Verification of nonclassical light with imperfect detection devices

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Abstract

We report on the theory and experimental implementations of detection schemes for the identification of nonclassical light. In particular, we investigate optical multiplexing layouts with on/off detector that are shown to be theoretically described through a binomial click-counting statistics, rather than a Poisson distribution. We discuss experimental applications of this approach to uncover nonclassical correlations between optical modes and to reconstruct negative phase-space distributions.

The reliable detection of photons is a main challenge to be overcome for the implementation of many quantum information protocols. Assuming an ideal photon-number-resolution, the photoelectric detection of quantized light is well understood, and it leads to a Poisson distribution of photocounts [1]. However, because of manifold of practical restrictions, modern implementations of photon measurement devices rely on optical multiplexing and on/off detectors (see Ref. [2] for an overview), not following the same principles.

In contrast to the photoelectric counting model, it was demonstrated that the click-counting distribution c_k for multiplexing layouts with on/off detectors behaves like a binomial distribution [3],

$$c_k = \left\langle :\binom{N}{k}\hat{\pi}^k(\hat{1}-\hat{\pi})^{N-k}: \right\rangle, \tag{1}$$

where k is the number of coincidence clicks, N is the number of on/off detectors, $:\cdots:$ indicates normal ordering, and $\hat{\pi}$ corresponds to the measurement operator for a single click event. Because of the change of the theoretical description compared to ideal photocounting, well-established nonclassicality measures require significant modifications in order to apply them to click-counting devices.

We extended the theory to account for the binomial nature of the click-counting statistics and applied our findings in experiments. For instance, we measured the correlations between two click counting devices. For this reason, a photon-pair source was used to generate two-mode squeezed light, each mode being measured separately. From the resulting joint click-counting distribution, c_{k_A,k_B}, we were able to uncover quantum correlations between the modes with high significance [4].

In another experiment, a weak-field homodyning setup was employed in combination with a time-bin multiplexing scheme. This results in a distribution $c_k(\alpha)$, where α is the coherent amplitude of the local oscillator. Using our data, a phase-space distribution was reconstructed which was shown to be nonnegative for classical light. For our heralded single-photon state, however, clear negativities in this distribution certified the nonclassicality of the produced state [5]. For comparison, standard approaches, such as applied to reconstruct the Wigner function, require a full photon-number resolution and high detection efficiencies.

In summary, we developed a framework to characterize nonclassical properties of quantum light when employing imperfect detection devices. This theoretical model takes the binomial nature of the measured statistics into account. The experimental application demonstrated the effectiveness of our method to certify quantum correlations and reconstruct negative phase-space distributions.

[1] P. L. Kelley and W. H. Kleiner, *Theory of Electromagnetic Field Measurement and Photoelectron Counting*, Phys. Rev. **136**, A316 (1964).

[2] C. Silberhorn, *Detecting quantum light*, Contemp. Phys. **48**, 143 (2007).

[3] J. Sperling, W. Vogel, and G. S. Agarwal, *True photocounting statistics of multiple on-off detectors*, Phys. Rev. A **85**, 023820 (2012).

[4] J. Sperling, M. Bohmann, W. Vogel, G. Harder, B. Brecht, V. Ansari, and C. Silberhorn, *Uncovering Quantum Correlations with Time-Multiplexed Click Detection*, Phys. Rev. Lett. **115**, 023601 (2015).

[5] M. Bohmann, J. Tiedau, T. Bartley, J. Sperling, C. Silberhorn, and W. Vogel, *Incomplete Detection of Nonclassical Phase-Space Distributions*, Phys. Rev. Lett. **120**, 063607 (2018).