of the photon energy as

\[ \hbar \omega_p = \hbar \omega_s + \hbar \omega_i \]  

where \( \omega_{p,s,i} \) is the angular frequency of the pump, signal and idler photons respectively. The technique aiming at achieving momentum conservation is called phase matching. There are two approaches that can fulfill the momentum conservation law: birefringence and quasi phase matching (QPM). In this project the QPM approach has been chosen mainly because of two advantages with respect the birefringence technique. First, the highest nonlinear coefficient of the crystal can be used (in our crystal we will exploit \( d_{33} \)). Secondly, aligning the direction of propagation with one of the crystallographic axes, the beam does not suffer the walk-off effect because the wavevector
Spectral properties of an efficient entangled photon source based on bulk PPKTP and the poynting vector are parallel. Therefore, the beam is better confined and as a consequence the nonlinear interaction is more efficient.

The QPM is achieved in our case by means of a ferroelectric periodic poling technique of the PPKTP crystal. The periodically reversed crystallographic axes orientation enables the phase mismatch compensation between the pump, signal and idler. The domain inversion is engineered applying strong electric fields by means of patterned electrodes. The initial design of the photon source determined a value of 3.425\,\mu m for the poling period.

The periodically poled crystal structure has the key role in the momentum conservation equation. The phase matching condition for a collinear interaction can be written as [3]

\[ k_p = k_s + k_i + \frac{2\pi}{\Lambda} \]  

(2)

where \( k_{p,s,i} \) are the pump, signal and idler momenta and \( \Lambda \) is the poling period of the PPKTP crystal. Therefore, the momenta mismatch can be expressed as

\[ \Delta k = 2\pi \left( \frac{n_p(\lambda_p, T)}{\lambda_p} - \frac{n_s(\lambda_s, T)}{\lambda_s} - \frac{n_i(\lambda_i, T)}{\lambda_i} - \frac{1}{\Lambda} \right) \]  

(3)

where the dependence of the refractive indices \( n_{p,s,i} \) with respect to the wavelength and the temperature have been written. Using a continuous wave (CW) pump, the spectrum of the SPDC is [1]

\[ S(\lambda_{s,i}) \propto \text{sinc}^2 \left( \Delta k \frac{L}{2} \right) \]  

(4)

where \( L \) is the length of the PPKTP crystal, and \( \Delta k \) is the expression (3). The SPDC process in our experiments corresponds to type 0 (pump, signal and idler have the polarization along the \( z \) axis of the crystal).

Entanglement is created by crossing the crystallographic \( z \)-axis of two identical PPKTP crystals at 90 degrees with respect to each other. Signal and idler from the first and second crystals are superposed and the electric field can be written as a quantum superposition of both contributions, having orthogonal polarizations due to the crystal orientations. The most general form of the quantum state generated in this configuration may be written as

\[ |H_s\rangle \otimes |H_i\rangle + e^{i\phi} |V_s\rangle \otimes |V_i\rangle \]  

(5)

where \( H \) and \( V \) stand for the horizontal and vertical polarizations, and the subindices refer to signal or idler wavelengths. The phase \( \phi \) can be controlled to produce different Bell states. The quality of the entanglement depends on the indistinguishability of the field coming from the first and the second crystal. Any measurable property being different lowers the amount of entanglement. For this reason, a rigorous characterization of the SPDC spectra as well as comparison with the model calculation will be presented in the following.
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The numerical model is an implementation in MATLAB of the spectrum profile of SPDC shown in equation (4). The unknown parameters needed to be found in order to characterize the set-up are the refractive index of the pump \( n_p(\lambda_p, T) \) and the effective length of the crystals \( L_{\text{eff}} \). In section 4 the methods followed to find these parameters are detailed.

3. Set-up

The experimental set-up is shown in figure 1. Two different lasers were fixed, one being single-mode and the other multi-mode. The light is coupled into single mode fibers (SMFs). The laser is selected connecting the desired fiber with the launching fiber (dotted-line fibers indicate that they are used or not depending on the experiment). The polarization of the pump is controlled with the quarter-wave plate (QWP) and the half-wave plate (HWP). The fluorescence filter prevents possible long-wavelength radiation to cross the crystal and reach the avalanche photodiodes (APDs). The focusing lens plus the collimating lens enable to properly focus the pump beam inside the crystal. The pump cut filter plays the same role as the fluorescence filter, but in this case the pump beam is blocked. In both cases the goal is protecting the APDs from high power radiation. Finally the wavelength division multiplexer (WDM) splits the SPDC field in two different fibers, being one corresponding to the signal and the other to the idler. For the experiments in which the spectrum of the SPDC is recorded, the light is sent directly to a monochromator.

![Figure 1. Set-up of the experiments. Two different pumping lasers can be used, one being single mode and the other multimode. The beam is properly focused inside the PPKTP crystal with a focusing and collimating lenses. Two different SPDC detection stages are used, one being the monochromator (for spectral analysis) and the other the WDM plus the APDs (for photon coincidences analysis)](image-url)
4. Results

4.1. Thermal and wavelength expansion of the refractive index of the pump

The Sellmeier equations used [4] [5] in the numerical model have previously been reported to have limited applicability in the pump wavelength region [6], and only apply for signal and idler. Since the PPKTP is heated at different temperatures inside the oven and pumped with a multimode laser, a thermal and wavelength expansions of the refractive index are needed to complete the numerical model. First the 4th order wavelength expansion is computed at a fixed temperature (50°C). The fixed wavelength around which the polynomial expansion is calculated corresponds to the single mode laser center wavelength: 405.42 nm.

In figure 2(a) the result is shown. As it can be seen the center wavelengths of the different modes match, which validates the polynomial expression found. The spectral amplitudes provided by the simulation seem to be unprecise. The reason is that the multimode pump spectrum has a noisy behavior which affects the temporal evolution of the amplitudes of the modes. Since the spectrum recording process involves a time integration, the final amplitude has a random component.

![Multimode spectral intensity of SPDC at 50°C](a)

![Multimode pump spectrum for the wavelength expansion experiment](b)

**Figure 2.** (a) Multimode spectral intensity of SPDC at 50°C used to compute the wavelength expansion of the refractive index (b) Multimode pump spectrum for the wavelength expansion experiment

Once the wavelength dependence of the index of refraction is known, the thermal coefficients are computed. The method to do it consists of matching the signal and idler center wavelengths within a sufficiently wide range of temperatures. The reference temperature is 50°C because the wavelength expansion has been calculated at this value. The single mode laser is used this time. The 2nd order expansion provides a very good agreement between the simulation and the experimental data as it can be seen in figure 3.

To check that the thermal and wavelength expansion work fine together, a multimode SPDC spectrum is recorded experimentally and simulated at 48.3°C. Figure 4 confirms a good agreement of the joint expansion with the experiment.
Figure 3. Experimentally observed center wavelengths of signal and idler photons as a function of temperature. Simulated data shown using the optimized thermal expansion of the pump refractive index.

Figure 4. Multimode SPDC spectrum at 48.3°C of the 20mm PPKTP crystal. The center wavelengths of the multiple peaks are matched, therefore this experiment validates the thermal-wavelength joint expansion of the index of refraction at the pump wavelength region.

The expression of the pump refractive index with thermal and wavelength expansions can be finally written as

\[
n_p(\lambda, T) = n_p(\lambda_0, T_0) + A(T - T_0) + B(T - T_0)^2 + C(\lambda - \lambda_0) + D(\lambda - \lambda_0)^2 + E(\lambda - \lambda_0)^3 + F(\lambda - \lambda_0)^4
\]  

(6)

where \(T_0 = 50°C\) and \(\lambda_0 = 405.42\,nm\).

4.2. Bandwidth

Having analyzed the center wavelength of the peaks, the other important parameter from the communications point of view is the spectral full width half maximum (FWHM).
Like the center wavelength, the FWHM is temperature dependent [1], but also the length of the crystal defines the bandwidth. The longer the crystal the narrower the peaks. From experiments recorded for different temperatures we determined the effective length of the crystals. The specifications of the manufacturer only assure that the effective length is higher than 90% of the physical length, but do not provide the exact values. In figure 5 the FWHM of signal and idler are depicted for the \( L = 6.2\text{mm} \) crystal as a function of temperature. The simulation matches the experimental results at almost all temperatures. Only for very low temperatures near the degeneracy point the simulation provides slightly higher values than the experiments. The effective length that provides a better fitting of the experiment corresponds to 98% of the physical length.

In [1] the result of the theoretical FWHM with respect to the crystal length is provided. It turns out the bandwidth of the signal/idler is inversely proportional to the crystal length. A numerical simulation has been carried out to check the agreement of the experimental results with the numerical model. In figure 6 the FWHM dependency with respect to the crystal effective length is shown at \( T = 50^\circ\text{C} \). For large crystal lengths the non negligible 1.2\text{nm} resolution of the monochromators masks the real \( \frac{1}{L} \) dependence, and the experimentally recorded FWHMs are slightly higher than the values obtained with theory.

4.3. Angle detuning

Up to now the behavior of the system with respect to temperature, crystal length and pump wavelength have been analyzed. Another tolerance that needs to be tested is the angle of incidence of the pump beam. The quality of the optomechanics used to fix the components rely on the tolerance to misalignments. To check this issue a sweep of the angle of incidence of the pump has been performed. The center wavelength of the idler peaks is shown in figure 7. The highest center wavelength corresponds to
Figure 6. FWHM of signal and idler at 50°C in front of the effective length of the PPKTP crystal. Experimental data is shown for the 20mm crystal (18mm effective length) and the 6.2mm crystal (6.08mm effective length).

normal incidence, which means that the poling period seen by the beam corresponds to the value provided by the manufacturer. When the incidence angle is detuned (both positively and negatively), the effective poling period increases and this modifies the QPM equation, forcing signal and idler to move apart as they do when the temperature of the crystal is increased.

Figure 7. Experimental center wavelength drift as a function of the horizontal angle of incidence of the pump beam. This effect is caused, as a first approximation, by the increase of the effective poling period when the incidence of the pump is not normal to the input facet of the crystal.

4.4. Efficiency of the source using a WDM

One of the interesting parameters of the source is the number of photons per second emitted. The highest brightness (coincidences[MHz]/pump power[mW]) recorded during the project was $5.66 \frac{MHz}{mW}$, having a spectral brightness (coincidences[MHz]/pump power
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The dependence of the SPDC efficiency (brightness) as a function of temperature is discussed in this section.

As it is shown in figure 8, signal, idler and coincidence counts per second have a common maximum near the degeneracy point where the SPDC process is generated around 43.5°C. From this point on, the efficiency decreases. There are two effects contributing to this tendency: the FWHM dependence on the temperature and the WDM spectral profile. As it has been shown in figure 5, the FWHM of signal and idler decrease when temperature increases. As a result the overall power is steadily reduced. The other effect linked to the decrease of power is the WDM spectral distribution. The two output channels of this device have an optimum working wavelength where the losses of signal (idler) power is minimum and the isolation with respect to idler (signal) is at its maximum. When the working wavelengths move apart from this optimum the WDM introduces extra losses that bring a gradual decline of detected photons per second.

Apart from this contribution to the efficiency with respect to the temperature, the WDM has another interesting effect that impacts the coupling ratio. This ratio is defined as $\frac{R_c}{\sqrt{R_A R_B}}$ where $R_c$ is the coincidences rate, and $R_A$ and $R_B$ are the single photon rates of signal and idler. The coupling ratio is a figure of merit of the setup in terms of simultaneous coupling of signal and idler. The ratio has the optimal value at a slightly higher temperature (45.9°C) than the single and coincidences rates. At this temperature signal and idler are falling in the regions where the losses in their respective WDM channels bring an overall optimal coupling ratio. To visualize this effect the WDM spectral profiles can be seen in figure 9. The graph gives a qualitative idea of the different losses experienced individually by signal and idler when the temperature is changed.

![Figure 8](image.png)

**Figure 8.** Single photon, coincidences and coupling ratio of the source for different temperatures of the crystal (normalized values). Singles and coincidences have a common optimum temperature, while the coupling ratio reaches the optimum value at a slightly higher temperature.
Figure 9. WDM signal and idler channel losses (black lines) with a couple of SPDC spectra at different temperatures (red curves).

5. Conclusions

A number of experiments have been presented regarding the spectral properties of SPDC created in PPKTP. At the same time, a numerical model (MATLAB) characterizing the main parameters (center wavelength and bandwidth) in communication systems has been developed. The response of the set-up in front of temperature, pump wavelength, crystal length and angle tuning has been assessed. To the authors knowledge, there is not any multimode SPDC study published up to the present time. The numerical model could be used in the future to test the mechanical and thermodynamic tolerances in real-world working environments.

Acknowledgements

I want to thank Dr Valerio Pruneri for accepting me in the Optoelectronics group from ICFO. I am indebted to my supervisor Fabian Steinlechner for helping me all throughout these months. I also want to thank Marc Jofre for fruitful discussions.

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