arXiv:quant-ph/0511128v2 25 Jul 2006

# ANALYSIS OF THE GENERATION OF PHOTON PAIRS IN PERIODICALLY POLED LITHIUM NIOBATE

J. SÖDERHOLM, K. HIRANO, S. MORI and S. INOUE*

*Institute of Quantum Science, Nihon University,*
*1-8 Kanda-Surugadai, Chiyoda-ku, Tokyo 101-8308, Japan*
**E-mail: ino@phys.cst.nihon-u.ac.jp*

S. KURIMURA

*National Institute for Materials Science, 1-1 Namiki, Tsukuba-shi, Ibaraki 305-0044, Japan*

The process of spontaneous parametric down-conversion (SPDC) in nonlinear crystals makes it fairly easy to generate entangled photon states. It has been known for some time that the conversion efficiency can be improved by employing quasi-phase-matching in periodically poled crystals. Using two single-photon detectors, we have analyzed the photon pairs generated by SPDC in a periodically poled lithium niobate crystal pumped by a femtosecond laser. Several parameters could be varied in our setup, allowing us to obtain data in close agreement with both thermal and Poissonian photon-pair distributions.

*Keywords*: Photon-pair generation; periodically poled lithium niobate; photon statistics.

## 1. Introduction

Through optical nonlinearities in a crystal, one pump photon can be converted into two photons with longer wavelengths. The fact that these down-converted photons are always generated in pairs has made it possible to use them for many fundamental quantum-mechanical experiments.[1] These photon pairs are also suitable for fundamentally secure quantum-key distribution, which is usually referred to as quantum cryptography.[2] Recently, it was recognized that the efficiency of the photon-pair generation can be improved by using periodically poled crystals.[3] The ferroelectric polarization of these crystals is periodically inverted, resulting in flips of the sign of the nonlinear coupling $\chi^{(2)}$. Through quasi-phase-matching one may then exploit larger nonlinear coefficients than what is possible using birefringent phase matching.

In the present work, we have used single-photon detectors to analyze the down-converted photon pairs generated in a periodically poled lithium niobate (PPLN) crystal under various conditions.

## 2. Experimental setup

The experimental setup is schematically depicted in Fig. 1. Our 10-mm-long bulk PPLN crystal was doped with 5 mol% MgO and pumped by 200-fs-long pulses from a Titanium:sapphire laser with a repetition rate of 80 MHz. The poling periodicity of the crystal was 19.4 $\mu$m, corresponding to degenerate quasi-phase-matched parametric down-

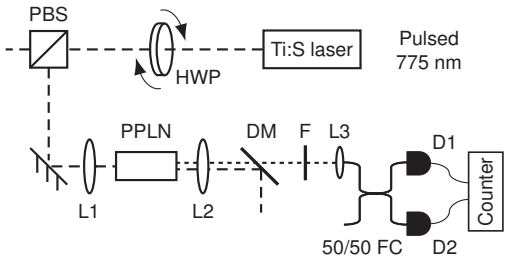


Fig. 1. Schematic drawing of our experimental setup used to analyze the photon pairs generated in a PPLN crystal. (See text for explanation.)

conversion at 1544 nm. However, in order to make the frequency of the degenerate photon pairs coincide with our interference filters' central frequency of 1550 nm, the wavelength of the laser was set to 775 nm. A half-wave plate (HWP) and a polarizing beam splitter (PBS) were used to attenuate the laser power without distorting the laser mode and pulse. As the polarization direction of the laser beam depended on the rotation angle of the HWP, the intensity of the pump beam emerging from the PBS could be varied.

Three different pairs of lenses were used to focus the pump beam in the crystal, and collect the down-converted light. In the case with closest focus, we did not have two matching lenses at hand, so the focal length of L1 was 8.2 mm, whereas that of L2 was 10 mm. In the other two cases, both L1 and L2 had a focal length of 14.8 mm and 50 mm, respectively. Effective down-conversion was restricted to the focus, since the pump intensity was much higher there.

A dichroic mirror (DM) and a filter (F), with a full-width-at-half-maximum bandwidth of either 10 or 30 nm, were used to discriminate the down-converted light from the pump. The down-converted light was subsequently coupled into a fiber using a third lens (L3). After splitting the beam with a 50/50 fiber coupler (50/50 FC), both single and coincidence events at the single-photon detectors (D1 and D2) were recorded. The detectors were gated at a rate of 316 kHz and synchronized with the pump pulses.

## 3. Theory

Since our detectors cannot distinguish if one or more photons make them "click", the single-count rate at detector $k$ (when neglecting dark counts) can be expressed as

$$S_k = R\sum_{m=0}^{\infty}\frac{p(m)}{4^m}\sum_{n=0}^{2m}\binom{2m}{n}[1-(1-T\eta_k)^n], \quad (1)$$

where $R$ is the gate rate, $p(m)$ denotes the probability for $m$ photon pairs to be generated, $T$ is the transmittivity of the optical components, and $\eta_k$ is the detector efficiency. Similarly, the coincidence-count rate, i.e., the rate with which both the detectors click during the same gate pulse, can be written as

$$C = R\sum_{m=0}^{\infty}\frac{p(m)}{4^m}\sum_{n=0}^{2m}\binom{2m}{n}[1-(1-T\eta_1)^n] \times[1-(1-T\eta_2)^{2m-n}]. \quad (2)$$

### 3.1. *Photon-pair distributions*

In the present setup, most photon pairs will be composed of photons with different wavelengths. With no initial photons in the down-conversion modes, the nondegenerate SPDC process is known to generate the two-mode squeezed vacuum state. The photon-pair distribution is then thermal[4]

$$p_{\rm th}(m) = \frac{\mu^m}{(\mu+1)^{m+1}}, \quad (3)$$

where $\mu = \sinh^2 r$ is the average number of photon pairs, and the squeezing parameter $r$ is proportional to the electric field of the pump.[5] Assuming that the form of the pump pulse is independent of the pump power, we thus obtain $\mu = \sinh^2\sqrt{KP_{\rm ave}}$, where $K$ is a constant and $P_{\rm ave}$ is the average pump power. We note that $\mu \approx KP_{\rm ave}$ as $\sqrt{KP_{\rm ave}} \ll 1$.

On the other hand, when the detected photons originate from many distinguishable down-conversion processes, the photon-pair distribution can be approximated[6] by the Poissonian distribution

$$p_{\rm poi}(m) = \frac{\nu^m e^{-\nu}}{m!}, \quad (4)$$

where $\nu$ is the average value of the total number of photon pairs generated by a single pump pulse. As there are many distinguishable processes, the average photon-pair number in each of them is usually small ($\mu \ll 1$), and therefore proportional to the average pump power. We then get $\nu \approx \mathcal{K}P_{\rm ave}$, where

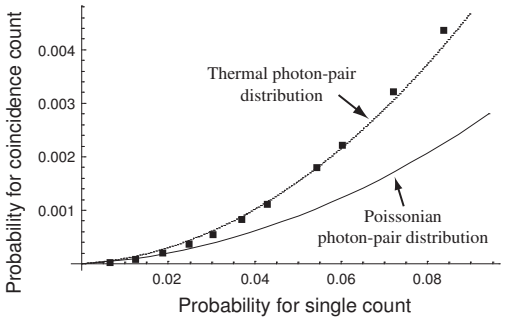


Fig. 2. Experimental results (■) obtained with a focus length of 8.2 mm and a 10-nm filter.

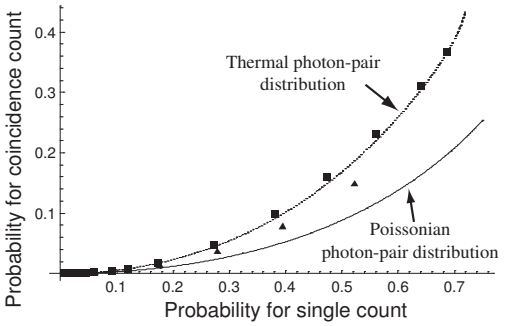


Fig. 3. Experimental data obtained with a 10-nm filter and pairs of lenses with a focus length of 14.8 mm (■) and 50 mm (▲).

$\mathcal{K}$ is a constant. In a recent experiment[7] similar to the one reported here, but employing a semiconductor laser and a 3-cm-long PPLN waveguide, we have been able to fit both single and coincidence counts versus pump power to such a Poissonian photon-pair distribution.

### 3.2. *Dark counts*

As there is a probability for the detectors to click even when no photon is incident, the effects of these dark counts should be compensated for before comparing the experimental data with the expressions in the previous section. Noting that the raw single-count rates $S_k^{(\mathrm{raw})}$ are due to either incident photons, dark counts, or both, one finds that the photon-induced single-count rates are given by

$$S_k^{(\mathrm{ph})} = \frac{S_k^{(\mathrm{raw})} - \delta_k}{1 - \delta_k R^{-1}}, \qquad (5)$$

where $\delta_k$ denotes the dark-count rate at detector $k$. Neglecting terms that include the product $\delta_1\delta_2$, we obtain the following approximation for the photon-induced coincidence-count rate:

$$C^{(\mathrm{ph})} \approx \frac{C^{(\mathrm{raw})}R - S_1^{(\mathrm{ph})}\delta_2 - \delta_1 S_2^{(\mathrm{ph})}}{R - \delta_1 - \delta_2}, \qquad (6)$$

where $C^{(\mathrm{raw})}$ is the raw coincidence-count rate.

## 4. Experimental results

Using a laser emitting light with a wavelength of 1550 nm, the transmittivity of the optical components was measured. Also the detector efficiencies $\eta_1$ and $\eta_2$ were determined in independent measurements. Plugging in these values into Eqs. (1) and (2), the single-count and coincidence-count rates for a thermal or Poissonian photon-pair distribution with a given average number of photon pairs could be calculated. In Figs. 2–4, the resulting relations between the probabilities for a single and a coincidence count have been plotted as curves. Here, the single-count probability is the probability for one or two detectors to click, which is given by $(S_1 + S_2 - C)/R$.

In Fig. 2, the data obtained with a focal length of 8.2 mm and a 10-nm filter are presented. The different data points correspond to different pump powers, and the effects of dark counts have been compensated for. These measurements are seen to be in agreement with a thermal photon-pair distribution. The results obtained after changing the focal length to 14.8 and 50 mm are shown in Fig. 3. We see that also with a focal length of 14.8 mm, the data are in agreement with the thermal distribution, whereas the longest focal length resulted in a distribution lying between the thermal and Poissonian photon-pair distributions. This can be understood

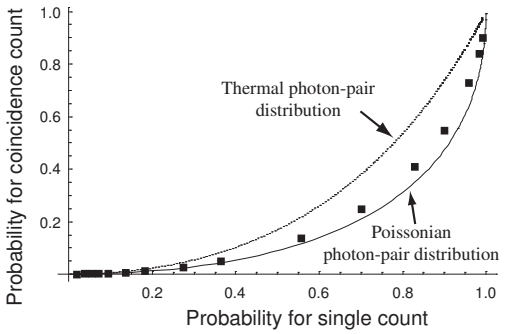


Fig. 4. Experimental results (■) obtained with a focus length of 50 mm and a 30-nm filter.

considering the dispersion between the pump and down-converted light in the crystal. For a sufficiently large focus, i.e., for a sufficiently long focal length of the lenses, photon pairs generated in different locations within the focus will not emerge from the crystal at the same time. The contributing processes can thus be distinguished, resulting in a photon-pair distribution that is closer to Poissonian.

In Fig. 4, we present the data obtained with a focal length of 50 mm and a 30-nm filter. In this case, our measurements are seen to be close to the Poissonian curve. This can be explained by the fact that a broader filter allows for a shorter coherence time of the transmitted down-converted light,[6,7] which makes it easier to distinguish the generated photon pairs.

We note that a high number of photon pairs were generated in some of our measurements. Assuming that the down-converted light generated with a focal width of 14.8 mm indeed is described by a thermal photon-pair distribution, and that the overall detection efficiency equals the measured value of 2%, the maximum average number of generated photon pairs per pulse is found to be 60. Similarly, the data presented in Fig. 4 corresponds to a maximum average number of photon pairs of 100, if the generated photon pairs are assumed to have a Poissonian distribution and the measured overall transmittivity of 2.8% is correct. In this case, the power of the down-converted light after the filter was measured to be 2 nW using a simple power meter.

Finally, we note that, in contrast to our experiment with a waveguide,[7] we have not been able to fit the measured single-count and coincidence-count rates as functions of pump power to the theoretical expressions given in the previous section. We believe that this is due to the high pump power and/or the very high peak intensity achieved with the Titanium:sapphire laser. This should increase the temperature of the crystal, and consequently change the properties of the material and the phase-matching conditions.

## 5. Conclusions

We have shown that even with only two single-photon detectors and a low overall detection efficiency, insight into the photon statistics can be gained. By changing the experimental conditions, our experimental data could be varied from the expected results for a thermal photon-pair distribution to those for a Poissonian photon-pair distribution. This was explained by the increasing degree of distinguishability within the distributed generation of photon pairs.

## References

1. L. Mandel, *Rev. Mod. Phys.* **71**, S274 (1999); A. Zeilinger, *Rev. Mod. Phys.* **71**, S288 (1999).
2. N. Gisin, G. Ribordy, W. Tittel and H. Zbinden, *Rev. Mod. Phys.* **74**, 145 (2002).
3. S. Tanzilli *et al.*, *Electron. Lett.* **37**, 26 (2001); K. Sanaka, K. Kawahara and T. Kuga, *Phys. Rev. Lett.* **86**, 5620 (2001).
4. B. R. Mollow and R. J. Glauber, *Phys. Rev.* **160**, 1076 (1967).
5. M. O. Scully and M. S. Zubairy, *Quantum Optics* (Cambridge University Press, Cambridge, 1997), Chap. 16.
6. H. de Riedmatten *et al.*, *J. Mod. Opt.* **51**, 1637 (2004).
7. S. Mori, J. Söderholm, N. Namekata and S. Inoue, quant-ph/0509186.