Bright source of spectrally pure polarization-entangled photons with nearly single-mode emission

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(Dated: September 9, 2010)

We present results of a bright entangled photon source operating at 1552 nm via type-II collinear degenerate spontaneous parametric down-conversion in periodically poled KTP crystal. We report a conservative inferred pair generation rate of 44,000/s/mW into collection modes. Minimization of spectral and spatial entanglement was achieved by group velocity matching the pump, signal and idler modes and through properly focusing the pump beam. By utilizing a pair of calcite beam displacers, we are able to overlap photons from adjacent collinear sources to obtain polarization-entanglement visibility of 94.7 +/- 1.1% with accidentals subtracted.

PACS numbers: 03.67.Bg, 42.50.Ex, 03.65.Ud

Spontaneous parametric down conversion (SPDC) is the leading mechanism for realizing photonic quantum states [1–3]. Although it is an inherently probabilistic process, the heralding efficiency of SPDC sources for single-photon state preparation is much greater than contending sources, e.g., those based on single-photon emitters. Recent demonstrations of heralded biphoton entanglement by Wagenkneckt *et al.* [4] and Barz *et al.* [5], however, have highlighted the technical challenges of extending SPDC to preparing polarization-entangled states from independent sources. In particular, the overall brightness of an SPDC source is found to be relative to the spatial and spectral purity of each generated photons. This is because multimode downconverted photons provide distinguishing information that undermines the interference used for preparing polarization-entangled states [6]. If SPDC is to be used in the future for heralding multi-photon entangled states [7], then the brightness of each pair source will need to be optimized relative to the spatial and spectral purity of the generated photons.

In this Letter, we demonstrate a bright source for polarization-entangled biphoton states that has been optimized for maximal spatial and spectral state purity. Unlike previous SPDC sources [4, 5, 8], we do not appeal to the use of spectral filters for ensuring spectral purity. Rather, we engineer the SPDC phase-matching criterion through the selection of the nonlinear crystal, phase-matching angle, and pump properties [9]. Specifically, our source is based on collinear SPDC in periodically-poled potassium titanyl phosphate (PP-KTP) that uses calcite beam displacers to separate and then recombine photons generated by either of two parallel pump beams. We experimentally confirm that the spectral entanglement of this configuration is minimized through control of the pump bandwidth, crystal length, and operational wavelengths by measuring the joint spectral intensity of the down-converted photon pair. Simultaneously, we maximize brightness through control of the pump focus and photon coupling optics while minimizing the spatial entanglement of the down-converted pair.

The spectral and spatial properties of SPDC photons are determined by the pump field and by the dispersive properties of the crystal. Specifically, the two-photon probability amplitude is the product of a pump function and a phase-matching function. Entanglement can be eliminated only if this product yields no correlations between the signal and idler photon properties. By careful selection of the wavelength, pulse duration, and focus of the pump, as well as the crystal material and length, it is possible to minimize entanglement in these degrees of freedom. In general, the spectral and spatial properties are not mutually independent, but for the purposes of illustrating the design principles, it is sufficient here to treat them separately.

To eliminate spectral entanglement, the shapes of the pump function and phase-matching function must be chosen correctly [9]. The pump function, which describes the range of energies available for down-conversion, generally yields negatively correlated photon energies —the signal and idler energies must sum to an energy somewhere in the pump spectrum, so a longer wavelength for one photon is necessarily accompanied by a shorter wavelength for the other. This correlation is strongest for a monochromatic pump, for which there is but a single pump energy. Therefore, one requirement for the elimination of spectral entanglement is a broad pump spectrum. However, this alone will not eliminate spectral entanglement if the phase-matching function also leads to negatively correlated energies.

Whereas the pump function describes the range of energies available for down-conversion, the phase-matching function describes the ways that the pump energies may be distributed to the signal and idler photons. The influence of the phase-matching function on the spectral properties of the photons is revealed by noting that the function has appreciable value only for $\Delta k L \simeq 0$, where L is the crystal length and where $\Delta k = k_p - k_s - k_i$

is the wavevector mismatch. Using the approximation $k \simeq k_0 + \nu k'$ and the fact that $k_{p0} - k_{s0} - k_{i0} = 0$ for a phase-matched interaction, we have $\Delta k \simeq (\nu_s + \nu_i)k'_p - \nu_s k'_s - \nu_i k'_i$. Here $\nu = \omega - \omega_0$ and $k' = \partial k/\partial\omega$. Imposing the requirement that $\Delta k \simeq 0$ yields

$$\nu_s = -\nu_i \frac{k'_p - k'_i}{k'_p - k'_s}. \tag{1}$$

From this expression, it is clear that the phase-matching function leads to positively correlated photon energies only if k'_p lies between k'_s and k'_i or, since the group velocity $v_g = 1/k'$, if the group velocity of the pump lies between the group velocities of the signal and idler photons.

It is difficult to satisfy this group velocity matching condition for visible wavelengths in most materials since normal material dispersion results in lower group velocities for the bluer pump wavelengths. However, dispersion is more accommodating at longer wavelengths and solutions can be found for several type-II materials [9]. In particular, group velocity matching can be achieved with Type-II SPDC in KTP with a pump wavelength range of 650-900 nm for degenerate down-conversion to 1.3-1.8 μm. Once the material and pump wavelength have been specified, the widths of the pump and phase-matching functions must be chosen so that the resulting probability amplitude exhibits neither positive nor negative correlations in the photon energies. This requirement leads to a specific relationship between the pump bandwidth and the crystal length. For the 20-mm PPKTP crystal used in our source, our calculations predict that the spectral entanglement will be minimized, with a spectral Schmidt number of 1.06, using a 776 nm pump with a bandwidth corresponding to a transform-limited pulse duration of 1.3 ps.

The factors that must be considered to minimize the spatial (transverse momentum) entanglement are similar to those pertaining to the spectral entanglement. In particular, the pump function and phase-matching functions must have the right shapes in the transverse momentum domain. As in the spectral domain, the pump function leads to a tendency toward negatively correlated transverse momenta — the signal and idler momenta must sum to a momentum somewhere in the pump spectrum, so the emission directions of the photons are negatively correlated. As above, this correlation is strongest when the pump transverse momentum spectrum is narrow, i.e., when the pump is collimated. A necessary condition for the elimination of spatial entanglement, therefore, is a pump with a broad transverse momentum spectrum, a requirement that is easily met by focusing.

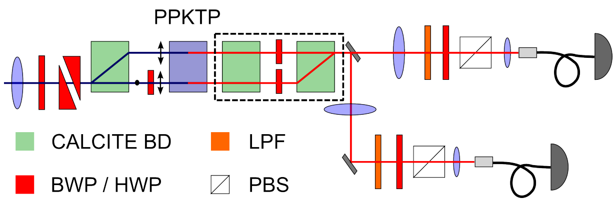
The requirement that the phase-matching function yield toward positively correlated transverse momenta is satisfied in most down-conversion materials, particularly when there is no spatial walk-off, as is the case for the non-critically phase-matched PPKTP. All that remains then is to choose the widths of the pump and phase-matching functions so as to eliminate the spatial entanglement. For the 20-mm PPKTP crystal used in our source, calculations predict the best performance with the pump having a divergence of 13.1 mrad and focused at the center of the crystal. It is shown elsewhere [11] that the conditions that minimize spatial entanglement are the same conditions that maximize coupling to single-mode collection optics. In our case, the signal and idler photons are predicted to be emitted collinearly into well-defined single modes with divergences of 18.4 and 18.1 mrad, respectively.

Our approach provides several advantages in comparison to traditional multi-photon entanglement experiments, namely:

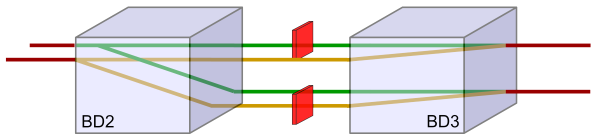
- the pump wavelength of 776 nm is accessible with a tunable pulsed Ti:Sapphire laser, without the requirement for a SHG crystal to double the pump wavelength as in the usual UV $\rightarrow$ Vis down-conversion schemes,
- the minimization of spectral and spatial entanglement by the source removes any need for interference filters to be used, with SPDC photons emitted into a single spatial mode for optimal coupling to collection optics and
- 776 nm $\rightarrow$ 1552 nm SPDC occurs in the technologically important telecom band where optical fibers exhibit minimal attenuation and standard telecoms equipment is readily available.

The experimental setup, which is a modification of the scheme first presented in [10], is illustrated in Figure 1. A 776 nm pump beam from a Coherent Mira Ti:Sapphire laser is incident upon a lens, half-wave plate HWP1, birefringent wedge pair BWP and beam displacer BD1. BD1 displaces the orthogonal polarizations of the pump components by 4.2 mm; the vertically polarized pump component is passed through the half-wave plate HWP2 oriented with the fast axis at 45°. The two pump beams incident on the PPKTP crystal are horizontally polarized with a focus of 13.1 mrad to satisfy Type-II phase-matching and to minimize spatial entanglement as described above. Both pump waists are located midway along length of the PPKTP crystal.

Upon emergence from the PPKTP crystal, the signal and idler photons from the two sources are incident upon beam displacer BD2, which acts to displace the signal and idler photons vertically, thus creating four beam paths. Thin half-wave plates rotate the photon polarizations in two of the paths before all four beams are incident on beam displacer BD3, which acts to recombine photons such that both signal photons are emergent in the upper path and both idler photons in lower path. Lenses following the beam displacers are used to match the spatial



(a)Experimental setup



(b)Detail of beam displacer pair inset

FIG. 1: (Color online) (a) Experimental setup. (b) Detail of the beam displacer pair. BWP: birefringent wedge pair; HWP: half-wave plate; BD: beam displacer; LPF: long-pass filter; PBS: polarization beam splitter.

mode of the signal and idler photons to the collection optics. A pair of long-pass filters remove the residual pump from each arm and the photons are coupled into single-mode fibers. Wave plates and polarizers are placed in the two beams for analysis of the polarization-entangled state.

Photon detection is accomplished using two fiber-coupled idQuantique id200 InGaAs/InP avalanche photodiodes with a reported detection efficiency of approximately 10%. Both detectors are set to use a 2.5ns gate width and are triggered at 4.75MHz synchronized with the 76MHz pulse train from the Ti:Sapphire. TTL output pulses from the id200s, corresponding to photon detection events, are input into ORTEC counting, delay and coincidence logic circuits for computer readout.

The singles and coincidence counts are measured as a function of incident pump power and are displayed in Figure 2. The half-wave plates and polarization beam splitters were removed from both collection arms for this measurement. The singles counts are linear with respect to increasing pump power. However, the coincidence counts exhibit a slight non-linear trend that we attribute to multiple-pair generation at higher pump power [12]. By taking into account Fresnel losses from uncoated optics, free-space to fiber coupling and the limitations of our detectors, we conservatively infer a pair generation rate of 44,000/s/mW pump. To the best of our knowledge, this is the brightest source operating in the telecom band reported to date.

Polarization correlation measurements were carried out with the half-wave plates and polarization beam splitters re-inserted in both arms. Figure 3 shows polarization correlation plots in the $\pm 45°$ basis. The incident pump power was set to 16mW and accidentals were subtracted. By curve fitting to the data, we report a visibility of 94.7 $\pm$ 1.1%.

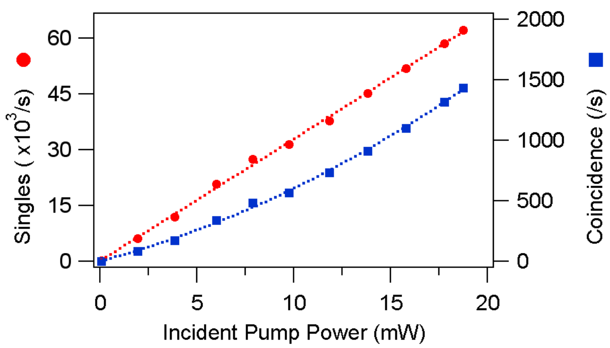


FIG. 2: (Color online) Singles $\sqrt{A.B}$ (left axis) and coincidence counts (right axis) vs. incident pump power. The dashed lines serve as guides to the eye.

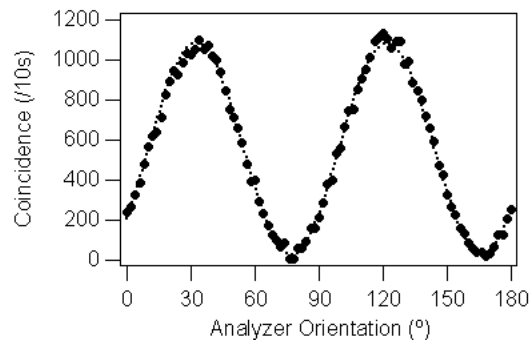


FIG. 3: Coincidence counts vs. analyzer orientation angle in the $\pm 45°$ polarization basis showing a visibility of 94.7 $\pm$ 1.1%. Incident pump power is 16mW and accidental counts have been subtracted.

In order to examine the effect of multi-pair generation on the $\pm 45°$ basis visibility, we conducted several polarization correlation measurements with various incident pump powers. This data is shown in Figure 4. The open circles show the uncorrected data and exhibit a linear decrease with respect to increasing pump power, providing evidence of multi-pair generation at higher pump power. The filled circles represent the corrected data, i.e., raw data with accidentals subtracted, which average 94% and is constant with respect to incident pump power as one would expect. We considered several explanations that would lead to our visibility being capped to 94%: individual photon delays through the system, small differences in signal and idler photon wavelengths due to poling inhomogeneities and errors in wave plate positioning. Relative photon delay was cancelled by positioning the birefringent wedge pair BWP to maximize visibility. We measured the spectra of all four photons using a monochromator and found that any wavelength differences were on the order of the monochromator resolution. Thus we conclude that the likely source of the reduced visibility is positioning error for the two wave plates placed between BD2 and BD3.

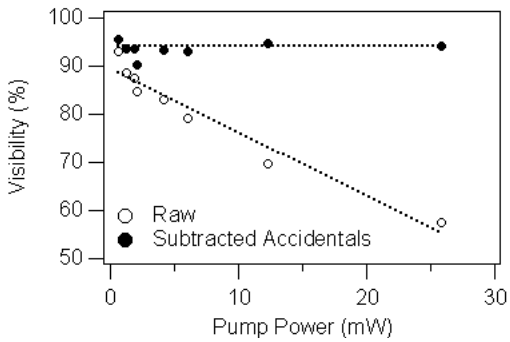
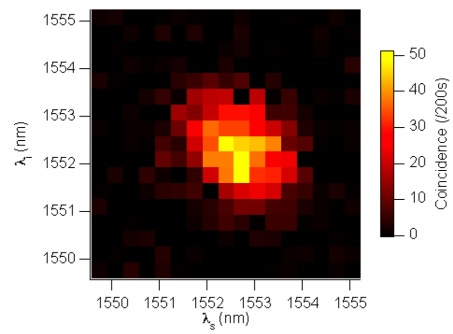


FIG. 4: Raw (open circles) and corrected (i.e., accidentals subtracted - filled circles) visibilities in the ±45° polarization basis as a function of incident pump power. Dashed lines indicate linear fits to the data.

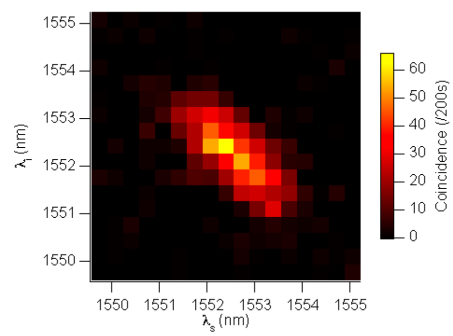
We performed joint spectral intensity measurements on our source using a customized dual-slit scanning monochromator with 0.3 nm resolution. By controlling the pump laser mode-locking, we were able to adjust the pump pulse duration and measure the joint spectral intensity at with several different the pump pulse durations. Figure 5 shows the measured joint spectral intensity taken with an incident pump power of 25mW, 200s counts per measurement and with accidental coincidences subtracted, for an optimal pump laser pulse duration of 1.3ps (Figure 5(a)) and 1.9ps (Figure 5(b)) respectively. Analysis of the raw data yields spectral Schmidt numbers of 1.07 and 1.16 respectively, in good agreement to 1.06 as predicted by our calculations for the optimal case. Furthermore, the change in the joint spectral intensity can clearly be seen between the different pump pulse durations. We refer the interested reader to recent work by Levine *et al.* [3] regarding similar work.

In summary, we have demonstrated a unique source insofar as entanglement in the spatial and spectral degrees of freedom has been minimized by appropriate pump focusing and careful selection of pump bandwidth, wavelength and phase-matching with Type-II PPKTP. As a result, photons are emitted into single spectral and spatial modes which require no spectral or spatial filtering to observe high multi-photon visibility of 94.7 ± 1.1% with an inferred pair generation rate of 44,000/s/mW of pump. A novel arrangement using calcite beam displacers splits signal and idler photons, recombining both signal and idler photons into two distinct paths. We are in the process of constructing a 4-photon polarization entangled source using the same procedure.

We thank M. Fiorentino and A. Migdall for enlightening discussions. Research sponsored by the Laboratory Directed Research and Development Program of Oak Ridge National Laboratory, managed by UT-Battelle, LLC, for the U. S. Department of Energy.



(a)1.3ps pump



(b)1.9ps pump

FIG. 5: (Color online) Joint spectral intensities using two different pump pulse durations, 1.3ps (a) and 1.9ps (b). Analysis yields spectral Schmidt numbers of 1.07 and 1.16 respectively.

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