

A FREQUENCY-NONDEGENERATE ENTANGLEMENT SOURCE USING PERIODICALLY-POLED LITHIUM NIOBATE

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We demonstrate efficient generation of highly nondegenerate photon pairs with a type-I phase-matched, periodically-poled lithium niobate parametric downconverter. The signal photons at 800 nm and the idler photons at 1600 nm were generated in a collinear-propagation configuration with an inferred pair generation rate of 1.4×10^7 /s/mW of pump power. Detection of a signal photon triggered a thermoelectrically cooled, 20%-efficient InGaAs avalanche photodiode for the detection of the 1600-nm conjugate idler photon. Using single-mode fibers as spatial mode filters, the signal-conditioned idler-detection probability was $\sim 3.1\%$.

1 Pair generation

Most applications in discrete-variable quantum information physics make use of entangled photon pairs as an important resource. High brightness of entangled photon-pair sources is essential for future development of this field. For example, a recently proposed singlet-based quantum communication system requires an efficient source of entangled photons at 795 nm for local trapped-Rb quantum memories and at $1.55 \mu\text{m}$ for fiber-optic entanglement distribution.^{1,2} The required photon-pair characteristics for this proposal exemplify those for systems involving resonant coupling to atomic systems as well as efficient fiber-optic delivery. The pairs should be highly nondegenerate, with one photon at 795 nm and the other at 1550 nm. For efficient coupling to a narrowband atomic transition the photons must have bandwidths of only a few tens of MHz. Furthermore, it is important that they are in a well-defined spatial mode for coupling to an atomic cavity (at 795 nm) or to a single mode fiber delivery system (at 1550 nm). The requirements can be met using an optical parametric amplifier (OPA) with a quasi-phase matched nonlinear crystal. By engineering the phase matching, the wavelengths of signal and idler can be freely chosen. A cavity can be utilized to enhance the resonant modes that have narrow bandwidths and well-defined spatial modes. Using a properly designed type-I phase matched downconverter, the outputs propagate collinearly without walkoff. Note that a nonlinear waveguide is not a good choice for a narrowband cavity configuration, because of its high propagation loss. Polarization-entangled photon pairs can be generated using two independent but coherently pumped OPA sources.³

In this paper we present experimental results from a single-pass para-

metric downconverter⁴ as a precursor to the narrowband OPA source. The experimental configuration is shown in Fig. 1. We used a 2-cm-long crystal

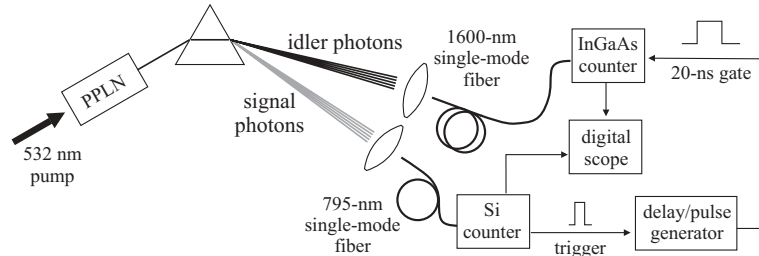


Figure 1. Experimental configuration for pair coincidence measurements. The signal photon is detected by the silicon (Si) photon counter, whose electrical output pulse is used to trigger the gate for the InGaAs detector.

of periodically-poled lithium niobate (PPLN) pumped by a cw frequency-doubled Nd:YVO₄ laser at 532 nm. Phase matching in PPLN was achieved by poling a third-order grating in the crystal with a grating period of 21.6 μm . The confocal parameter of the pump inside the crystal was chosen to be 20 cm, about ten times the crystal length. We obtained tunable outputs centered at 800 nm and 1580 nm by varying the temperature of the crystal between 140°C and 185°C. We characterized the PPLN downconverter by difference-frequency generation (DFG) of tunable ~ 800 nm light with a strong pump at 532 nm and a 1580-nm tunable probe laser. We measured a temperature tuning coefficient of ~ 1.3 nm/°C for the 1580-nm tunable source. At a fixed temperature, the DFG showed a bandwidth in the probe wavelength of 1.26 nm (~ 150 GHz), in good agreement with the expected value for a 2-cm-long PPLN crystal.

In the spontaneous downconversion mode, we inferred a pair-generation rate of 1.4×10^7 /s/mW of pump power at 532 nm from our measurements, based on the 54% quantum efficiency of our Si detector and the 85% propagation efficiency of our experimental setup. Typical pump powers were 1–2 mW. When the signal was coupled into a single-mode fiber, the singles rate decreased to 30,000 counts/s/mW, because the spontaneous emission was distributed over many modes and only a single mode was selected by the fiber. Since the photons are produced in pairs, the rate of detected coincidences should be, in principle, equal to the inferred single-mode singles rate. However, the quantum efficiencies of the InGaAs detector ($\sim 20\%$), the idler propagation efficiency (85%), the fiber coupling efficiency ($\sim 50\%$) and the efficiency of collecting the same spontaneous mode in the signal and idler fibers (η_{mode}) reduce the observed coincidence rate. Therefore, we observed a single-mode coincidence rate of only 930 pairs/s/mW with a 3.1% conditional probability for the idler photon detection. A counting histogram is shown in Fig. 2, show-

ing that the coincident idler photons were well localized in time and that dark counts were negligible. By comparing the observed coincidence rate with the

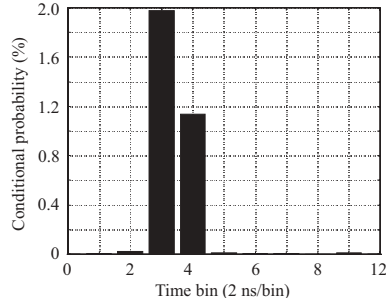


Figure 2. Histogram of signal-conditioned idler detection probability. The width of the distribution is due to the rise time of the detector electronics.

rate predicted from the singles rate, we infer the signal-idler mode-matching efficiency η_{mode} to be 36%. Had the signal and idler fibers collected the same mode ($\eta_{mode} = 1$), the observed conditional probability would have been $\sim 8\%$.

In order to obtain polarization entanglement, we plan to pump the PPLN crystal from both sides with counter-propagating pump beams. The photon pairs are then extracted and the two signal photons as well as the two idler photons are combined using a polarizing beam splitter to yield the required polarization entanglement at two highly-nondegenerate wavelengths.

2 Detectors

The detection of the 800-nm photon is easily achieved with a commercial silicon photon counting module (PerkinElmer SPCM-AQR-14). For the detection of single photons at 1600 nm we built a compact all-solid-state In-GaAs avalanche photodiode detector.^{4,5} We used a fiber pigtailed avalanche photodiode [JDS Uniphase (EPM239BA)] that was cooled with a four-stage thermoelectric cooler to -50°C . For single-photon detection the diode was biased just below its breakdown voltage and a gating pulse provided an overbias of 2–4 V at appropriate times. The 20-ns gate pulses had a rise/fall time of 3–4 ns. The avalanche output pulses were then amplified by 40 dB with resultant pulse amplitudes of 1–2 V and rise times of less than 2 ns. We found good operating conditions at a temperature of -50°C , where dark counts were sufficiently low and afterpulsing due to trapped charge carriers was negligible at a gating frequency of 100 kHz. Figure 3 shows typical quantum efficiencies and dark-count probabilities as functions of the overbias voltage. The quantum efficiency reaches 20% at an overbias voltage of 3.5 V, at which point the dark count probability is $\sim 0.1\%$ within the 20-ns gate.

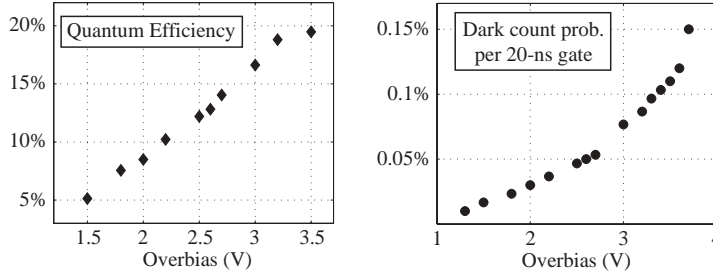


Figure 3. Plots of (left) quantum efficiency and (right) dark count probability of the InGaAs avalanche photodiode with a 20-ns gate at -50°C versus overbias voltage.

3 Conclusion

In conclusion, we have demonstrated efficient parametric downconversion in PPLN with highly-nondegenerate output pairs. The inferred pair-production rate was 1.4×10^7 pairs/s/mW of pump power. We also achieved coincidence detection using a thermoelectrically-cooled InGaAs avalanche photodiode.⁴ Future works include the generation of polarization entangled pairs as well as the implementation of a cavity configuration to increase the flux within a certain spectral and spatial mode.

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