Bright Photon Pair Source with High Spectral and Spatial Purity

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Abstract: We report the design and experimental characterization of a down-conversion source optimized for high spectral and spatial purity. Spatial and spectral entanglement are minimized through careful control of pump properties and material parameters.

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Spontaneous parametric down-conversion (SPDC) is a very reliable source of entangled photon pairs for fundamental studies of quantum mechanics, as well as for specific quantum information applications. SPDC sources can be configured for polarization or time-bin entanglement, or they can be used as heralded single-photon sources. However, entanglement may also be present in the spectral and spatial degrees of freedom. As with polarization or time-bin entanglement, these entanglements can also carry information, often with unwanted consequences. For example, asymmetric spectral information has been shown to reduce the visibility in two-photon Hong-Ou-Mandel interference [1]. Moreover, these auxiliary entanglements can carry distinguishing information that undermines interference effects critical to a broad class of multi-photon experiments, including entanglement swapping and quantum teleportation [2]. With the increasing interest in multi-photon experiments [3], it is important to be able to generate photon pairs that are free of spectral and spatial entanglement.

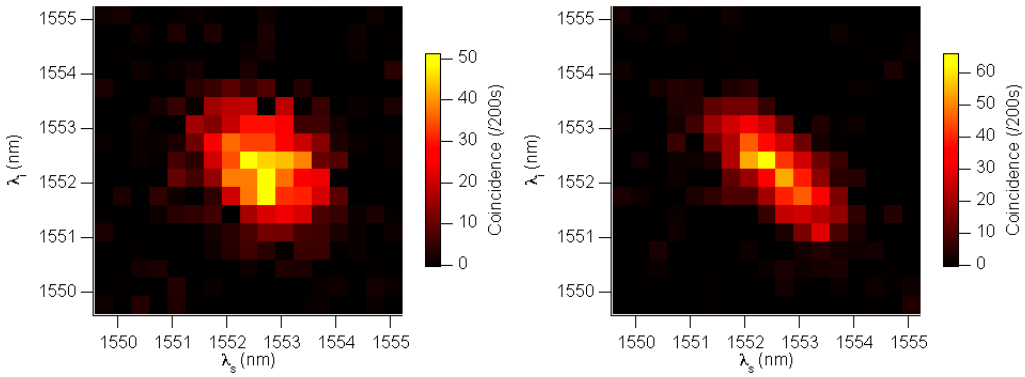
We describe here an SPDC source that has been designed specifically for minimal spectral and spatial entanglement [4]. Spectral purity is achieved through the choices of the pump properties and phase-matching characteristics, while spatial entanglement is minimized via a collinear configuration in non-critically phase-matched periodically-poled potassium titanyl phosphate (PPKTP). This geometry eliminates walk-off effects and maximizes the overlap of the pump, signal, and idler fields. With a properly focused pump, nearly all of the photons are emitted into a single spatial mode, thus yielding a single-mode emission rate of 123,000 pairs/s/mW. With its high brightness and spectral and spatial purity, this source is ideal for experiments requiring multiple pairs of identical photons, or for use as a heralded single-photon source.

The most general expression for the two-photon SPDC state is

$$|\Psi\rangle = \int d\omega_s d\omega_i d^2\mathbf{q}_s d^2\mathbf{q}_i f(\omega_s,\omega_i,\mathbf{q}_s,\mathbf{q}_i)\hat{a}^\dagger_{\mu s}(\omega_s,\mathbf{q}_s)\hat{a}^\dagger_{\mu i}(\omega_i,\mathbf{q}_i)|0\rangle, \tag{1}$$

where the μj ($j = s,i$) indicate the polarizations of the two photons, and where ω_j and $\mathbf{q}_j$ describe their frequencies and transverse wave vectors, respectively. The spectral and spatial properties of the two-photon state are completely described by the joint amplitude $f(\omega_s,\omega_i,\mathbf{q}_s,\mathbf{q}_i)$, which is determined by a number of factors, including the spectral content of the pump, the dispersive properties of the SPDC medium, and the geometry of the interaction. In general, the joint amplitude cannot be factored, and so the spectral and spatial properties are not independent of one another. However, with some reasonable assumptions, they can be studied independently.

In the spectral domain, the two-photon probability amplitude is the product of a pump function and a phase-matching function. The pump function is non-zero only for signal and idler energies that sum to some value in the pump field, thereby enforcing energy conservation in the interaction. Because larger signal energies can only be accompanied by smaller idler energies, the pump function generally yields negative correlations in the photon energies. Spectral entanglement can be eliminated if this negative correlation can be limited or offset by a phase-matching function yielding positive correlations. It has been shown elsewhere that this condition is satisfied if the group velocity of the pump lies between the group velocities of the signal and idler [5].



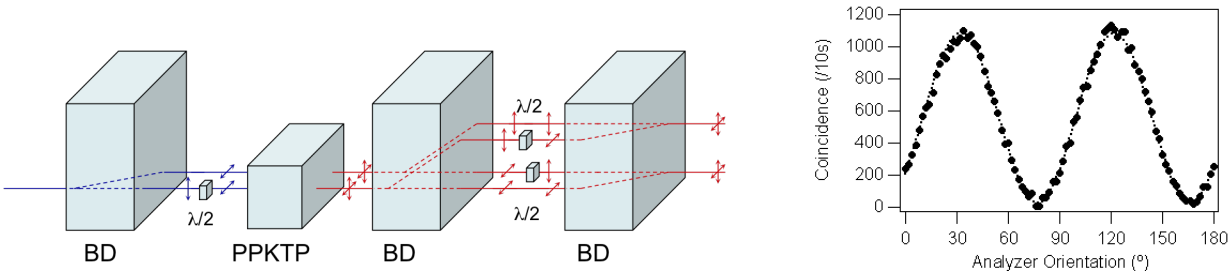
(a) 1.3 ps pump (b) 1.9 ps pump

Fig. 1. Joint spectral intensities using two pump pulse durations, 1.3 ps (a) and 1.9 ps (b). Analysis yields spectral Schmidt numbers of 1.07 and 1.16 respectively.

This constraint is difficult to satisfy in most materials, since dispersion typically results in a lower group velocity for the bluer pump wavelengths. However, dispersion is more accommodating at longer wavelengths, and solutions can be found for several type-II materials when the pump is centered in the near-infrared. In particular, group velocity matching can be achieved in KTP for degenerate type-II SPDC with a pump wavelength in the range 650-900 nm. Once this condition is satisfied, spectral entanglement can be eliminated if the widths of the pump and phase-matching functions are such that the product yields neither positive nor negative correlations in the photon energies. For a pump wavelength of 776 nm, our calculations predict that spectral entanglement is minimized for a crystal length of 20 mm and a transform-limited pump pulse duration of 1.3 ps. Shorter crystals (with a broader phase-matching function) would require shorter pump pulses (having a broader bandwidth). The relationship between pump bandwidth and spectral entanglement can be clearly seen in Fig. 1, which shows the joint spectra measured with two different pump pulse durations. With a 1.3-ps pump pulse duration, very little correlation is evident in the signal and idler wavelengths. On the other hand, a negative correlation is seen when the pump pulse duration is increased to 1.9 ps, a consequence of the narrower pump bandwidth. The stronger correlation is an indicator of spectral entanglement.

Entanglement is minimized in the spatial (transverse momentum) domain in much the same way as in the spectral domain. Namely, the transverse momentum pump function leads to negatively correlated momenta, manifested as negatively correlated photon emission directions. Spatial entanglement can be eliminated only if this negative correlation is balanced by a phase-matching function yielding positively correlated momenta. Fortunately, this condition is satisfied in almost all SPDC materials, particularly when there is no spatial walk-off, as is the case for the non-critically phase-matched PPKTP. As in the spectral domain, the final step in minimizing the spatial entanglement is to match the widths of the pump and phase-matching functions. The width of the phase-matching function is determined by the dispersive properties of the material, as well as the crystal length. The width of the pump is determined by the divergence of the pump–a strongly focused pump has a larger transverse momentum bandwidth. In a sense, focusing the pump matches the pump divergence to the signal and idler divergences. For the 20-mm PPKTP used in our source, the optimum pump divergence is 13.1 mrad, which yields signal and idler divergences of 18.4 and 18.1 mrad, respectively. One consequence of minimizing the spatial entanglement is that nearly all of the photons are emitted into single spatial modes [6]. And because the overall brightness does not change significantly when the pump is focused, the single-mode brightness can be quite high. In our case, the single-mode pair production rate was found to be 123,000 pairs/s/mW.

The geometry of our source—non-critically phase-matched collinear SPDC—does not lend itself to direct emission of polarization-entangled photons. However, collinear photon pairs can be transformed into polarization-entangled pairs using only a few optical elements. Our scheme, which is a modification of the layout presented in [7], is shown in Fig. 2(a). Two regions of the PPKTP crystal are pumped by a pair of beams from a 776-nm modelocked Ti:Sapphire laser. The two beams come from the outputs of a calcite beam displacer (BD), which splits the incident pump beam into two orthogonally polarized parallel beams. A waveplate ($\lambda/2$) in one of the beams gives both pumps the proper polarization for down-conversion, so that a photon pair (e and o) can be produced in either region of the crystal.



(a) Experimental setup (b) Polarization correlation

Fig. 2. (a) Experimental setup. (b) Coincidence counts vs. analyzer orientation angle in the $\pm 45°$ polarization basis showing a visibility of $94.7 \pm 1.1\%$. Incident pump power is 16 mW and accidental counts have been subtracted.

The emitted beams are incident on a second beam displacer that acts simply as a polarization beamsplitter, directing the orthogonally polarized photons into vertically displaced parallel paths: the *e*-photons in the upper paths, and the *o*-photons in the lower. Waveplates in two of the beams rotate the polarizations so that a third beam displacer simultaneously combines the two upper beams and the two lower beams. The result is a pair of vertically displaced beams in the entangled state $|\psi\rangle_{pol} = \frac{1}{\sqrt{2}}(|H\rangle_u|H\rangle_l + e^{i\phi}|V\rangle_u|V\rangle_l)$, where H and V denote polarization, and where u and l denote upper and lower, respectively. The phase ϕ can be adjusted via a pair of birefringent wedges in the pump beam preceding the first beam displacer (not shown). Also not shown are long-pass filters to block the pump, as well as lenses in the input and output beams. The pump lens focuses the pump beams to a divergence of 13.1 mrad, while the output lenses couple the emitted divergences to collection optics for the single-mode fibers leading to the detectors. Waveplates and polarizers are also included for analysis of the polarization-entangled state. Fig. 2(b) shows the coincidence rate as a function of orientation of one of the analyzers, with the other analyzer set to 45 degrees.

We have described an SPDC source having minimal spectral and spatial entanglement. The high brightness, single-mode emission, and the spectral and spatial purity make this source is ideal for experiments requiring multiple pairs of identical photons, or for use as a heralded single-photon source.

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