Single-photon source heralding efficiency and detection efficiency metrology at 1550 nm using periodically poled lithium niobate

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Abstract. We explored the feasibility of using high-efficiency periodically-poled crystals configured to produce downconverted photons for photon counting detector calibration at 1550 nm, with obvious importance for metrology and quantum communication applications. Moreover key considerations for both applications is the coupling of the downconverted photons into single-mode fibers. This study ties together the results of our efforts to model the single-mode heralding efficiency of a two-photon parametric downconversion source and our work to improve the accuracy of photon-counting calibrations made with which such a source.

1. Introduction

Parametric down-conversion (PDC) consumes pump photons and produces light with a two-photon field description [1]. This two-photon light, which allows one photon to indicate or herald the existence of its twin, is key to applications such as quantum metrology [2] and quantum information [3, 4]. In particular, these PDC applications work by preparing one photon in a well defined state by measuring its twin, effectively creating a single-photon source. To realize such a single-photon source [5] for these applications, there are two key demands we address here. First, high efficiency photon pair production and collection is critical for the utility of the applications. Second, there is strong interest in having the heralded photon at a wavelength convenient for telecom (1550 nm) and collected in a single-mode fiber.

For high efficiency of pair production, the use of periodic poled crystals is becoming common [11], although they have not yet been used for metrology applications. While metrology applications would certainly benefit from the advantage of high pump conversion efficiency, it is not clear that other characteristics of the periodically poled crystals would be compatible with these applications. Specifically, the level of background fluorescence may limit the uncertainty that can be achieved.

As for the efficiency of collection of PDC light into a single mode fiber, there have been a number of such efforts recently. The goal of these efforts is to accurately understand and model the two-photon process whereby the detection of one photon of a PDC pair, in a well defined spatial and spectral mode, defines the correlated spatial and spectral mode which can then be efficiently collected. These efforts have included experiments and theoretical work in both continuous wave (CW) [6, 7] and pulse-pumped [8, 9, 10] PDC, generated in bulk crystals, and have highlighted the critical problem of coupling of the PDC photons into single-mode fibers (SMF) due to the difficulty of spatial and spectral matching of the photon pairs. The results show that optimization of the heralding efficiency is extremely sensitive to spectral and spatial mode selection.

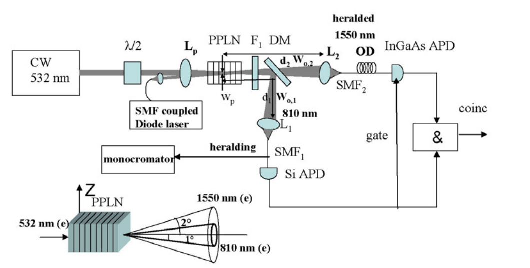

Figure 1. Setup to herald single-photons from CW PDC from a PPLN crystal.

We have set up (fig. 1) a 5 mm periodically poled lithium niobate (PPLN) crystal pumped by a CW laser at 532 nm to produce 810 nm and 1550 nm

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photon pairs in a slightly noncollinear geometry. We use this source to measure the detection efficiency of an InGaAs APD at 1550 nm and in doing so also test our two-photon collection efficiency model. In our experiment, the crystal was operated in a quasi-phasematching configuration, with noncritical phase-matching (90° phase-matching angle) and a 7.36 μm period to produce PDC photons at 810 nm and 1550 nm at external angles of 1° and 2°. Fine tuning of this output was achieved by adjusting the crystal temperature to 149 °C. A lens, L_p was used in the pump beam to produce a gaussian beam waist of $w_p \simeq 100$ μm at the crystal, a cutoff filter F_1 blocked the pump laser and a dichroic mirror (DM) separated the 810 nm (beam 1) and 1550 nm (beam 2) photons. A monochromator was inserted in the heralding path to align the 810 nm light, measure its spectral width, and as a filter. The heralding arm was routed to a SMF and then to a Si APD, while the heralded arm, also coupled to a SMF, was sent to a InGaAs APD, operating with gated bias. The heralded arm optical delay was adjusted with an appropriate length SMF to observe coincidences when the InGaAs detector was gated by the detection of a 810 nm photon in the heralding arm. The InGaAs detector, including the SMF and coupling lens optical losses, was calibrated against a conventional detector standard using a attenuated laser source, yielding a raw detection efficiency of $\eta_{det} = 9.8\%$.

The detector efficiency as measured by the PDC source is given by

$$\eta_{det} = (\chi_P \cdot \tau_{opt} \cdot \tau_{SMF-lens})^{-1} \times \frac{P_{coinc} - P_{uncorr}}{(1 - P_{uncorr})(1 - P_{backgnd}^{heralding})}, \quad (1)$$

where χ_P is the heralding efficiency (single-mode preparation efficiency)[7, 12], τ_{opt} is the overall heralded arm optical transmittance (including PPLN, F_1, DM), $\tau_{SMF-lens}$ is the optical transmittance of the L_2 and the SMF on the heralded arms, P_{coinc} is the probability of coincident counts per gate, P_{uncorr} is probability of uncorrelated or accidental coincidence counts per gate (determined by changing the heralding delay so the detection gate misses photons correlated to the herald photons), and $P_{backgnd}^{heralding}$ is the probability of gating counts produced by uncorrelated photons and dark counts on the heralding arm. The heralding efficiency χ_P [7] is the efficiency of preparing a photon in the heralded channel in a definite spectral and spatial mode, by specific mode selection of the heralding arm. This factor is in addition to the other optical transmittances in the *heralded* channel. It basically quantifies how well the collection system geometrically catches photons correlated to those seen by the trigger detector. To calibrate a SMF-coupled detector, the heralding efficiency must be optimized and estimated. It has been calculated in ref. [7] in the case of bulk crystal. For PPLN [12] it is

$$\chi_P = \frac{4\, w_p^2 w_1^2 w_2^2 (w_1^2 + w_p^2)}{(w_2^2 w_p^2 + w_1^2\, (w_2^2 + w_p^2))^2} \frac{\Delta_2}{(\Delta_1^2 + \Delta_2^2)^{\frac{1}{2}}} f(L), \quad (2)$$

where $\Delta_{1,2}$ =1 nm, 2.7 nm are the spectral bandwidths selected by the SMF in the two arms and $f(L)$ is a correction function depending on the crystal length. We used two lenses configuration to mode match the fields. With L_1 and L_2 both f=8 mm aspheric lenses, at d_1=270 mm and d_2=220 mm, and $w_1 = w_2$=100 μm, from Eq.(1), we obtained the experimental value of χ_p =64%, while from Eq. (2) we estimate χ_p=61%. With L_1 and L_2 both 20x microscope objectives at d_1=560 mm and d_2=190 mm, and $w_1 = 144\mu$m and w_2=76 μm, we obtained the experimental value of χ_p =77% and the theoretical χ_p=78 %. Those values are in good agreement considering the difficulty to measure the bandwidths and waists at the crystal. The measured values in Eq.(1)are P_{coinc}=2.2%, 2.9%, $P_{uncorr}^{heralded}$=0.2 %, 0.3 % and $P_{backgnd}^{heralding}$=41%, 29%. We measured the τ_{opt}=65 % and $\tau_{SMF-lens}$=83 %, 73%, for the lenses and objectives configuration, respectively. The heralding background, properly measured using the monochromator, is due to the fluorescence of the PPLN. This experiment, with the high level of 0.07 pairs/(mW gate) produced indicates that PPLN should be compatible with the detector efficiency application for direct calibration of single-mode coupled InGaAs photon-counting detectors at 1550 nm. In addition, the level of consistency (although very rough at this early stage of our work) between the two detector calibration methods reflects favorably on the validity of our mode-matching model. Because in this initial experiment the PDC source and optical collection system was not optimized for 1550 nm and losses were relatively high, we expect that there is significant room to improve the system to allow a high accuracy test to be performed.

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