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Bright Entangled Photon Source Optimized for Single Mode Emission and Minimum Spectral Entanglement

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We describe an entangled photon source based on collinear down-conversion in periodically-poled KTP at 1552 nm. The pump bandwidth, crystal length, and pump spatial mode are chosen so as to minimize spectral and spatial entanglement.
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Spontaneous parametric down-conversion (SPDC) has proven to be a very reliable source of entangled photon pairs for fundamental studies of quantum mechanics, as well as for specific quantum information applications—in particular, those that require only two photons at a time. For more complex applications involving interference between multiple pairs of photons, SPDC still represents the most practical approach, although the requirements on the photon pair properties are significantly different for multi-pair experiments. When photons from different sources are brought together in an interference experiment, high-fidelity interference will be observed only if the system does not contain information that could link a particular photon to its source [1]. Such information might be carried not only in the individual photonic degrees of freedom, but also in correlations, or entanglement, between SPDC photons. For this reason, it is important to be able to generate photon pairs with no unwanted entanglement in auxiliary degrees of freedom. Here, we describe a bright source of polarization-entangled photon pairs that has been optimized for minimal spectral and spatial entanglement. The source is based on collinear SPDC in periodically-poled potassium titanyl phosphate (PPKTP) and makes use of a novel configuration in which polarization beam displacers are used to separate and then re-combine photons generated by either of two parallel pump beams. Spectral entanglement is minimized through the relationship between the pump bandwidth, crystal length, and wavelengths of operation, while the pump focus and photon coupling optics are chosen so as to minimize spatial entanglement and to simultaneously optimize coupling to single-mode collection optics [2].

The entangled photon source makes use of three polarization beam displacers, which exploit double refraction in calcite to separate the orthogonally polarized components of an incident beam into two parallel output beams. As shown in Fig. 1, the first beam displacer in the set-up is oriented to split the pump into beams *A* and *B*, with one displaced horizontally from the other. After a half waveplate rotates the vertically polarized beam to horizontal, both beams impinge on the PPKTP crystal, which is poled for degenerate type-II SPDC of the 776-nm pump. Orthogonally polarized photon pairs can be generated in either beam and propagate collinearly with their respective pumps. The photons pass through a second beam displacer, which is oriented to displace one polarization vertically with respect to the other. That is, the two input beams are separated into four distinct beams: an upper and lower beam for source *A*; and an upper and lower beam for source *B*. The photons in the upper beams are horizontally polarized, while the lower photons are vertically polarized. Waveplates in two of the beams rotate polarizations so that the photons from source *A* are both horizontally polarized, while the photons from *B* are both vertically polarized. Finally, a third beam displacer combines the two upper paths and also the two lower paths. A down-conversion event in either *A* or *B* will result in one photon in each output beam, either both horizontally polarized or both vertically polarized.

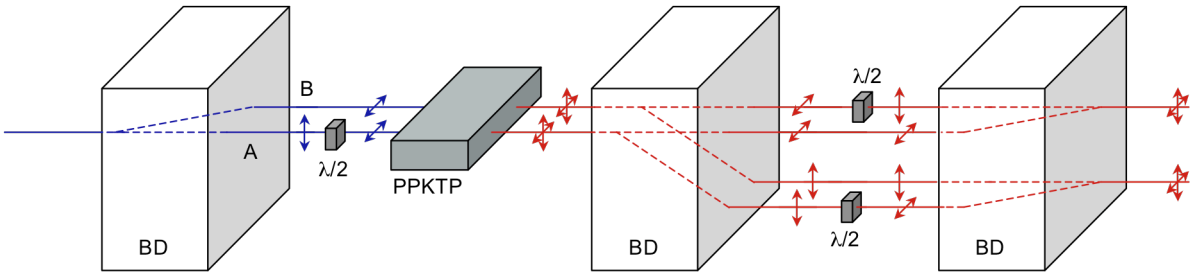

Fig. 1. Schematic of polarization-entangled source showing positions of PPKTP crystal, beam displacers (BD) and waveplates (λ/2).

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Like other sources based on the overlap of photons from multiple collinear downconversions [2-4], the paths in our source are configured so that the signal photons always end up in one output beam, while the idlers are always in the other. For this reason, any spectral differences between the two photons will not affect the polarization entanglement. In fact, the configuration presented here can easily accommodate non-degenerate SPDC (although the signal and idler wavelengths should not be too different, since beam displacement varies with wavelength). The use of beam displacers provides for a compact and extremely stable source and makes it possible to realize all of the benefits of collinear SPDC: a longer interaction region, better coupling to single-mode fiber, etc. The arrangement presented here differs from previous beam displacer SPDC sources through the introduction of the vertically oriented beam displacer, making it possible to use the same set of beam displacers for all beams. Finally, we point out that beam displacer configurations also have the advantage that they can be extended to include more than two sources for, say, the generation of a GHZ state.

The beam displacer source described thus far serves as a bright, compact, stable source of polarization-entangled photons. As noted above, however, additional requirements are placed on the photons if they are to be used in multi-source experiments, namely that the photon pairs must be free of entanglement in auxiliary degrees of freedom. Spectral entanglement is manifested as a strong correlation between the photon energies and is determined by the interaction between the pump spectrum (which describes the range of energies available for down-conversion) and the phase-matching function (which determines how those energies may be distributed to the two photons). The latter is determined by the wavelengths of operation and by the crystal material and length. It has been shown previously that spectral entanglement can be eliminated if the group velocity of the pump lies somewhere between the group velocities of the signal and idler [1]. Given that the pump wavelength is half that of the signal and idler, this is difficult to achieve at visible wavelengths. However, materials are less dispersive at longer wavelengths and solutions are more accessible—for the PPKTP used in our source, the group velocity of the 776 nm pump is very nearly the average of the group velocities of the 1552 nm signal and idler. In this case, the spectral entanglement is determined by the relationship between the crystal length and pump bandwidth. For the 20-mm crystal used in our source, the optimum pump pulse duration is 1.3 ps.

The PPKTP source also incorporates a number of features designed to minimize the spatial entanglement—equivalently, the transverse momentum entanglement. As with spectral entanglement, the spatial entanglement is determined by the properties of both the pump and the SPDC crystal. By matching the transverse momentum spectrum of the pump to the momentum spread determined by the phase-matching function, it is possible to reduce the degree of spatial entanglement. This is accomplished by properly focusing the pump. For the 20-mm crystal used in our source, numerical modeling indicates that the pump should be focused at the crystal center with a divergence of 13.1 mrad (full angle at half intensity), which then leaves nearly all the signal and idler photons in single spatial modes with divergences of 18.4 mrad and 18.8 mrad, respectively. This divergence is small enough that the output beams remain spatially separated after propagating through the two beam displacers. The heralding efficiency, defined as the probability that, say, the idler photon will be emitted into the idler collection mode given that the signal photon is emitted into the signal collection mode, is predicted to be 84%.

Reducing the spatial entanglement also has the benefit of improving the coupling to single-mode systems, e.g., single-mode fiber. In our set-up, a mirror is used to separate the two output beams and lenses are used to couple the light into single mode fibers leading to two idQuantique InGaAs avalanche photodiodes. At the time of submission, the detectors register 321 coincidences per second, with only 19.5 (5.9, 18.8) mW incident on the crystal. The coincidences-to-singles ratio is 1.5%, which compares favorably to the maximum achievable ratio of 3.0% calculated by taking into account the low (~10%) detector efficiency, filter losses, Fresnel losses at uncoated optics, and the heralding efficiency cited above. Based on these numbers, we conservatively estimate that the emission rate into the signal and idler collection modes is 44,000 pairs per mW of pump.

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