

# Towards improved end-to-end system efficiency of photon pair systems

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## ABSTRACT

We report on our efforts in integrating a source and detection system of photon pairs that have a high end-to-end system efficiency. This requires combining appropriate detectors and photon pair sources. Preliminary measurements show that an observed heralding efficiency of 65% for single photons is readily achieved.

**Keywords:** parametric down conversion, photon counting, heralded single photons

## 1. INTRODUCTION

Photon pair sources based on spontaneous parametric down conversion inside a nonlinear crystal [1], have been the workhorse process for obtaining quantum states of light, used in both basic and applied research. Such sources have played pivotal roles in fundamental tests of quantum physics [2] (Bell Inequality Tests) as well as in demonstrating secure communication protocols based on quantum mechanics [3] (e.g. Quantum Key Distribution). Performance of all applications can be improved when the end-to-end system efficiency is increased. Proposed applications involving the simultaneous generation and detection of multiple pairs of photons will be practical only if the overall system efficiency is high. The system efficiency (measured by the coincidence-to-singles ratio, or C/S) depends on the preparation and collection of the photon pairs, their transmission and detection.

We choose to focus on three areas to improve system efficiency: the intrinsic level of noise photons that pollute the optical channel (leading to a low C/S ratio), good coupling efficiency of the generated photon pairs, and finally the detection efficiency of the detectors. Good progress has been achieved in all three areas in the past decade. In this paper, we would like to report our efforts that incorporate all the recent advances to demonstrate a photon pair system whose observed efficiency exceeds 65%.

## 2. OPTIMIZING COLLECTION EFFICIENCY

### 2.1 Investigation of crystal poling quality

The efficiency of fiber coupled photon pair sources has been widely studied and dramatically improved over the last decade [4]. Further improvements have been predicted from models of collinear down conversion sources, where pump and down converted light are emitted in the same direction [5]. This has led to some experimental work that attempted to quantify collection efficiencies [6].

At the same time, periodically poled nonlinear materials are now widely used so that the spectral brightness of sources can be improved. Such materials are effective at improving spectral brightness because they allow access to larger effective nonlinearities. Materials that are popular are periodically poled lithium niobate (PPLN) or periodically poled potassium-titanyl phosphate (PPKTP).

The system efficiency of a photon pair source is closely related to the concept of heralding efficiency, when photon pair sources are treated as heralded single photon sources. For ideal sources and detectors, with no optical or electrical noise, the C/S ratio is equal to the collection efficiency of the desired photon pairs. Any intrinsic optical noise or electrical noise (such as detector dark counts) cause additional single photon events to be registered, lowering the observed C/S. In a first approximation, the increase in accidental coincidences due to an increase in noise may be ignored.

One source of intrinsic optical noise arises from the imperfection of the poling period in nonlinear materials [7]. This period variation leads to a broadening of the collected single photon frequency spectrum. This can be understood as

imperfect destructive interference. A perfect poling period would enable undesired down conversion to be canceled; imperfect poling (e.g. due to engineering limitations) result in a background level of undesired down conversion, showing up as a broadening in the spectrum. Often, the partners for these background photons are not matched to the collection mode. Hence, the single photons in the broadened spectrum appear as uncorrelated single photons, i.e. noise.

One way of determining the poling quality is to measure the absolute efficiency of wavelength conversion (e.g in a difference frequency generation experiment). However, this is time consuming and may not be necessary when the aim is to select the best sample from a selection of crystals. We report that a Fourier analysis on the images of poling regions can be used as a basis for this selection.

Typical poling lengths in a crystal are several  $\mu\text{m}$ . Such length scales can be easily resolved under optical microscopes, and photographs of the poling regions can be obtained. Photographs of two different crystals are shown in Figure 1. These crystals were for frequency doubling 775 nm light, but manufactured using different methods.

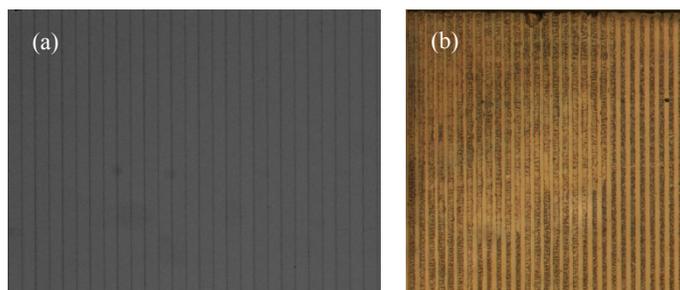


Figure 1 Photographs of poling regions for two different down conversion crystals.

The photographic images are processed to determine the boundary between adjacent poling periods. This information can be analyzed to obtain the Fourier spectrum of the poling period in each row of the image. The Fourier spectra from the two crystals is shown in Figure 2.

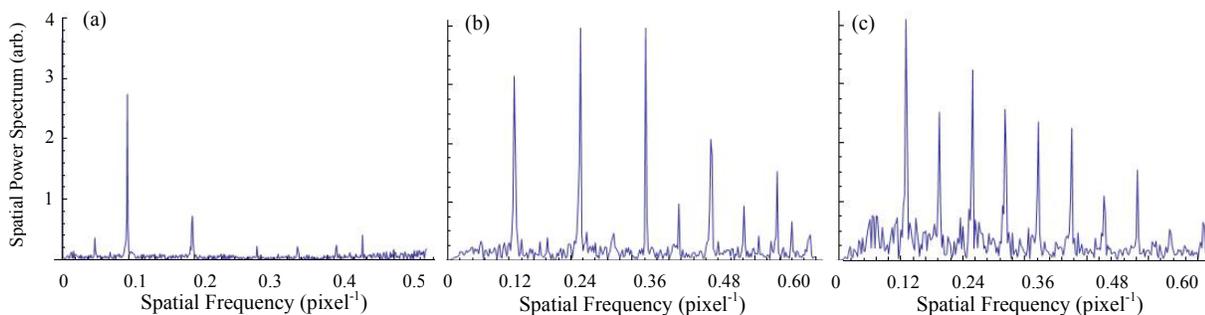


Figure 2 Fourier spectra for poling period in a typical pixel row from Figure 1. (a) The Fourier spectra from row 2 of Figure 1(a). (b) The Fourier spectra from row 2 of Figure 1(b). (c) The Fourier spectra from row 400 of Figure 1(b).

Figure 2 reveals that the crystal in Figure 1(a) has a single dominant peak in its Fourier spectrum, corresponding to less variation in the poling period. The poling period variation within a single crystal depends on location as well. This is observed for the crystal in Figure 1(b), where the envelope of the envelope of its Fourier spectrum at two different rows is significantly different. The crystal in Figure 1(a) is more suitable in a down conversion source that produces less intrinsic noise. This example illustrates the utility of using Fourier analysis in assessing periodically poled crystals for use in a down conversion experiment.

## 2.2 Experimental determination of optimum beam sizes

We have chosen a source design that would maximize coupling efficiency into single-mode fibers [6]. The source is based on a 25 mm long bulk periodically poled KTP crystal, aligned for degenerate Type-II collinear parametric down

conversion ( $y \rightarrow y+z$ ). The crystal is pumped with a grating stabilized 405 nm laser diode whose linewidth is measured to be  $\approx 200$  MHz. The crystal faces are anti-reflection coated to reduce scattering losses at the crystal-air interface.

In order to determine the appropriate beam waists for maximizing the coupling efficiency, a range of beam sizes was investigated with the setup shown in Figure 3. The pump waists were always centered on the crystal. The down converted photons were always collected into a single fiber. For each pump waist, a range of collection waists was investigated. Beam waists are measured directly with a CMOS camera.

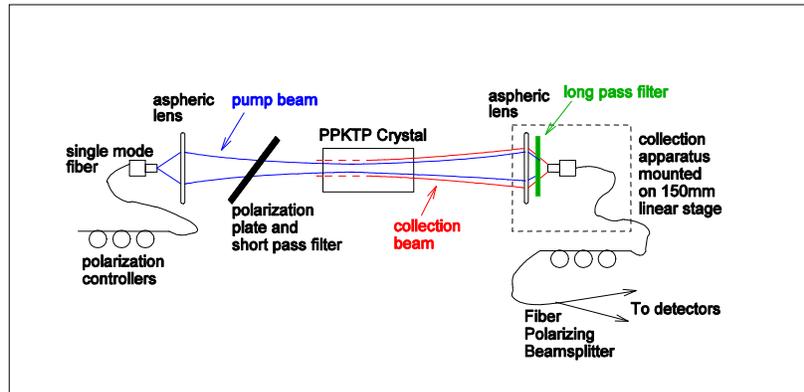


Figure 3 The experimental setup to determine optimum beam waists for collection into single-mode fibers. The collected down conversion photons are sent to avalanche photodiodes (with a measured efficiency of  $\approx 40\%$ ).

Figure 4 illustrates how the collection efficiency changes with the pump waist. This measurement result suggests that using beams with a longer Rayleigh range leads to more efficient collection of the photon pairs. The drawback of this result is that fewer photon pairs are collected (resulting in larger statistical uncertainties for larger pump waists). Our observation of the trend in collection efficiency is in qualitative agreement with previous results [6,8].

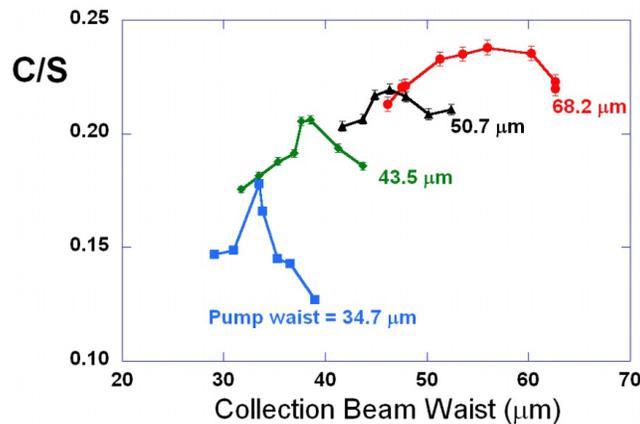


Figure 4 Coincidence-to-singles ratio for pump and collection waists in a collinear downconversion setup. The pump waists are indicated. All detected photon pairs were first collected into a single-mode fiber. Error bars correspond to a statistical uncertainty of one standard deviation.

We also observed a novel result. The beam waist conditions for maximum photon pair rate are distinct from the conditions for maximizing the photon pair collection efficiency. This is illustrated in Figure 5. In this measurement set, the pump waist was fixed at  $31 \mu\text{m}$ , while the collection lens was moved to alter its distance from the center of the crystal. However, the focus of the collection beam was always at the center of the crystal; this corresponded to changing the collection beam waist from between  $30$  to  $50 \mu\text{m}$ .

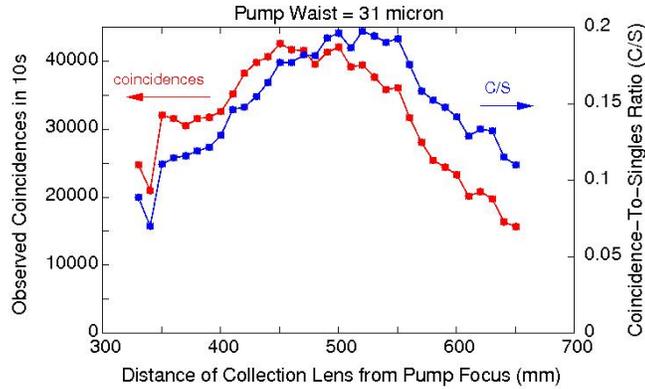


Figure 5 Collection beam waists for maximizing coincidences and C/S ratio are different. Error bars (obscured by data point size), correspond to a statistical uncertainty of one standard deviation.

Figure 5 clearly demonstrates that the maximum coincidence rate and the maximum collection efficiency, require different beam parameters. This is in agreement with analytical models for collection efficiencies using collinear Gaussian beams [8].

### 3. TOTAL SYSTEM EFFICIENCY

#### 3.1 Efficient Detectors

The standard detectors for detecting photons have been avalanche photo diodes (APD), triggered by the presence of at least one photon. These detectors have no photon number resolving capability, and have a maximum efficiency of  $\approx 60\%$  at 700 nm. In recent years, much progress has been made in developing photon number resolving fiber-pigtailed detectors at NIST [9]. These devices are based on superconducting Tungsten films, with high detection efficiency ( $>95\%$  at 1550 nm), and no dark counts due to electrical noise. We have recently obtained similar detectors optimized for 810 nm. Laboratory measurement of these detectors reveals a consistent detection efficiency of about 90% (including fiber losses).

#### 3.2 Integrating Superconducting Detector and Source

In this experiment, a polarizing beam splitter is used to separate the photon pair, and each individual photon is collected into two separate single-mode fibers. Both fibers are adjusted to have the same collection beam parameters. Let  $S$  denote the total rate of photon pairs produced in the collection mode. The singles rate observed at the first superconducting detector,  $S_1$  is given by  $S_1 = \eta_1 S$ , where  $\eta_1$  is the total transmission efficiency in the system traversed by photons ending at the photo diode. The singles rate observed with the second superconducting detector is  $S_2 = \eta_2 S$  where  $\eta_2$  is the total system transmission efficiency for photons detected by the superconducting detector. The rate of coincidences,  $C$ , is given by  $C = \eta_1 \eta_2 S$ .

In the reconfigured setup the pump beam waist was  $\approx 66 \mu\text{m}$  while the collection beam waist was  $\approx 61 \mu\text{m}$ . In the first iteration of the experiment, both fibers were directed to APDs whose detection efficiency was  $\approx 42\%$ . The C/S value for this setup was found to be  $\approx 0.25$ , corresponding to an overall system efficiency of 25%.

A 2 nm bandpass filter was then introduced into one arm of the source. It was found that the ratio of coincidences-to-filtered-singles increased to 30%. This was strong evidence that despite choosing to use a crystal with minimal poling uncertainty, uncorrelated single photons were still being collected into the single-mode fibers. This filtered arm was chosen as the heralding arm. In order to maximize the heralding efficiency, the collection beam in the heralding arm was tuned to have a smaller acceptance angle (i.e. longer Rayleigh range). In this configuration, the heralding efficiency observed was 34%.

To illustrate the use of high efficiency detectors, both collection fibers were directed to the superconducting detectors. However, these detectors cannot be operated at arbitrary pump power levels. This was because at high pump power,

photon pair production can occur so close together that a superconducting detector would detect additional photons before the signal from the first photon would have decayed. This pile up of photo events causes noise. Hence, the system had to be operated at a sufficiently low pump power. The final results are shown in Figure 6, illustrating the observed ratio of coincidences-to-filtered-singles as the pump power is changed. Superconducting detectors were used in both the heralded and heralding channels. We find that the maximum observed system efficiency is  $65.8 \pm 1.1\%$ .

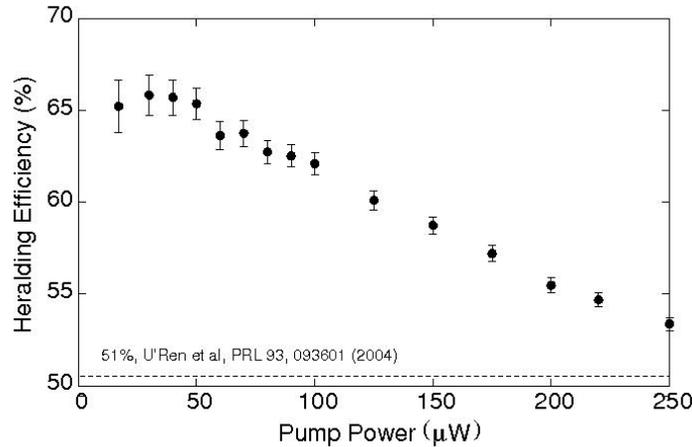


Figure 6 Heralding efficiency of filtered singles as a function of pump power. Above 50  $\mu\text{W}$  of pump power the pulse counting electronics saturate. The highest reported heralding efficiency (including all detection efficiencies) we are aware of is 51%. Error bars correspond to a statistical uncertainty of one standard deviation.

Losses in the transmission and detection system for the heralded single photons are summarized in Table 1. Neglecting losses in the optical fiber splices and length and detection inefficiency, we estimate a coupling efficiency of 84%. We note that this is comparable with previously reported results [10].

Table 1. Summary of measured transmission in the system. The heralded singles are selected from the reflected output of the polarizing beam splitter. The extinction ratio of this beam splitter is  $\approx 500:1$ , and its effect on the heralding efficiency is negligible.

Transmission for Heralded Singles		
Superconducting detector	90.0%	$\pm 5.0\%$
Aspheric Lens	96.2%	$\pm 0.8\%$
Longpass Filter (estimated)	98.0%	$\pm 1.0\%$
Polarizing Beam Splitter (in reflection)	92.0%	$\pm 3.0\%$
<b>Total Transmission</b>	<b>78.0%</b>	<b><math>\pm 5.0\%</math></b>
Transmission Optical Fibers (4 splices, $\approx 20$ m)	measurement in progress	

## DISCUSSION AND CONCLUSION

We have demonstrated a photon pair system consisting of a source and detection setup that can achieve an observed heralding efficiency of  $\approx 66\%$ . This value can be improved significantly by using custom coated polarizing beam splitters and aspheric lenses. The superconducting detectors may also be improved, but that is technically challenging. An unknown quantity is the exact transmission in the optical fibers, and measurements are being made to obtain this value.

The system efficiency of 66% represents a 33% improvement in the heralding efficiency of photon pair sources [10]. Such a source also has implications for tests of fundamental physics. To close the detection loophole of Bell's Inequality using Eberhard states, requires a system efficiency of 67% [11]. To close the same loophole, but using more exotic hyperentangled states requires a system efficiency of only 61% [12]. At the same time, such sources will be useful for testing and fine-tuning quantum metrology protocols [13].

## ACKNOWLEDGMENTS

A. L. acknowledges useful discussions with Alessandro Fedrizzi, Thomas Jennewein, Thomas Gerrits and Sae Woo Nam.

## REFERENCES

- [1] Burnham, D. C. and Weinberg, D. L., "Observation of simultaneity in parametric production of optical photon pairs," *Physical Review Letters* **25**, 84 (1970)
- [2] Ou, Z. Y. and Mandel, L., "Violation of Bell's Inequality and Classical Probability in a Two-Photon Correlation Experiment," *Physical Review Letters* **61**, 50 (1988)
- [3] Ekert, A. K., Rarity, J. G., Tapster, P. R. and Massimo Palma, G., "Practical quantum cryptography based on two-photon interferometry," *Physical Review Letters* **69**, 1293 (1992)
- [4] Kurtsiefer, C., Oberparleiter, M., and Weinfurter, H., "High-efficiency photon pair collection in type-II parametric fluorescence," *Physical Review A* **64**, 023802 (2001), Bovino, F. A., Varisco, P., Colla, A. M., Castagnoli, G., Giuseppi, G. D. and Sergienko, A. V., "Effective fiber-coupling of entangled photons for quantum communication," *Physical Review A* **227**, 343 (2003)
- [5] Ljunggren, D. and Tengner, M., "Optimal focusing for maximal collection of entangled narrow-band sources of photon pairs into single-mode fibers," *Physical Review A* **72**, 062301 (2005)
- [6] Fedrizzi, A, Herbst, T., Poppe, A., Jennewein, T., and Zeilinger, A., "A wavelength-tunable fiber-coupled source of narrowband entangled photons," *Optics Express* **15**, 15377 (2007)
- [7] Fejer, M., Magel, G., Jundt, D., and Byer, R., "Quasi-phase-matched second harmonic generation: tuning and tolerances," *IEEE Journal of Quantum Electronics* **28**, 2631 (1992)
- [8] Bennink, R. S., "Optimal co-linear Gaussian Beams for Spontaneous Parametric Down-Conversion," [arXiv:1003.3810v1](https://arxiv.org/abs/1003.3810v1) (2010)
- [9] Rosenberg, D, Lita, A. E., Miller, A. J. and Nam, S. W., "Noise-free high-efficiency photon-number-resolving detectors," *Physical Review A* **71**, 061803 (2005)
- [10] U'Ren, A. B., Silberhorn, C., Banaszek, K., and Walmsley, I., "Efficient Conditional Preparation of High-Fidelity Single Photon States for Fiber-Optic Quantum Networks," *Physical Review Letters* **93**, 093601 (2004)
- [11] Eberhard, P. H., "Background level and counter efficiencies required for a loophole-free Einstein-Podolsky-Rosen experiment," *Physical Review A* **47**, R747 (1993)
- [12] Tamas, V., Stefano, P., and Brunner, N., "Closing the detection loophole in Bell experiments using qudits," *Physical Review Letters* **104**, 060401 (2010)
- [13] Cable, H., and Durkin, G., "Quantum Phase Estimation with Entangled Photons produced by Parametric Down Conversion," [arXiv:0910.1957v2](https://arxiv.org/abs/0910.1957v2) (2010)