Measurement of two-mode squeezing with photon number resolving multi-pixel detectors

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The measurement of the two-mode squeezed vacuum generated in an optical parametric amplifier (OPA) was performed with photon number resolving Multi-Pixel Photon Counters (MPPCs). Implementation of the MPPCs allows for the observation of noise reduction in a broad dynamic range of the OPA gain, which is inaccessible with standard single photon avalanche photodetectors. © 2014 Optical Society of America

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Multiphoton entangled states attract considerable attention in modern quantum optics, as they represent promising resources for quantum communications, quantum computing, quantum lithography, and quantum imaging [1, 2]. One of the most accessible ways to generate such states is by using parametric down conversion (PDC), a non-linear process producing pairs of strongly correlated photons. The state produced by frequency non-degenerate PDC is a two-mode squeezed vacuum (SV) state written as follows [3]:

\[ |\psi\rangle = \sum_{n=0}^{\infty} C_n |n_s\rangle |n_i\rangle, \tag{1} \]

where \(|n_j\rangle\) denotes the Fock-state of \(n\) photons in the \(j\)-th mode, \(j = s, i\) denote signal and idler modes respectively, and \(C_n\) is the probability amplitude. Strong correlation between the photon numbers in the signal and idler modes, referred to as two-mode squeezing, results in the suppression of the variance of their difference below the shot-noise limit [4, 5] and can be quantified by the noise reduction factor (NRF) given by

\[ NRF = \frac{\text{Var}(\hat{N}_s - \hat{N}_i)}{\langle \hat{N}_s + \hat{N}_i \rangle}, \tag{2} \]

where \(\hat{N}_s\) and \(\hat{N}_i\) are the photocount numbers of the detectors in the signal and idler modes respectively, and \(\langle \hat{O} \rangle = \text{tr}(\hat{\rho} \hat{O})\) defines the mean value of an observable \(\hat{O}\) for a given state \(\hat{\rho}\). The two-mode squeezing can be studied with various types of photodetectors, depending on the photon fluxes of the PDC. At a moderate gain, when the SV state contains several photons per pulse, it is essential that the detector is able to resolve several simultaneously impinging photons. Such detectors are referred to as photon number resolving detectors (PNRDs).

Development of the PNRDs attracts a considerable interest in modern optical engineering. Several PNRD technologies are available up to date, including cryogenic detectors [6–8], branched single photon avalanche detectors (SPADs) [9, 10], hybrid photodetectors [11], intensified and electron-multiplied CCDs [12].

Here we consider a multi-pixel photon counter (MPPC) which is a commercially accessible PNRD [13]. In a MPPC, several hundreds of SPADs (pixels) are embedded into a chip which is illuminated by a diffused light beam, such that the chance of more than one photon hitting the same pixel is negligible. Upon photon detection, a pixel produces an electrical signal, which is summed with the signals from other pixels at an output circuit, thus enabling the photon number resolution. Despite its attractive features, such as ease of operation, low cost, and high quantum efficiency (q.e.), the crucial drawback of the MPPC is the optical crosstalk between pixels. During an avalanche in a pixel, some spurious photons are emitted, and eventually registered by the neighboring pixels [14]. As the crosstalk happens almost simultaneously with the detection of real photons, its contribution cannot be distinguished from the actual counts, and therefore requires an accurate theoretical modeling [14–16].

The performance of the MPPC has been studied in earlier experiments with coherent and pseudo-thermal light [14–18]. In [19] the MPPC was used in the measurements of the intensity correlation function of the SV state, however restricted to the regime of much less than one photon per pulse. In this work we expand the application of the MPPC to the study of a relatively bright SV state with up to almost 5 photons per pulse by the direct observation of the two-mode squeezing.

For modeling a realistic MPPC, we follow [15], where loss and crosstalk are considered as Bayesian processes. Let us denote \(\langle \hat{n} \rangle\) as the mean photon number impinging on the detector, \(P\) as the crosstalk probability, and \(\eta\) as the q.e. of a single SPAD pixel, which also accounts for the losses in the optical system. Here, beams of relatively high intensities have been considered hence the saturation of the MPPCs has to be taken into account by
assuming that each MPPC can only resolve up to \( N_{\max} \) photocounts. We assume that the two MPPCs used in joint detection have the same values of \( \eta, P, \) and \( N_{\max} \). Then the positive-operator valued measure for detecting \( N_j \) photocounts in the \( j \)-th mode is given by

\[
\Pi_{N_j} = \left\{ \sum_{n=0}^{\infty} \sum_{k=0}^{\infty} B_{n,k,N_j} |k\rangle \langle k| \right\}, \quad N_j < N_{\max}
\]

\[
I - \sum_{k=0}^{N_{\max}} \Pi_k, \quad N_j = N_{\max}.
\]

where

\[
B_{n,k,N_j}(\eta, P) = \binom{n}{N_j - n} \binom{k}{n} P^{N_j-n}(1-P)^{2n-N_j}\eta^n(1-\eta)^{k-n}. \tag{4}
\]

The variance of the difference of photocount numbers is given by [20]:

\[
\text{Var}(\hat{N}_s - \hat{N}_i) = \langle \hat{N}_s^2 \rangle - \langle \hat{N}_s \rangle^2 + \langle \hat{N}_i^2 \rangle - \langle \hat{N}_i \rangle^2 \tag{5}
\]

\[
-2\langle \hat{N}_s \hat{N}_i \rangle + 2\langle \hat{N}_s \rangle \langle \hat{N}_i \rangle,
\]

where the p-moment operator of the photocount number operator is given by

\[
\hat{N}_j^p = \sum_{N_j=0}^{N_{\max}} N_j^p \Pi_{N_j}. \tag{6}
\]

The NRF can be calculated for any given two-mode squeezed state by [20]:

\[
\eta_{\text{NRF}} = \frac{1 + 3P}{1 + P}\eta. \tag{7}
\]

The theoretical fits of the coherent and SV states.

Fig. 1. (Color online) The experimental setup: Nd:YAG laser at 266 nm pumps two BBO crystals. OA, optical axis; UVM, UV-mirror; DM, dichroic mirror; M, mirror; L1 (f=500 mm), L2 (f=200 mm), lenses; D1 (d1=10 mm), D2 (d2=11.4 mm), iris apertures. The inset shows the setup for measurements of the coherent state: cw Nd:YAG laser at 532 nm is chopped by an acousto-optical modulator (AOM); ND, neutral density filter; NPBS, non-polarizing beamsplitter.

Similar measurements were performed for the coherent light obtained by attenuating the 2-nd harmonic of a continuous wave (cw) Nd:YAG laser at 532 nm (Photop, power 50 mW) and chopping it by an acousto-optical modulator at a frequency of 20 kHz with a pulse duration of 30 ns.

Fig. 2 shows the experimental data and theoretical fits of NRF versus \( \langle \hat{n} \rangle \) for the coherent and SV states. From the difference of the measured NRFs for the two states close to \( \langle \hat{n} \rangle = 0 \) one finds the experimental value of the effective q.e. of the squeezed state at 568 nm. The value yields \( \eta_{\text{NRF}}^{\text{exp}} = 0.17 \pm 0.03 \), and it was further used for the conversion of photocounts to photon numbers. Effective q.e. for the coherent state at 532 nm was found from \( \eta_{\text{NRF}}^{\text{exp}} \), assuming the dependence of q.e. on the wavelength, provided by the manufacturer, and yielding \( \eta_{\text{NRF}}^{\text{exp}} \approx 0.20 \pm 0.03 \). The theoretical fits of the data to the model yield \( N_{\max} = 3, P = 0.280 \pm 0.005, \) and
\[ \eta = 0.163 \pm 0.007 \text{ for the coherent state and } N_{\max} = 3, \]
\[ P = 0.30 \pm 0.02, \quad \text{and } \eta = 0.145 \pm 0.009 \text{ for the SV state}. \]
These parameters yield \( \eta_{E,\text{coh}} = 0.21 \pm 0.01 \) and \( \eta_{E,\text{SV}} = 0.19 \pm 0.01 \), which are in good agreement with the experimental values of \( \eta_E \) used for the calculation of photon numbers. The results clearly demonstrate that NRF gradually decreases with the increasing \( \langle \hat{n} \rangle \) for both studied states, which is caused by the saturation of the MPPC. At the same time, the NRF for the SV state lies below the one for the coherent state - a signature of squeezing. The crosstalk elevates the NRF at relatively high photon numbers (up to 5). The main conclusions we can make are: (1) the crosstalk in the MPPC leads to an increase in the NRF for both coherent and SV states, (2) saturation of the MPPC leads to a decrease of NRF with increasing photon numbers. The experimental data agrees with the theoretical model which takes into account the saturation and the crosstalk although the fits deviate at higher mean photon numbers, where the photon number resolution of the detectors is limited. These results extend the use of MPPCs for the characterization of quantum light in a significantly broader range than that of conventional SPADs.

In conclusion, we have performed an experiment in which the NRFs of coherent and SV states have been measured with commercially available MPPC modules at relatively high photon numbers (up to 5). The main conclusions we can make are: (1) the crosstalk in the MPPC leads to an increase in the NRF for both coherent and SV states, (2) saturation of the MPPC leads to the decrease of NRF with increasing photon numbers. Using customized electronics [23].

Fig. 2. (Color online) Dependence of the NRF on the mean number of photons measured for the coherent state (black circles) and the SV state (red squares). The theoretical fits for the NRF are done for the range of average photon numbers up to 5 photons (vertical dashed line), which marks the range of reliable photon-number resolution. The solid lines are fits to the theoretical model with \( R^2 = 0.9999 \) and \( R^2 = 0.9994 \) for the coherent and SV states, respectively.

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