Measuring Nonclassicality of Mesoscopic Twin-Beam States with Silicon Photomultipliers [†]

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Abstract: The study of nonclassical properties of quantum states is a relevant topic for fundamental Quantum Optics and Quantum Information applications. In the mesoscopic domain, promising results have been obtained using photon-number-resolving detectors. Here we show recent results achieved with the class of Silicon Photomultipliers: by a proper analysis of the output signal, the nonclassicality of twin-beam states can be detected and exploited.

Keywords: Photon Statistics; Photodetectors; Nonlinear optics; Parametric Processes

1. Introduction

Silicon Photomultipliers (SiPMs) are commercial and cost effective silicon-based photon-number-resolving detectors, extensively used for particle physics applications [1], which have been only marginally exploited in the field of Quantum Optics due to the presence of cross-talk effects and low quantum efficiency [2,3]. In the past, we have demonstrated that, by properly modeling the detector response, it is possible to recover the statistical properties of classical states of light [4], namely photon-number distribution and correlations. The model developed for classical light also applies to quantum states, and the limitations to the observability of quantum features are only set by the actual amount of cross talk and dark counts affecting detection [5,6]. Here we demonstrate that, by suitably operating on the parameters of the new generation of Hamamatsu SiPMs [7,8], we can observe sub-shot-noise correlations between the two parties of a mesoscopic twin-beam state (TWB) [6]. In particular, we show that the value of the noise-reduction factor, R, strongly depends on the size of the gate over which the detector output is integrated: the shorter the gate, the better the nonclassicality detection. In fact, since the light pulses we studied are very short (5 ps) and the detector response is very fast (10 ns), shortening the integration gate allows us to discard a large part of the spurious contributions to the detection signal.
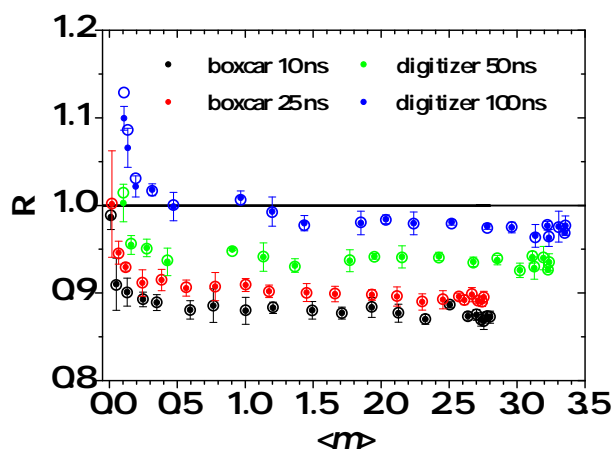
2. Results

We test the nonclassicality of the TWB state by measuring the noise reduction factor

$$R = \frac{\sigma^2(n_1 - n_2)}{\langle n_1 + n_2 \rangle} ,$$ (1)

$\sigma^2(n_1 - n_2)$ being the variance of the difference in the number of photons detected in the two arms of the TWB. The measurements are performed on pulsed states shot-by shot. It can be demonstrated [9] that the condition $R < 1$ is sufficient to assess the nonclassicality of the TWB state.

In Figure 1, we plot the measured values of R as a function of the mean number of photons measured in one of the two TWB arms. According to the description in Section 4, the detector's signals are recorded with two different acquisition systems and integrated over different gate widths. The theoretical curves displayed in the figure as open circles are evaluated according to the model in [10].

The comparison among the data obtained with the different gate widths demonstrates that, on shortening the gate, the values of R lower, that is the detection of the nonclassicality of the states improves. We note that the shortest gates can be achieved with the boxcar integrator, since the digitizer has a limited sampling rate (250 MS/s).


Figure 1. Noise reduction factor as a function of the number of photons measured in a single arm. Different colors correspond to different gate widths. Dots: experimental data; open circles: theoretical expectations.

3. Discussion

The results shown in Figure 1 demonstrate that SiPMs can be used to diagnose nonclassicality of TWB states in spite of their limited quantum efficiency ($\sim 40\%$) and of the presence of some spurious effects. The effective quantum efficiency, as derived from the measured values of R as $\eta = 1 - R$, can be estimated to be $\eta \sim 12\%$ at best. This is due to the presence in the experimental setup of many other sources of loss: imperfect selection of signal and idler, imperfect injection of light in the fibers, imperfect transmission of the fibers, imperfect coupling of the light in the detector. All these imperfections can be reduced by optimizing the experimental scheme.

4. Materials and Methods

The experimental setup is depicted in Figure 2. Mesoscopic TWB states are generated by parametric downconversion in type-I quasi-collinear interaction geometry in a β-barium-borate (BBO) crystal pumped by the fourth harmonics of a Nd:YLF laser (4.5 ps pulse duration and 500 Hz repetition rate). The TWB state is selected at degeneracy (523 nm) by means of two irises and two bandpass filters. The light is then delivered to the sensors by two multi-mode optical fibers (600-μm core diameter). Although the TWB states are intrinsically multimode [11,12] and the photon-number statistics of signal and idler is multi-mode thermal, in the present experimental conditions we have about 100 modes, so that the statistics is very similar to a Poissonian distribution.
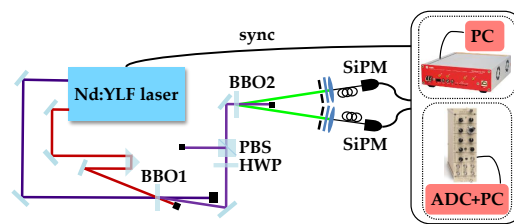
Figure 2. Experimental setup for the measurement of multi-mode TWB states. The acquisition chains included in the dotted boxes are inserted alternatively.

The state characterization is performed as a function of the pump intensity, which is modified through a half-wave plate (HWP) followed by a polarizing cube beam splitter (PBS). For each energy value, 10^5 single-shot acquisitions are performed by using two SiPMs (MPPC S13360-1350CS, Hamamatsu Photonics [7,8]) made of 600 pixels having a 50-μm-pixel pitch and operated at a bias voltage of 54.7 V. This particular model of SiPM was chosen to optimize the tradeoff between increasing quantum efficiency and photon-number-resolving capability and reducing the incidence of cross talk.

The typical output signal delivered by the detectors is shown in Figure 3. In order to devise the best signal acquisition strategy allowing the removal of as many spurious effects as possible, we implemented two different signal acquisition procedures (see dotted boxes in Figure 2). First of all, the electronic signal from both the SiPM detectors was split in two and simultaneously sent to two synchronous boxcar-gated integrators (SR250, Stanford Research Systems) and to a desktop waveform digitizer (DT5720, CAEN) operating at 12-bit resolution and at 250-MS/s sampling rate. The boxcar integrator was set to perform an analogical integration of the signal over a gate of variable width centered on the signal peak. To compare the results between the acquisition chains, the gate width of the boxcar was set at $\tau = 50$ ns, while the output of the digitizer was integrated off-line over different time gates, $\tau = 50, 100, 350$ ns. We note that the gate width can be pushed down to 10 ns for the boxcar [6], while the minimum gate necessary to have a reasonable number of points in the integral is 50 ns. Figure 4 shows two pulse-height spectra recorded for similar light with the digitizer (left panel) and the boxcar gated integrator (right panel).
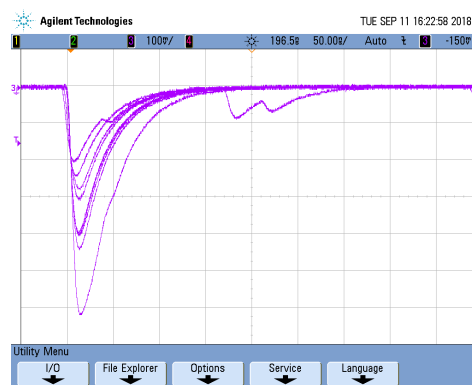
Figure 3. Typical SiPM output signal displayed by a fast oscilloscope. Note that the detector response is quite fast: the front edge takes less than 2 ns and the entire development of the signal is completed in less than 200 ns. Features happening at longer times are due to spurious effects (dark counts and cross-talk events).
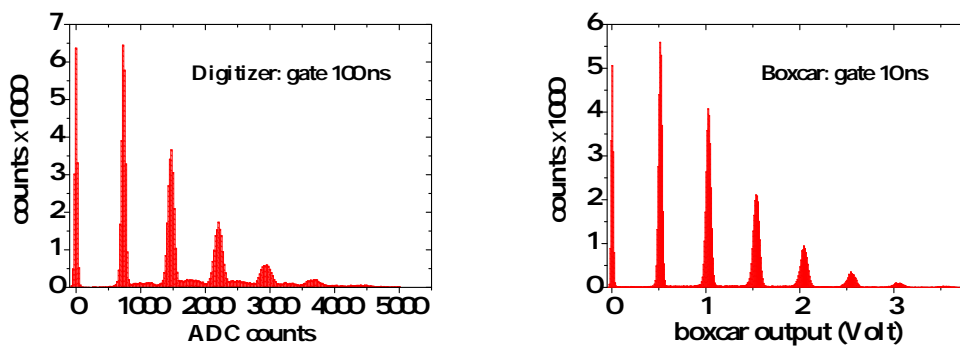
Figure 4. Typical pulse-height spectra recorded on the signal of the multimode twin beam at similar intensity. Left panel: digitizer; right panel: boxcar gated integrator.

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