Quantum description of timing jitter for single photon ON/OFF detectors

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Discrete variable quantum optics stands as one of the most prominent platform for quantum cryptography with an increasing number of promising out-of-the-laboratory implementations [1, 2].

The quest for competitive systems, compatible with future practical applications, has promoted huge developments concerning both photonic sources [3, 4] and detection systems [5, 6]. Nevertheless, a critical point is still represented by experimental operation rates. Time multiplexing techniques allows in principle to pump photonic sources at rates in the gigahertz regime [7]. However, a strong limitation to ultra-fast operation lies in timing errors at the detection stage. Detection timing jitters introduce random variations in the time delay between the photon arrival time and the time at which the output electrical signal is delivered: important jitters can thus lead to counts associated with a given optical clock cycle to appear as temporally indistinguishable from those corresponding to neighbouring ones [6]. Accordingly, limited resolution directly affects the quality of any time-correlated single photon counting or quantum state engineering operations [7].

In anticipation to further technological advances as well as in the perspective of promoting future conceptual developments on existing quantum communication protocols, it is thus extremely pertinent to correctly describe the effects of detectors' timing performances. Despite a huge number of papers reporting the experimental time response of photon-counting devices [6], to our knowledge, no quantum description taking into account these effects has been developed so far.

We explicitly address this point by providing a theoretical model able to describe the temporal behaviour of standard single photon detectors affected by non negligible timing jitter and in presence of dead-time.

We will adopt the formalism of positive operator-valued measurements (POVM) [8]. This approach has already been employed to describe detector with photon-number abilities and has been successfully used to experimentally investigate the characteristics of unknown single photon detectors [9]. A first step towards the description of timing-effects in terms of POVM has been recently performed by including dead-time effects in the description of standard single-photon detectors [10].

We propose a new model exploiting a multi-mode formalism to describe temporal degrees of freedom to fully describe timing-resolution effects in ON/OFF detector by a POVM, taking into account the effect of dead-time and finite detection efficiency. Based on the analysis of probability distribution for the measurement results in the case of different temporal distribution for the photons at the detector input we reconstruct by linearity the POVM. We then apply our results to the quantitative study of timing jitter effect on some usual quantum optics experiments, such as coincidence measurements. As for an example, this fully quantum approach allows expressing the density matrix of a heralded photon explicitly, and taking into account the imperfections of the heralding detector.

Our study can be easily generalized to detection systems involving multiplexing strategies where different detectors are used in parallel such as in photon number resolving schemes.

References

[1] J. Yin et al. "Quantum teleportation and entanglement distribution over 100-kilometre free-space channels". In: *Nature* 488.7410 (Aug. 9, 2012), pp. 185–188. ISSN: 0028-0836. DOI: 10.1038/nature11332. arXiv: 1205.2024.

[2] J. Yin et al. "Satellite-based entanglement distribution over 1200 kilometers". In: *Science* 356.6343 (2017), pp. 1140–1144. ISSN: 0036-8075. DOI: 10.1126/science.aan3211. arXiv: 1707.01339.

[3] A. Orieux et al. "Semiconductor devices for entangled photon pair generation: a review". In: *Reports on Progress in Physics* 80.7 (2017), p. 076001. arXiv: 1702.08823. URL: http://stacks.iop.org/0034-4885/80/i=7/a=076001.

[4] O. Alibart et al. "Quantum photonics at telecom wavelengths based on lithium niobate waveguides". In: *Journal of Optics* 18.10 (2016), p. 104001. DOI: 10.1088/2040-8978/18/10/104001.

[5] M. D. Eisaman et al. "Invited Review Article: Single-photon sources and detectors". In: *Review of Scientific Instruments* 82.7 (2011), p. 071101. DOI: 10.1063/1.3610677.

[6] R. H. Hadfield. "Single-photon detectors for optical quantum information applications". In: *Nature Photonics* 3.12 (Dec. 2009), pp. 696–705. ISSN: 1749-4885. DOI: 10.1038/nphoton.2009.230.

[7] L. A. Ngah et al. "Ultra-fast heralded single photon source based on telecom technology". In: *Laser & Photonics Reviews* 9.2 (2015), pp. L1–L5. ISSN: 1863-8899. DOI: 10.1002/lpor.201400404. arXiv: 1412.5427.

[8] A. Ferraro, S. Olivares, and M. G. A. Paris. "Quantum measurements on continuous variable systems". In: *Gaussian states in continuous variable quantum information*. Lecture notes. Chap. 5, p. 44. ISBN: 88-7088-483-X. arXiv: quant-ph/0503237.

[9] V. D'Auria et al. "Quantum Decoherence of Single-Photon Counters". In: *Phys. Rev. Lett.* 107 (5 July 2011), p. 050504. DOI: 10.1103/PhysRevLett.107.050504. arXiv: 1105.4090.

[10] J. Fiurá šek et al. "Analysis of counting measurements on narrowband frequency up-converted single photons and the influence of heralding detector dead time". In: *Phys. Rev. A* 91 (1 Jan. 2015), p. 013829. DOI: 10.1103/PhysRevA.91.013829.