On/off detection method for reconstructing the statistics of quantum optical states: an overview

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Abstract

We give a brief overview of the demonstration of a photon statistics reconstruction method based on Maximum Likelihood estimation and on/off detection. This method has been successfully applied to a large number of cases and, recently, extended to a scheme for a full reconstruction of the density matrix. Experimental results concerning the heralded single-photon state and the seeded parametric down-conversion are presented in some details.

1. Introduction

The reconstruction of photon statistics of quantum optical states is of the utmost relevance for various applications ranging from quantum information [1] to the foundations of quantum mechanics [2] and quantum optics [3]. However, photo-detectors well suited for this purpose are not available, since the few existing examples [4, 5, 6, 7, 8, 9] still have very severe limitations. Furthermore, reconstruction by quantum tomography [10, 11, 12] is not an easily implementable technique suited for a diffuse use.

This situation has been solved by a theoretical scheme [13, 14, 15, 16] addressed to achieve a Maximum Likelihood (MaxLik) reconstruction of the (diagonal) density matrix elements $\rho_n = \langle n | \rho | n \rangle$ of quantum optical states $\rho$ by exploiting data collected with on/off detectors with different quantum efficiencies $\eta_\nu$ ($\nu = 1, \ldots, K$). In this case, the information provided by experimental data is contained in the collection of frequencies $f_\nu = \eta_\nu f_0(\eta_\nu) = n_{0\nu}/n_\nu$ where $n_{0\nu}$ is the number of “no click” events and $n_\nu$ the total number of runs with quantum efficiency $\eta_\nu$. Then the probability of no click, given by:

$$p_0(\eta_\nu) = \sum_n (1 - \eta_\nu)^n \rho_n,$$

can be regarded as a statistical model for the parameters $\rho_n$ to be solved by MaxLik estimation. Furthermore, since the model is linear and the parameters to be estimated are positive, the solution can be obtained by using the Expectation-Maximization algorithm [15, 16]. This method has been successfully applied to a large number of cases [17, 18, 19, 20] and, recently, extended to a scheme for a full reconstruction of density matrix [21].

The paper is structured as follows. In Sec. 2 we consider the application of the reconstruction method to two different cases: heralded single photon and seeded parametric down-conversion (PDC). Sec. 3 closes the paper with some concluding remarks.

2. Applications

As a first exemplar case of relevant application of this method to quantum information protocols and to experiments on foundations of quantum mechanics, we consider the heralded photon state reconstruction [17].

In Figure 1 we present the reconstructed photon distribution for a heralded single-photon state produced in type-II PDC. As expected, also a small two photons component and a vacuum one are observed. The $\rho_2$ contribution is expected, by estimating the probability that a second photon randomly enters the detection window, to be 1.85% of $\rho_1$, in agreement with what observed. A non zero $\rho_0$ is also expected due to background, whose estimate, $(2.7 \pm 0.2)\%$, is in good agreement with the reconstructed $\rho_0$. 
Figure 1. Reconstruction of the photon distribution for a heralded single-photon state produced in type-II PDC. As expected also a small two photons component and a vacuum one are observed. The \( \rho_2 \) contribution is expected, by estimating the probability that a second photon randomly enters the detection window, to be 1.85\% of \( \rho_1 \), in agreement with what observed (1.9 \pm 0.2\%). A non-zero \( \rho_0 \) is also expected due to background, whose estimate, (2.7 \pm 0.2)\%, is in good agreement with the reconstructed \( \rho_0 \) (data from Ref. [17]).

As second example, in the following we will consider in details the reconstruction of seeded PDC, presenting some unpublished results on the subject. In line of principle, this reconstruction can also allow an estimate of the seed: a result of interest when this is in IR region, since in this region only photo-detectors with low quantum efficiency (\( \eta < 10\% \)) are available, so that the direct measurement of the photon number distribution becomes a challenging task. To overcome the problem, we can produce stimulated PDC with the IR signal as seed and, then, reconstruct the photon statistics of the stimulated emission (which is, now, in the visible range as in our experiment): as we will see, this process can give useful information also about the IR seed beam statistics, with much better results than the ones given by a direct implementation of this reconstruction method with low-efficiency detectors.

Our experimental setup (Figure 2) hosted a CW Argon laser (\( \lambda_{\text{pump}} = 351.1 \) nm) pumping a \( 10 \times 10 \times 5 \) mm LiIO\(_3\) crystal, in order to generate type-I PDC. Together with the pump beam, we injected into the crystal a CW Nd:Yag laser (\( \lambda_{\text{seed}} = 1064 \) nm) in the proper way to generate stimulated PDC, and we look at the emission in the \( k_{\text{stimul}} \) direction (\( \lambda_{\text{stimul}} = 524 \) nm). The set of different quantum efficiencies was obtained by means of a polarizer inserted on the \( k_{\text{stimul}} \) optical path, starting from \( \eta_{\text{max}} \approx 18\% \) (polarizer’s polarization plane parallel to the type-I PDC one); after this, we put a variable pinhole, regulating the number \( M \) of collected spatial propagation modes, a narrow-band interference filter (IF, FWHM 10 nm) to cut off the noise due to the Nd:Yag laser dispersion and to the background light, and finally a fiber coupler connected by a multimode fiber to the detector (avalanche photodiode, Perkin Elmer SPCM-AQR-15). The APD was gated by a pulse generator, opening 210^5 detection windows per second, each one of 15 ns; the pinhole diameter was regulated in order to collect only few spatial modes (more precisely \( M = 10 \)) of the stimulated emission. Moreover, each spatial mode consists of many temporal modes: to evaluate them, we simply divided our acquisition time (15 ns) by the typical coherence time of type-I PDC, obtaining an estimate of the order of magnitude of the total number of modes, \( M = 1.5 \times 10^6 \).

We have performed three separate data collections. The first one, A, with the spontaneous PDC only (seed off), and the other two corresponding to two different stimulation regimes, keeping the same spontaneous PDC power of the first experimental run. By indicating with \( x \) the percentage of stimulated emission on the whole PDC amount collected, acquisitions B and C were respectively characterized by \( x_B = 85.7 \pm 0.4 \% \) and \( x_C = 93.6 \pm 1.3 \% \) (of course, \( x_A = 0 \% \)). The \( x \) parameter was estimated by means of the formula \( N_{\text{tot}} = N_{\text{sp}} + xN_{\text{tot}} \), \( N_{\text{sp}} \) and \( N_{\text{tot}} \) being the counts given by the ungated detectors with seed


After regulating the seed beam in order to reproduce the same conditions of the B and C acquisitions we mentioned before (checked by controlling the $x$ percentage with the detection system on the stimulated PDC branch), we performed a single experimental run, obtaining the data shown in Figures 5 and 6. Again, the background photons resulted to be totally negligible with respect to the seed ones.

First of all, let us present the results obtained by applying the MaxLik method to a multimode stimulated PDC optical beam (setup shown in Figure 2). In Figure 4, the three data sets (A, B and C) collected are shown together with the respective reconstructed photon distributions: the three fidelity values between the expected photon statistics and the reconstructed one are all above 99.8%, and the reconstructed $x$ values are in good agreement with the empirical ones, thus the reliability and efficiency of this reconstruction method has been confirmed even by this further test.

The results related to the direct acquisitions on the infrared seed beam, with intensity comparable to the one used to produce the stimulated PDC states studied in case B and C (respectively with $x_B = 85.7 \pm 0.4\%$ and $x_C = 93.6 \pm 1.3\%$), are reported in Figures 5 and 6. As can be easily seen by these figures, the MaxLik method completely failed to recover the expected (poissonian) photon distribution in both the cases: this is due to the fact that the maximum quantum efficiency available ($\eta_{\text{max}} = 0.9\%$) was too low to allow a discrimination between the no-click frequencies given by a thermal state and the ones coming from a poissonian one. However, when the number of propagation modes of the stimulated PDC is not too high (i.e., $M \leq 10$), information on the photon statistics of the stimulating seed could be inferred by the no-click frequency distribution given by the stimulated PDC light: this could be useful when dealing with infrared beams and on/off detectors in the visible regime.

3 Conclusions

In this paper we have given a brief overview of the demonstration of a method based on MaxLik estimation and on/off detection. This allows the reconstruction of the photon statistics of any optical signal. Here, we presented two different experimental studies, showing the good agreement between the predicted and the reconstructed statistics. The first concerned the heralded single-photon state; the other one dealt with the seeded PDC: three different regimes have been investigated. We remark that an improvement of this last experiment can also allow the estimation of the seed itself, which is a result of interest in the infrared region, where efficient detectors are not available.
Figure 4. Data plots of acquisitions A, B and C (top to bottom). On the left: $f_0$ no-click frequencies (gray disks) given by the stimulated PDC with different stimulation regimes vs. $\eta$. The black disks are the “off” probabilities obtained by means of the MaxLik reconstructed photon distribution; the solid line corresponds to the theoretical fit, giving the average number of photons ($N_{\text{ave}}$) reported together with the percentage of stimulated emission $x$ and the $\chi^2$ of the the MaxLik fit. On the right: MaxLik reconstructed photon distributions (gray bars) and expected ones (black bars). In each plot we report also the fidelity $F$ between them.

Figure 5. Left plot: $f_0$ no-click frequencies (gray disks) given by the infrared seed beam vs. $\eta$ (condition B). The black disks are the “off” probabilities obtained by means of the MaxLik reconstructed photon distribution; the solid line corresponds to the theoretical fit. Right plot: MaxLik reconstructed photon distribution (gray bars) and expected poissonian one (black bars). The fidelity between the two distributions is quite low ($F = 81.25\%$), in fact the reconstructed distribution and the expected one show a very poor overlapping degree.

Figure 6. Left plot: $f_0$ no-click frequencies (gray disks) given by the infrared seed beam vs. $\eta$ (seed power level of acquisition C). The black disks are the “off” probabilities obtained by means of the MaxLik reconstructed photon distribution, while the solid curve is the theoretical fit. Right plot: MaxLik reconstructed photon distribution (gray bars) and expected one (black bars). The fidelity between the two here is even lower than before ($F = 69.09\%$).

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References


