High-Flux Entanglement Sources using Periodically Poled Nonlinear Crystals

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Abstract: We have efficiently generated colinearly-propagating entangled photon pairs from a nondegenerate type-I and a degenerate type-II quasi-phase matched parametric downconverter based on periodically poled lithium niobate and potassium titanyl phosphate.

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Entangled photons are essential in many quantum information applications such as quantum communications, implementation of quantum computation algorithms, and cryptographic key distributions. Typically UV-pumped optical parametric downconversion in a thin angle-phase-matched beta barium borate (BBO) crystal produces spatially-separated, entangled photon pairs that are emitted in a cone.

The use of BBO is far from optimal in terms of wavelength tunability, generation efficiency, and angular spread. In recent years the material of choice is that of engineerable microstructured nonlinear crystals via periodic poling of ferroelectric materials such as lithium niobate and potassium titanyl phosphate (KTP). Quasi-phase matching using periodically poled lithium niobate (PPLN) or periodically poled KTP (PPKTP) allows a wide range of operating wavelengths, noncritical angle phase matching, and a choice of nonlinear coefficients. A parametric downconverter based on PPLN or PPKTP can yield a significantly improved pair production efficiency by utilizing a longer crystal and by propagating along one of the crystal's principal axes. This is especially important in long-distance quantum communication systems [1] in which propagation losses can be substantial. Also, a colinearly propagating downconverter can be modified to incorporate an optical cavity to further enhance the downconversion efficiency and to obtain narrowband, single spatial mode outputs.

In a recently proposed singlet-based quantum communication system [1] there is a need for a high-flux source of entangled photons at 795 nm for local trapped-Rb quantum memories and at $1.55\,\mu$m for low-loss fiber-optic transmission to remote locations. Here we report the use of type-I phase-matched PPLN to realize a 532-nm-pumped, high-flux, frequency-nondegenerate entanglement source with outputs at 800 nm and $1.6\,\mu$m. We will also report on a 795-nm frequency-degenerate polarization entanglement source based on type-II phase-matched PPKTP.

We have fabricated a 2-cm-long PPLN crystal with a grating period of $21.6\,\mu$m that was type-I quasi-phase matched (third order) at an operating temperature of $\sim$140°C to yield

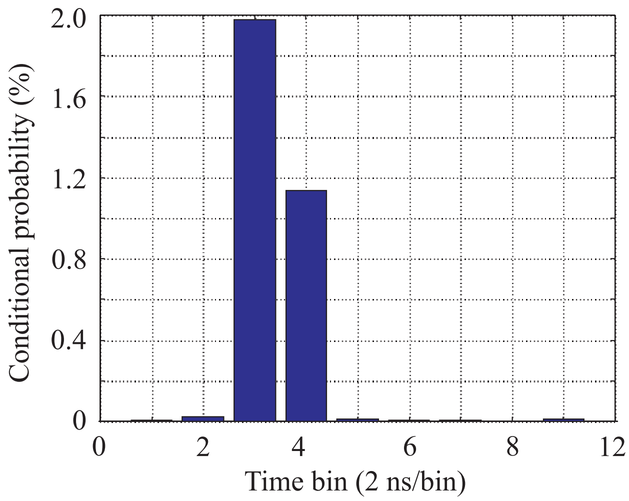

FIG. 1: Histogram of conditional detection probability of an idler photon per 2-ns time bin.

colinearly propagating downconverted photon pairs at output wavelengths of 808 nm and 1559 nm. By varying the temperature of the crystal oven (∼50°C range), we were able to tune the signal wavelength from 794 to 810 nm and the corresponding idler wavelength from 1550 to 1610 nm. The co-polarized signal and idler outputs were separated using a prism and each output was coupled into a single-mode fiber. The signal photons at 808 nm were detected using a commercial Si single photon counting module with a quantum efficiency of 55%, while the 1559 nm output was detected using an InGaAs avalanche photodiode (APD) operating in Geiger mode.

Figure 1 shows a histogram of idler-photon detection probability, conditional on the detection of a signal photon. It shows clearly that the dark count noise was quite small and the photon pairs were time coincident within a 4-ns window (2-ns digitizing time bin). The measured conditional detection probability is 3%, limited by the detector quantum efficiency (∼20%), propagation loss (∼15%), and fiber coupling efficiency of the idler mode that was matched to the signal mode (∼17%). By collecting all of the signal photons (without the single-mode fiber) we measured a singles rate of $\sim 3.8 \times 10^6$/s for 0.5 mW of pump power that yields an inferred pair generation rate of $\sim 1.4 \times 10^7$/s/mW of pump power over a signal bandwidth of ∼150 GHz. We will discuss the prospect of generating frequency-nondegenerate polarization-entangled photon pairs by combining the outputs of a PPLN downconverter that is pumped in both forward and backward directions [2].

For frequency-degenerate operation, we have constructed a type-II phase-matched PP-KTP downconverter operating at an output wavelength of 795 nm. An 8-mW diode laser at 397.2 nm was used to pump a 1-cm-long flux-grown PPKTP crystal that had a 8.9 μm periodic grating for quasi-phase matched operation. When the PPKTP downconverter was

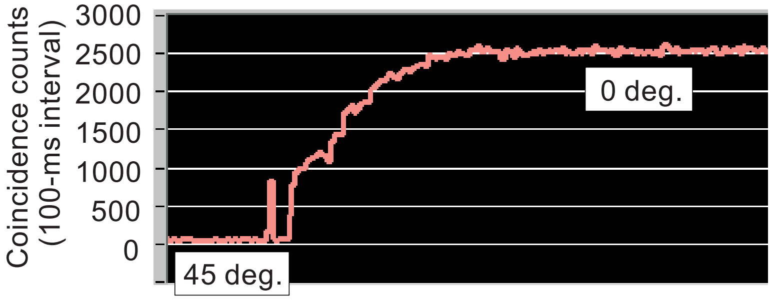

FIG. 2: Measured coincidence count rates as the half-wave plate was rotated over time.

operated at frequency degeneracy, the orthogonally polarized outputs were in polarization-entangled triplet states [3]. The outputs were sent through a 5-mm-long KTP compensating crystal to symmetrize the time delay caused by the crystal's birefringence. A half-wave plate (HWP) was used to rotate the output polarizations by 0 or $\pi/4$, after which the resultant outputs were analyzed with a polarizer and coincidences were measured. At zero rotation, we measured an inferred pair production rate of $\sim 10^6$/s, assuming an overall detection quantum efficiency of $\sim$20%. The detector efficiency is estimated to be 50% and the 3-nm interference filter has a 85% transmission at 795 nm. At $\pi/4$ rotation, the coincidence count rate dropped significantly because of quantum interference between the entangled photons. Figure 2 shows a plot of the coincidence count rates as a function of time during which the HWP was manually rotated. The maximum count rate occurred at zero rotation while the minimum was obtained when the output polarizations were rotated by $\pi/4$. A visibility of $\sim$98% is obtained from Fig. 2.

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