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On the measurement of photon flux in parametric down-conversion

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Abstract. We report the measurement of the photons flux produced in parametric down-conversion, performed in photon counting regime with actively quenched silicon avalanche photodiodes as single photon detectors. Measurements are done with the detector in a well defined geometrical and spectral situation. By comparison of the experimental data with the theory, a value for the second order susceptibilities of the non linear crystal can be inferred.

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1 Introduction

Parametric down-conversion, also referred to as parametric fluorescence, parametric noise etc., is a well established phenomenon in the realm of quantum optics, whose applications range from the techniques of non-linear optics, based on optical parametric amplifiers, to the fundamental tests of quantum mechanics with entangled photons pairs. It has been extensively studied since the mid 70's and severely tested on the experimental side, even recently.

The majority of experiments on the subject, however, was mainly aimed at verifying the spatial-temporal entanglement of idler and signal beams and eventually test the contribution of the pump spectral width [1]. These experiments, therefore, are primarily concerned with measurements of coincidence rates between correlated photons: there seems to be lack, at least to authors' knowledge, of experimental tests of parametric down-conversion emission rate on a single channel. This may well be due to the fact that the latter quantity is experimentally linked to scarcely known ones, notably the actual value of phase-matching angle and of the non-linear susceptibilities of the dielectric employed in the experiment. Last but not least, the uncertainties among different Sellmeier relations for the determination of refraction indices play themselves a major negative role. To the authors' opinion, however, there is a definite interest in testing the theoretical predictions regarding photon flux emission on a single channel in parametric down conversion. An experiment in this sense, of course, requires a very good knowledge of the solid angle of view of the detector, its optical bandwidth and, most important, its quantum efficiency.

The latter of the forementioned points has been addressed to in a recent experiment on quantum efficiency measurement by correlated photon pairs [2] and a couple of avalanche photodiodes with active quenching is now calibrated at the per cent level as regards the efficiency. With slight modifications, the experimental set-up employed in quantum efficiency measurements can be of use for measuring photon fluxes on a single channel, in the way described below.

The essence of the parametric down-conversion effect is fully described by the relation between the pumping power P_p and the power δP_s of the fluorescence signal emitted by a non-linear medium (*i.e.* a crystal) in a spectral interval $\delta\lambda_\mathrm{s}$, integrated over the whole solid angle [3]:

$$\delta P_\mathrm{s} = (2\pi)^4 \frac{2\hbar c d_\mathrm{eff}^2}{\varepsilon_0 n_\mathrm{p}^2} \frac{\lambda_\mathrm{p}}{\lambda_\mathrm{s}^5 \lambda_\mathrm{i}^2} \int_0^L P_\mathrm{p}(l) \mathrm{d}l \delta\lambda_\mathrm{s} \qquad (1)$$

where L is the length of the crystal, and n and λ denote the index of refraction and the wavelengths, respectively. Subscripts s, i and p refer to the signal, the idler and the pump, and the relation:

$$\frac{1}{\lambda_\mathrm{p}} = \frac{1}{\lambda_\mathrm{s}} + \frac{1}{\lambda_\mathrm{i}}$$

is satisfied by the three wavelengths.

The integration over the pump power takes into account the absorption of lithium iodate at 351 nm. For $P_\mathrm{p}(l)$ we assume Beer's law:

$$P_\mathrm{p}(l) = P_\mathrm{p}(0)\mathrm{e}^{-\alpha l}$$

and coefficient α was measured to be 104.28 m^{-1} [4].

The effective non-linear coefficient d_eff is related to the second-order susceptibilities of the medium through both the phase-matching angle θ_m and the double-refraction angle ρ in a way depending on the used crystal and on the type of phase-matching performed.

Expression (1) has been extensively used for the sake of measuring non-linear susceptibilities in some crystals

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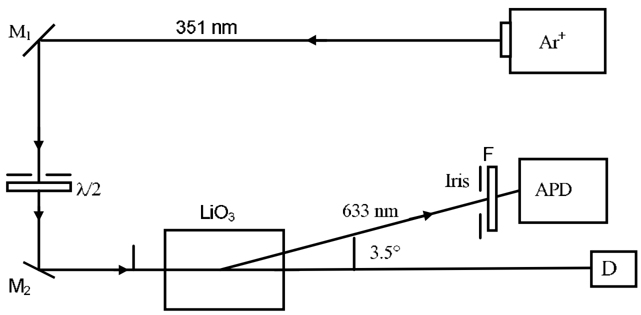

Fig. 1. Experimental set-up.

[3,4], as d_{eff} is linked in (1) to directly measurable quantities. In the experiments reported in literature the fluorescence power δP_{s} is usually measured with a calibrated detector by integration over a finite spectral interval λ_{s}, so that a total power in the nanowatt range results: this level of power is well suited for measurements in analogous regime with calibrated optical detectors [4].

As hinted before, the previous expression has never been tested down to very low photon fluxes, at the limit of detectors' dark noise. Even if expression (1) is an integral expression, a direct comparison with measurements through narrow solid angle of view is possible, as will be apparent in the following.

2 The experiment

The same experimental set-up employed for measurement of detector's quantum efficiency by means of correlated photon pairs, discussed elsewhere [2], was used for measurement of photon fluxes in well defined solid angles and spectral bandwidths. A small iris at some distance from the parametric fluorescence source does the job of defining precisely the detector solid angle, whereas the bandwidth is determined by means of a narrow interference filter. Such an arrangement has the benefit, among others, of reducing the problem of stray light to negligible levels, a major problem in photon counting, as will become apparent in the discussion of results.

The experiment takes the form depicted in Figure 1.

A non-linear crystal of $LiIO_3$ of size $10 \times 10 \times 10$ mm^3, oriented for type I (*ooe*) phase matching is pumped by the UV line at 351.2 nm from a multiline argon ion laser. With a variable attenuator in front of the laser, made of a polarizing prism and a $\lambda/2$ waveplate, we can lower the power at 351 nm down to tens of microwatts. The pump power is monitored by a calibrated photodiode (D), 1.5 m downstream the crystal.

The iris of 1.5 mm diameter at a distance of 1.23 m from the crystal defines a solid angle of view of 1.4×10^{-6} sterad for the detector, and the interference filter of 3 nm FWHM bandwidth (F) fixes the spectral measurement conditions. By means of a noncollinear parametric amplifier arrangement the propagation direction of the parametric down-converted photons at 633 nm is easily found and its angle with respect to the pump direction out of the crystal ($\theta_{\text{ext}} = 3.5° \pm 0.5°$) is well defined [5].

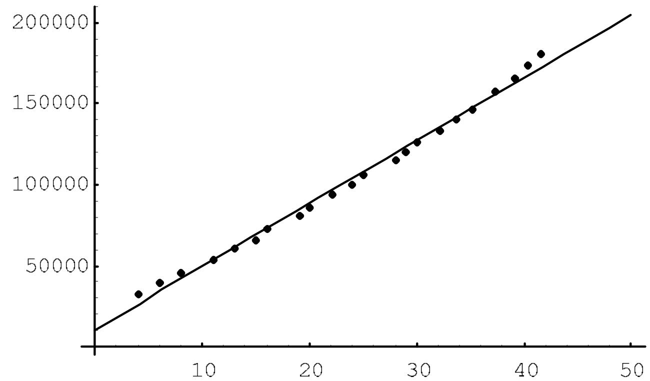

Fig. 2. Mean photon number over 100 s *vs.* photodetector current.

From this quantity, the actual phase-matching angle is found (51.33°). The single photon detector is an actively quenched avalanche photodiode (APD) provided for fibre coupling, whose quantum efficiency at the working wavelength was measured with the same set-up in a previous experiment [2].

3 Results

The measured photon fluxes are reported in Figure 2. Each point corresponds to 100 s integration time.

As it is apparent, the linear regression fits the results pretty well down to few tens of microwatts pumping power. The extrapolated counts at zero pumping power, *i.e.* 10^4 photons over 100 s, are quite in good agreement with the dark counts of the detector, which guarantees that, actually, no stray light affects the experiment

This experimental arrangement lends itself to a nice comparison against theory, even if expression (1) is relative to an integral power. The parametric fluorescence emission occurs in fact on different conical surfaces, nested one into the others, corresponding to different colours: a direct consequence of that is the strict bond between wavelength and propagation direction of the emitted photons.

Given the phase-matching angle, the angles of emission with respect to the pump direction, outside the crystal, *versus* the emission wavelength can be calculated [6]. Therefore, the iris in front of the detectors provides also a spectral selection which can be broader or narrower than the one fixed by the interference filter according to the geometry of the experiment. In the actual case, the phase-matching angle is known through the angle of emission at 633 nm, and the curve of Figure 3 results for the wavelength/angle dependence: the grey band in the figure corresponds to the angular spread and corresponding spectral bandwidth selected by the iris. Therefore, with reference to Figure 4, the area of the iris can be divided in slices whose distances from the pump (R_{i} in the figure) and whose widths define completely the spectral band $\delta\lambda_{\text{s}}$ seen by each slit, because of the forementioned relation. The total power in a spectral region λ_{s} is computed though expression (1), and the actual power through the slit under consideration is taken as the ratio between the slit length

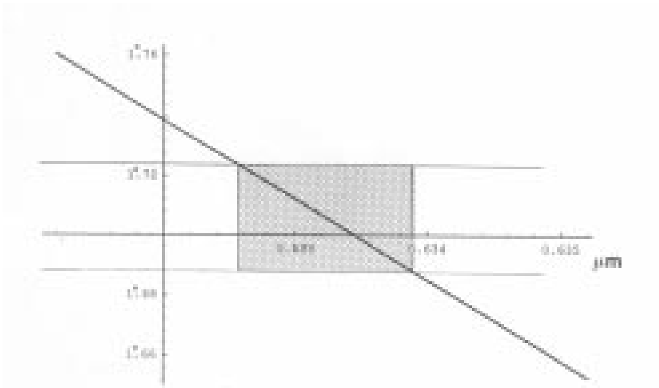

Fig. 3. Internal angle of emission $\theta_{\rm in}$ with respect to the pump *vs.* wavelength, for a phase-matching angle of 51.6°. The grey band corresponds to the angular spread and corresponding spectral bandwith selected by the iris.

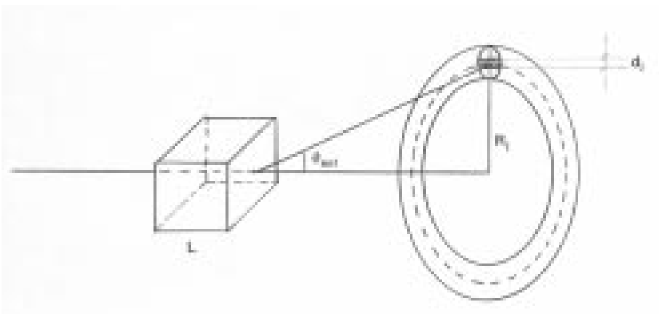

Fig. 4. Geometric relations for integration over solid angle of view.

and the circular ring of length $2\pi R_{\rm i}$. Incidentally, we have checked that the angular dispersion for a single frequency due to finite crystal size and pump spectral width [7] is much smaller than the angle under consideration: this effect ,therefore, can be completely neglected.

From the previous considerations, the flux of photons through the iris can be calculated through equation (1). One is led to the numerical evaluation of the expression below:

$$\frac{N_\gamma}{t} = (2\pi)^4 \frac{2d_{\rm eff}^2}{\varepsilon_0 n_{\rm p}^2} \hbar c \lambda_{\rm p} \sum_{j=-N}^{N} \frac{1}{\lambda_j^5 \left(\frac{1}{\lambda_{\rm p}} - \frac{1}{\lambda_j}\right)^{-2}} \times \phi(\lambda_j) \frac{d_j}{2\pi R_j} \delta\lambda_j \eta \int_0^L {\rm d}l P_{\rm p}(0) {\rm e}^{-\alpha l}$$

where the sum runs over the signal wavelength selected by the iris, N_γ/t is the flux in photons/s and η is detector quantum efficiency. $\Phi(\lambda_{\rm i})$ is the fitted dependence on the wave length of the interference filter.

Furthermore, we have measured the transmittance of the crystal at 633 nm and found a value of 0.80 ± 0.01. This value has been used for correcting the experimental data.

The theoretical ratio between N_γ/t and $P_{\rm p}$ is therefore calculated in terms of $d_{\rm eff}$ and, therefore, d_{31}. The d_{31} value which is in agreement with the best fit linear regression is found to be 3.5 ± 0.4 pm/V.

The quoted overall uncertainty is strongly dominated by the 20% uncertainty on the responsivity of the photodiode which monitors the pumping power, which turns out into the ± 0.4 pm/V on the final value of d_{31}.

The d_{31} in agreement with the present experiment turns out to be much lower than the value of 5.32 ± 0.33 measured time ago on the same crystal [4]. This requires some comments.

First of all, a direct and meaningful comparison with the previous measurements, at a distance of some years and in a different experimental situation, is difficult, if not impossible.

Second, in the time between the two experiments the crystal has always been pumped by UV. Despite the low powers involved, signs of damage are clearly visible in form of dark spots, whose nature and actual location, either in the bulk crystal or in the glass windows of the sealed cell which contains the crystal, are of difficult identification. The suspect rises, however, of a degradation of the crystal with time. Quite similar aspects, moreover, are found by different people [8].

4 Conclusions

The flux of photons in well defined spectral region and solid angle, emitted by parametric down-conversion, is in quite good agreement with the theoretical prediction, even at very low fluxes. The measurements with photon counting techniques show that there is no departure from linearity for the dependence of the flux of photons emitted on the pump power, even at pumping powers of few tens of microwatts, a situation never tested before.

The major uncertainties in the measurements come from the pump power, which is known at the 20% level, and from the non-linear susceptibilities of the crystal.

Actually, a best fit value for the susceptibility can be inferred from the measurement, and it turns to be lower than what was measured time ago on the same crystal. Even if a direct comparison with the previous measurement is made impossible because of the temporal distance and the quite different experimental situations, this result strongly support the evidence, reported by other people, of an aging effect in non-linear crystals.

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