Bright photon pair source with high spectral and spatial purity

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ABSTRACT
Spontaneous parametric down-conversion (SPDC) is a reliable and robust source of photons for quantum information applications. For applications that involve operations such as entanglement swapping or single-photon heralding, two-photon states are required to be factorable (uncorrelated) in their spectral and spatial degrees of freedom. We report the design and experimental characterization of an SPDC source that has been optimized for high spectral and spatial purity. The source is pumped by the 776 nm output of a mode-locked Ti:Sapphire laser and consists of a periodically-poled Potassium Titanyl Phosphate (PPKTP) crystal phase-matched for collinear type-II SPDC. The dispersive properties of PPKTP at these wavelengths is such that it is possible to minimize the spectral entanglement by matching the widths of the pump to the spectral phase-matching function. The spatial entanglement is minimized through careful control of the pump focus, yielding nearly single-mode emission. An advantage of this approach is that the emission rate into the collection modes is very high, resulting in a very bright SPDC source. We also report a scheme that employs the output of collinear sources such as these to produce polarization-entangled photon pairs. The scheme, which requires only simple polarization elements, can be scaled to N-photon GHZ states.

Keywords: entanglement, down-conversion, quantum information

1. INTRODUCTION
The use of spontaneous parametric down-conversion (SPDC) as a technique of generating entangled photons is widespread. SPDC produces photon pairs which may be entangled in numerous degrees of freedom such as spectral, spatial, polarization, and time-bin. Each has been explored theoretically and in experiments such as Hong-Ou-Mandel interference1, quantum teleportation2, entanglement swapping3, heralded photon generation4, linear optic gates for quantum computation5, and quantum key distribution6. Often, attention is restricted to entanglement in a single degree of freedom. In many cases, however, entanglement in auxiliary degrees of freedom must be managed so as to optimize the experimental effects of interest7. This is the case, for example, in experiments such as polarization entanglement swapping and quantum teleportation, where the best results are obtained when spectral and spatial entanglement is minimized8,9.

Here we describe an SPDC source of polarization-entangled photons in which spectral and spatial entanglement has been minimized10. As several works have shown, spectral and spatial entanglement can be removed or reduced by proper design of the pump and nonlinear medium11,12,13. We show here that both can be accomplished in a single source.

2. METHODOLOGY
Our SPDC source is designed with pump and phase matching functions which spectral entanglement and a geometry which eliminates spatial entanglement. This nonlinear medium is a non-critically phase matched periodically poled potassium titanyl phosphate crystal (PPKTP). The source design removes identifying information carried by photon momentum and energy, and accounts for material birefringence. As our source emits photons into a single spatial mode, we are able to achieve an estimated pair production rate of 123,000 pairs/s/mW without the need for spectral or spatial filtering.

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The bi-photon SPDC process in its most general form is given by:

$$|\Psi\rangle = \int \hat{a}_{\vec{k}_s}^\dagger \hat{a}_{\vec{k}_i}^\dagger \alpha(\vec{k}_s + \vec{k}_i) \phi(\vec{k}_s, \vec{k}_i) \hat{a}_{\vec{k}_s} \hat{a}_{\vec{k}_i} |0\rangle,$$

(1)

where $\hat{a}_{\vec{k}}$ represents a creation operator for the signal/idler mode with momentum $\vec{k}$, $\alpha$ or $\phi$. The probability amplitude is given by a product of a pump function ($\alpha$) and a phase matching function ($\phi$). The phase matching function describes the available ways in which pump energy can be distributed to the signal/idler pairs. The pump function describes the range of the pump field momentum available for down-conversion. The signal and idler momenta must sum to the momentum of the pump as $\vec{k}_p = \vec{k}_s + \vec{k}_i$. The spectral and spatial properties of the SPDC photons are completely determined by the product of the pump and phase-matching functions. The general scheme for eliminating either spectral or spatial entanglement is to refine the shapes of these functions so that their product yields no correlation between the signal and idler photons. The energy and spatial (transverse momentum) degrees of freedom are intricately linked in the probability amplitude. To lowest order, however, it is a good approximation to treat them independently.

As SPDC obeys energy conservation, the energies of the signal and idler photons must sum to some value in the pump spectrum. This behavior is displayed in the pump function. A narrow-band pump leads to a sharp anti-diagonal function, yielding a distinct relationship between the signal and idler wavelengths and a strong negative correlation between the signal and idler energies. If the shape of this function can be altered such that a given signal energy may be accompanied by a range of idler energies, then this identifying information can be removed. This alteration can be accomplished by broadening the pump spectrum. A narrow pump spectrum leads to correlated signal and idler energies. As the pump spectrum is broadened, these correlations decrease.

The phase-matching function determines how the pump energy is distributed to the signal and idler energies. In this case, one seeks to minimize the correlations between the signal and idler energies. This is accomplished by choosing the proper crystal material and crystal length. There exist materials in which the group velocity of the pump lies between the group velocities of the signal and idler wavelengths and a strong negative correlation exists between the signal and idler wavelengths. If the shape of this function can be altered such that a given signal energy may be accompanied by a range of idler energies, then this identifying information can be removed. This alteration can be accomplished by broadening the pump spectrum. A narrow pump spectrum leads to correlated signal and idler energies. As the pump spectrum is broadened, these correlations decrease.

The identifying spatial information arises from the transverse momenta of the signal and idler photons. As with spectral entanglement, the spatial entanglement is determined by the product of a pump function and a phase-matching function. If one of these functions tends toward positively correlated momenta, while the other tends toward negative correlations, then the correlations in their product can be eliminated if the widths are chosen properly.

Conservation of momentum leads to a pump function yielding negatively correlated transverse momenta. The strength of this correlation depends on the transverse momentum of the pump, which can be changed by altering the pump focusing conditions. A collimated pump gives a high degree of entanglement. Focusing the pump gives a much larger transverse momentum bandwidth.
The orientation and width of the phase-matching function is determined by the dispersion properties of the crystal material and by the crystal length. The desired positive momentum correlations are found in almost all SPDC materials. The crystal length determines the bandwidth of the down-converted photons with shorter crystals giving larger bandwidths.

With both the spectral and spatial phase-matching functions having the desired orientations, entanglement in both degrees of freedom can be eliminated with appropriate choices for the spectral and transverse momentum bandwidths of the pump. It is important to note that solutions can be found for any crystal length, but a crystal that is too short or too long may require pump conditions that are difficult to access. The plots in Fig. 3 show the optimum pump divergence and pulse duration (inverse spectral bandwidth) as a function of crystal length. A shorter crystal would be appropriate for a sub-picosecond pump, but the pump would have to be focused very tightly. On the other hand, a longer pump pulse allows for a more weakly focused pump. For our source, we settled on a 20-mm PPKTP crystal, with an optimum pulse duration of 1.3 ps and optimum pump divergence of 13.1 mrad.
3. SOURCE DESIGN

The source design is shown in Fig. 4. A PPKTP crystal is pumped by a mode-locked Ti-Sapphire laser operated in picosecond pulsed mode and tuned to 776 nm. An autocorrelation measurement gave a pulse duration of 1.3 ps although this could be varied somewhat. A lens was used to focus the pump in the center of the PPKTP crystal and give the necessary divergence of 13.1 mrad. A half wave plate (HWP) was placed in the beam to adjust pump polarization just before the first calcite beam displacer (BD1). The first beam displacer gave two pump beams which are orthogonal (H and V) separated by 4.2 mm. A HWP with its fast axis oriented at 45 deg was placed in the vertical beam giving two separate horizontally polarized pump beams.

Figure 3. Pump divergence and pulse duration as a function of crystal length.

Figure 4. Schematic of experimental setup
The newly created down-converted photons exit the PPKTP and pass through another beam displacer (BD2). This BD separates each down-converted photon pair vertically. This gives four separate beam paths upon exiting BD2. As before, HWPs are placed in selected beam paths to rotate polarization. In this case, a custom machined aluminum mount was made to hold thin 5 mm square HWPs. The HWPs were glued into the top right and bottom left corners (when looking back down the beam path). This placement of the HWPs results in a vertically displaced pair of recombined beam paths after the beams pass through BD3. This last beam displacer combines both signal photons into a single path and both idler photons into another lower path. The lower path was picked off by a D-mirror. A lens was placed in each path after the beam displacers to focus the photons and match the divergence of the collection optics. A long pass filter was placed in each arm to remove any remaining pump photons. After the filter, a HWP and a Glan-Thompson polarizer were placed in the beam. With this addition, we are able to analyze the polarization-entanglement of the photons. The photons were collected into single mode fibers using New Focus five axis stages. This allowed for very fine control of the fiber tip position to maximize collection efficiency. Any phase differences due to differing photon paths were corrected by the placement of a pair of birefringent quartz wedges placed in the pump before BD1.

The photons were detected using a pair of fiber coupled InGaAs/InP avalanche photodiodes. The efficiency of the detectors was reported by the manufacturer to be around 10%, although we measured a roughly 25% difference in measured counts between the two detectors. The detectors were set to a gate window of 2.5 ns to minimize accidental counts. The detectors were synchronized to the repetition rate of the Ti-Sapphire. The Ti-Saph rep rate (76MHz) was faster than the maximum trigger frequency of the detector so a divide by 16 circuit was used to output a 4.75 MHz signal used to synchronize the detectors. The coincidence logic was performed by a counting module, delay box, and coincidence counter.

4. DATA

As our detection scheme is not 100% efficient, we need to estimate our full pair production rate from the measured rate. The total estimation of all reflection losses in the system gives a 38% transmission rate for the 1552 nm signal/idler photons. We estimated a conservative 50% coupling efficiency for the coupling into a single mode fiber. Lastly, we have the earlier stated 10% detection efficiency with the idQuantique detectors. These factors give an overall detection efficiency of 1.9%. Our overall pair production rate is given by taking the measured coincidence rate and dividing by the square of the singles detection efficiency. These factors give an overall source production rate of 123,000 pairs per second per milliwatt of pump power.

Single and coincidence counts were measured as a function of pump power. It is shown in Fig 5 singles vs. pump power shows a linear trend while coincidences vs. pump power shows a slight nonlinear trend. For this data, the Glan-Thompson polarizers and HWPs were removed.

Next, the Glan-Thompson polarizers and HWPs were installed and the coincidence rate was measured as a function of analyzer angle. Due to the inefficiency of our detection system, the counts were taken over 10 seconds for each step. One HWP was set to give a ± 45 basis while the angle of the other HWP was rotated. This plot gives a measured visibility of 94.7 ± 1.1 % [Fig. 6]. The pump power was 16 mW and the accidentals were subtracted.
Any extra photon pairs produced by a single pulse would be detrimental to the fringe visibility. To quantify any effect of the multiple pair production, data was taken at multiple pump powers [Fig 7]. After the subtraction of accidentals, the visibility remains constant at 94%.

As our theoretical visibility was expected to be near 99%, we must look for explanations for our 94% findings. Possible identifying information may be present due to the birefringent calcite crystals for the beam displacers, possible differences in the stated poling period for the PPKTP, and differing optical path lengths for the two down-conversion processes. Also, the small wave plates used between BD2 and BD3 were mounted using the wave plate edges for alignment. It was noted that the actual fast axes may have been rotated slightly from the marked positions. As these wave plates could not be rotated individually, they are the most likely source of reduction in visibility in our experiment.
A joint spectrum of the source was also taken. The collected photons were sent to a custom-built dual slit scanning monochromator. Using this setup, joint spectra were taken for varying pulse durations. For comparison, the spectra for pulse durations of 1.3 ps and 1.9 ps [Fig. 2] are shown. When the data is processed, spectral Schmidt numbers of 1.07 (1.3 ps) and 1.16 (1.9 ps) were found. This is in good agreement with the calculation for the optimal arrangement of 1.06. The low throughput for the spectrometer required count times of 200 s per step with a 25 mW pump power. The resolution of our custom monochromometer is 0.3 nm.

Finally, we measured the quantum state prepared by the source using a 36-point polarization tomography. Quarter wave plates (QWP) were placed before the HWPs in each arm and tomography experiments carried out using an incident 16 mW pump power. Both the real and imaginary parts were calculated from the data [Fig. 8].
5. CONCLUSIONS

We have designed and characterized a source of polarization entangled photons with minimal spectral and spatial entanglement. This source’s high production rate (123,000/s/mW pump) and high visibility (94%) make it ideal for numerous experiments requiring entangled photon pairs. The unique design of this source can also be extended to enable entanglement of a greater numbers of photon pairs.
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REFERENCES


