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Twin Photon Source: Spatio-temporal Properties

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ABSTRACT

We propose a method to study and characterize the spatial and temporal properties of degenerate photon pairs emitted in SPDC, using a filtering system combined with temperature variation of the nonlinear crystal. The photons can be distinguished. We relate these to the measured Hong-Ou-Mandel interference dip of the photons, measured in a parallel experiment. The theoretical plots match very well with the experimental results.

Keywords: quantum information and processing; quantum communications, parametric down-conversion; nonlinear crystal, non-classical photon sources, entanglement.

1. INTRODUCTION

The field of quantum information has bloomed in recent years showing enormous advancement in the use and control of quantum systems, like atoms, ions and photons[1,2] (and references therein). This has triggered many applications in quantum computation, quantum communication and metrology.

One possible reason for this explosion of works, mainly in the quantum entanglement and communication, is due to the achievement of more efficient and more compact sources of entangled and correlated photons. Up to now, the most successful sources of entangled photons are based on the optical nonlinearities of certain types of crystals. In crystals with a sufficiently high second order optical nonlinearity, the process of Spontaneous Parametric Down Conversion (SPDC) can be observed. This effect can be briefly described as a spontaneous decay of a pump photon into a pair of correlated photons, called signal and idler, in a material with quadratic nonlinearity. Such pairs of correlated photons are called biphotons. One of the most elegant effects revealing the non-classical properties of biphoton fields is the so-called anti-correlation effect.

The process of SPDC is constrained by the so-called phase matching conditions, which can be casted in terms of energy and momentum conservation of the interacting photons. Under these conditions SPDC is usually very inefficient, mainly due to low nonlinearities in crystals that are grown and then cut to fulfill phase-matching conditions. This problem was later relaxed with an improved technique of crystal fabrication using quasi-phase matching. By periodically poling the crystal, it is possible to compensate the momentum mismatch of the photons, or in an equivalent explanation, to periodically compensate the dephasing of the interacting waves. In this way it is possible to allow for a better control of the optical frequency generation, and in particular to phase-match the interacting waves using the maximum nonlinearities of the crystal.

Another advantage of using periodically poled crystals is that it is possible to control the geometry of the generated waves. Thus, the three waves can propagate collinearly in the crystal along one of the crystal axis. This allows the use of longer crystals, as there is no spatial drift of the waves. Besides boosting the efficiency of the process by enlarging the interaction volume, this is also a way of controlling the spatio-temporal properties of the emitted fields. For all these reasons, periodically poled crystals are a pivotal element of bulk entangled photon sources. As long as other technologies, based on integrated waveguide approaches, do not reach more maturity, bulk entangled photon sources will remain the first choice for the generation of correlated photons. For this reason it is important to completely understand the characteristics of the photons emitted in this kind of setup.

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In this paper we will study both theoretically and experimentally the properties of photons emitted from a type II Spontaneous Parametric Down Conversion source for a collinear configuration with no walk-off in a periodically poled Potassium Titanyl Phosphate (ppKTP) crystal. This kind of sources can offer very high rates of entangled photons. We study the spatio-temporal properties of the generated photons. In particular, we show that the emitted photons can be distinguished due to their different spectra.

We start in Section 2 by theoretically reviewing the process of spontaneous parametric down-conversion. We briefly describe the analytical model for the studying the spatio-temporal properties of the emitted photons from a particularly useful SPDC source. In Section 3 we briefly describe the experimental setup and method using the ppKTP SPDC photon pair source. We also discuss the main experimental results we obtained with this kind of source in the same section. We will conclude the paper in Section 4.

2. SPONTANEOUS PARAMETRIC DOWN-CONVERSION REVISITED

SPDC is an optical process in which a nonlinear crystal of length *L* is illuminated by a laser pump beam propagating in the *z*-direction. The pump photon interacts with the crystal to generate a pair of photons: signal and idler. We assume: a) the interaction time in the crystal is much longer than the frequency beating of the three waves, b) the transversal dimensions of the crystal are longer than the typical width of the pump. Then, we can set the limits of the integrals in the Hamiltonian for the system to infinity and perform the spatio-temporal integrations. Focusing only on the two-photon state gives us the following general expression:

$$\left|\Phi_{s,i}\right\rangle = \alpha \int d\omega_s d\omega_i d\mathbf{p}_s d\mathbf{p}_i E_p\left(\mathbf{\Delta}_\perp, \omega_s + \omega_i\right) \mathrm{sinc}\left(\frac{\Delta_\mathrm{k} L}{2}\right) \left|\mathrm{p}_\mathrm{s}, \omega_s\right\rangle_s \left|\mathrm{p}_\mathrm{i}, \omega_i\right\rangle_i \cdot \tag{1}$$

Here, ω_b and $\mathbf{p_b}$ are the angular frequency and transverse momentum of b = *s* (signal) or *i* (idler), respectively. E_p Is the amplitude of the pump beam. $\mathbf{\Delta}_\perp$ and Δ_k are obtained from the volume integral of the interaction Hamiltonian and depend on the dispersion relations and the crystal geometry, defined as:

$$\begin{aligned} &\mathbf{\Delta}_\perp = \mathbf{p_s} + \mathbf{p_i}, \\ &\Delta_\mathrm{k} = k_p(\omega_s + \omega_i, \mathbf{p_s} + \mathbf{p_i}) - k_s(\omega_s, \mathbf{p_s}) - k_i(\omega_i, \mathbf{p}_i) - \frac{2\pi}{\Lambda}, \end{aligned} \tag{2}$$

where $k_b(\omega, \mathbf{p}) = \sqrt{\left[n_b(\omega; T)\,\omega / c\right]^2 - |\mathbf{p}|^2}$ is the longitudinal component of each wave vector and n_b is the corresponding index of refraction, which in general depends on the crystal temperature (*T*) and can be determined from Sellmeier equations. α is the normalization constant. Starting from Eq. (1), that represents the state of the photons at the center of the crystal, we have built a simpler model with the following approximations:

i. We will study the case where a single frequency of the signal and idler fields is detected by using a narrow interference filter in the experiment. This allows a first approximation of the optimal collection modes.

ii. We choose the signal, idler frequencies that fulfill perfect phase matching conditions along the propagation direction as $\omega_{s,i}^0$. Assuming paraxiality, we define $\omega_{s,i} = \omega_{s,i}^0 + \Omega_{s,i}$ and set $\mathbf{p_{s,i}} = 0$. This condition can be tuned by the temperature of the crystal. We denote T_d as the temperature at which frequency degenerate photons are achieved, i.e., $\omega_s^0 = \omega_i^0$.

iii. If we allow for a change of temperature, different from T_d, then Δ_k in Eq. (2) is no longer zero, but depends on the new temperature *T*. We call this new function $\Delta k_0(T)$ and express

$$\Delta_\mathrm{k}(\Omega_s, \Omega_i; T) = \Delta k_0(T) + \frac{1}{c}\left[N_p(T)(\Omega_s + \Omega_i) - N_s(T)\Omega_s - N_i(T)\Omega_i\right], \tag{3}$$

where $N_{(p,s,i)}(T)$ are the pump, signal and idler inverse group velocity indices calculated at the central frequencies. We have studied the variation of Eq. (3) with temperature. The change of $N_{(p,s,i)}(T)$ with *T* was found to be negligible and thus we will eliminate the temperature dependence in the inverse group velocities. Only $\Delta k_0(T)$ has a linear dependence on temperature and can be approximated as $\Delta k_0(T) \approx \kappa \Delta T$. This proves that a change of temperature implies a change of frequency, and doing either are equivalent.

iv. Also for narrowband sources we only need to keep the first order of the frequencies in a Taylor expansion of the wave vectors in Eqs. (2).

v. We will consider the case of a monochromatic pump, where the frequency dependence be approximated by a delta function, implying, $\Omega_s = -\Omega_i$.

A simple model combining the above approximations leads to the following expression:

$$\left|\Phi_{s,i}\right\rangle = \alpha \int d\Omega_s d\mathbf{p_s} d\mathbf{p_i} E_p(\mathbf{p_s} + \mathbf{p_i}) \,\mathrm{sinc}\left(\frac{L}{2}\left[\left(\kappa\Delta T - \frac{(N_S - N_i)\Omega_s}{c}\right) - \frac{|\mathbf{p_s} - \mathbf{p_i}|^2}{2k_p(0)}\right]\right)\left|\mathbf{p_s}, \Omega_s\right\rangle_s \left|\mathbf{p_i}, -\Omega_s\right\rangle_i \tag{4}$$

Equation (4) gives an intuitive understanding of the effects that we have experimentally observed.

3. EXPERIMENT & RESULTS

The experimental setup is illustrated in Figure 1. A laser beam at 427 nm with a typical power of 30 mW pumps a ppKTP crystal designed for a type-II degenerate collinear SPDC. The crystal is enclosed in a temperature stabilization unit allowing to control the crystal temperature with stability better than 0.01 degrees. Pump photons at 427 nm are down-converted to 854 nm degenerate photon pairs with orthogonal polarizations at an optimal temperature of T_d =10 deg.C. After being split by a polarizing beam splitter (PBS), the photons are fiber-coupled into single mode fibers. The collection mode could be varied either with an iris or with a set of lenses before the PBS. Typical single photon detection rates are around 5 Mc/s in each arm and coincidence rates of up to 200 kc/s. For more details on the setup, see reference[3]. In order to study the spatio-temporal properties of down-converted photons we performed two independent experiments, depicted as (a) and (b) in Fig. 1.

(1) Setup (a) depicts the method to study the photon pair spectral properties. One photon is directly sent to a photo-diode (SPCM). While, the partner photon is coupled into a filtering Fabry-Perot cavity (finesse = 600, line width = 2.5 GHz, FSR = 1500 GHz) [1] and then detected with a second photodiode. The output pulses from each detector are sent to a photon-counting system (PicoHarp). The single and paired photon spectra are analyzed as a function of the crystal temperature. We recorded the singles spectra of the photons by observing the photon counts in the filtered arm. For measuring coincidence spectra, the PicoHarp records a histogram of the time delay between detections in the filtered arm and the unfiltered arm. A typical data we obtained is plotted in Fig. 2(a) (Top), for a collection mode of 28 µm. This compares well to a corresponding theoretical plot, shown in Fig. 2(a) (Bottom), obtained by numerically computing Eq. (4). In general, we observed an asymmetry in the single photons spectra, both in the experimental and theoretical plots. This is due to the asymmetry of the frequency state of the photons, as evident in Eq. (4). Even if the separate spatial and temporal states present symmetries, the spatio-temporal state is asymmetric, which can be easily observed if we trace out the spatial part in Eq. (4), and plot only the probability of finding the signal photon in a certain frequency. This is due to the mix of frequency and transversal momentum inside the 'sinc' function. This feature can be observed in Fig. 2(a). Another feature that appears in Fig. 2(a) due to this intertwined spatiotemporal state is that the maximum number of single photon counts and coincidences are not collected at the perfect phase matching frequency ω_s^0 (at T_d), but somewhat detuned from it. This again is due to the intrinsic asymmetry of the state. The asymmetry in the frequency spectra of the photons will allow some amount of distinguishability between the two photons, even when their polarizations have been rotated to the same one. Then, a Hong-Ou-Mandel interference experiment would show a visibility not equal to one [4].

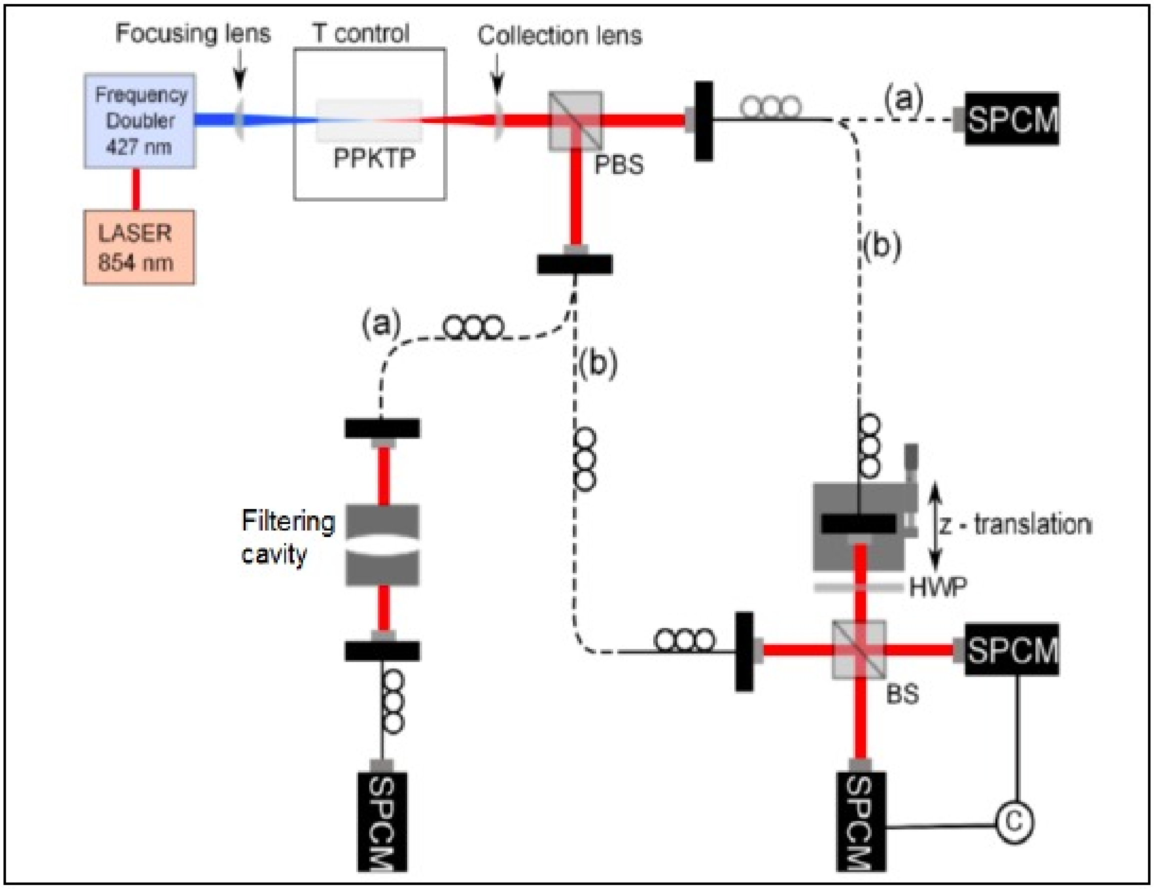

Fig. 1. Schematic of the experimental set-up in two parts: (a) to study the down-converted photon pair spectral properties; (b) to implement a Hong-Ou-Mandel (HOM) interferometer. Here PPKTP: periodically poled KTP crystal; PBS: polarization beam splitter; BS: 50-50 beam splitter; HWP: half-wave plate; SPCM: single photon counting module; C: coincidence counter (Pico-Harp). (ii) Top: Experimental coincidences (dot-dashed) and single counts (continuous) spectra for a collection mode of 28μm. Bottom: Theoretical coincidence (dashed) and single counts (continuous) spectra for a collection mode of 20μm. (iii) Top: Experimental HOM interference dip as a function of crystal temperature and a collection mode of 92 μm. Bottom: Corresponding theoretical HOM dip for a fixed delay.

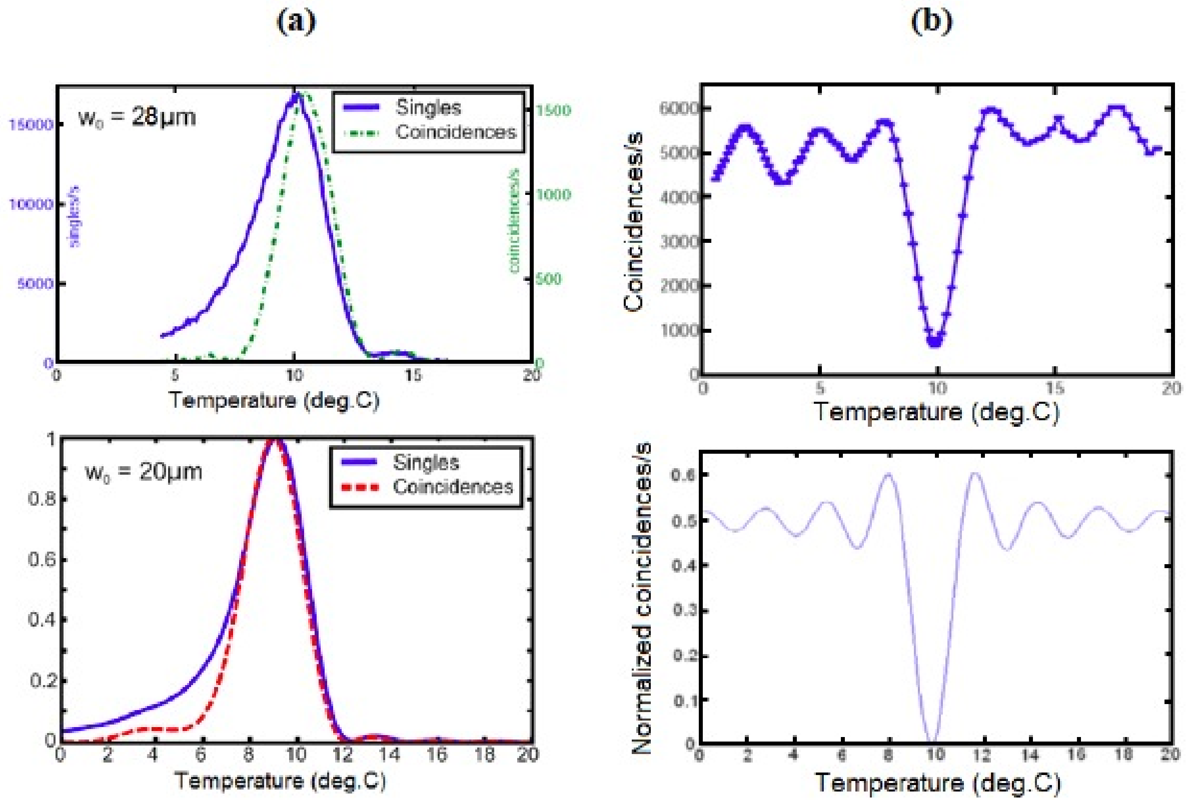

Fig. 2. (a) Top: Experimental coincidences (dot-dashed) and single counts (continuous) spectra for a collection mode of 28μm. Bottom: Theoretical coincidence (dashed) and single counts (continuous) spectra for a collection mode of 20μm. (b) Top: Experimental HOM interference dip as a function of crystal temperature and a collection mode of 92 μm. Bottom: Corresponding theoretical HOM dip for a fixed delay.

(2) In setup (b), we implemented a Hong-Ou-Mandel (HOM) interferometer. A HWP is included in one arm to render the photon pairs indistinguishable as they carry orthogonal polarizations. Each out-coupled mode is then overlapped on a beam splitter whose output ports are directed onto two multimode fibers and finally coupled to the SPCMs. We first observed the HOM interference dip for T_d=10 deg.C by varying the path length of one photon. This is done by using a translation stage (as shown in the figure). We fixed this delay at the position where we obtained the HOM dip. After this we observed the behavior of the photon coincidences detected from both output ports of the BS as a function of the crystal temperature. The result is shown in Fig. 2(b) (Top). As expected the HOM interference dips show a minimum around the optimal temperature T_d that is required to produce the degenerate down-conversion photons. This also corresponds to the maximum number of coincidences (between degenerate indistinguishable photons) that are observed in Fig. 2(a) (Top, dot-dashed). Apart from the dip, the figure shows appearance of secondary lobes. To understand all this, we theoretically studied the number of photon pairs detected in coincidence from the output ports of the BS. This can be written as:

$$P_C = \int d\Omega_s \left| \varphi(\Omega_s) - \varphi(-\Omega_s)\, e^{-i(DL+2\tau)\Omega_s} \right|^2, \tag{5}$$

Where $\left|\Phi_{s,i}\right\rangle = \alpha \int d\Omega_s\ \varphi(\Omega_s)\left|\Omega_s\right\rangle\left|-\Omega_s\right\rangle$ and $D = N_s - N_i$. We plotted the number of coincidence as a function of temperature, fixing the value of delay to $\tau = -DL/2$, shown in Fig. 1(iii) (Bottom). The reason for the appearance of wiggles is the existence of secondary lobes in the mode function $\varphi(\Omega_s)$ (consisting a *sinc* function) whose amplitude is not negligible when compared to the amplitude of the main lobe. Effectively, when $\tau = -DL/2$, the phase term in Eq. (5) remains zero. Therefore, while taking coincidences, when the photon spectrums do not completely overlap, the position of the secondary lobes in the *sinc* function, as we change temperature, will also significantly change the number of coincidences we get.

4. CONCLUSION

We have presented a series of experiments where we show how the spatio-temporal correlations of photons, generated from an SPDC source, affect the visibilities in a HOM interferometer. The drop of the visibility in the HOM for the optimal coupling situation is due to those correlations and would compromise experiments where the HOM effect is used for example to make quantum information gates for photons. Finally, it is possible to use advanced techniques to control the spatio-temporal state, which could in principle decouple the spatial and temporal properties of the photons [5] and allow them to be treated as separable.

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