Quantum tomography of a single-photon state by photon-number parity measurements

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Abstract: A single-photon state was generated by heralding cavity-enhanced spontaneous parametric downconversion in a PPKTP optical parametric oscillator. The Wigner distribution was reconstructed by quantum state tomography, using photon-number-resolving measurements with a system efficiency of 58±2%. ©2018 $The Author(s)$

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Quantum state preparation and characterization is a key task of quantum information processing. Quantum state tomography reconstructs the Wigner function from the measurement statistics of quantum optical field quadrature amplitudes [1]. In general, this requires a reconstruction step using the inverse Radon transform, which is prone to artefacts, or a computing-intensive maximum-likelihood procedure [2]. A more direct method uses photon-number-resolving (PNR) measurements, first proposed by Wallentowitz and Vogel [3] and by Banaszek and Wodkiewicz [4], and first implemented by phonon-number-resolved measurements of a trapped ion [5].
The phase-space quasi-probability distribution $W(\alpha)$ of a density operator ρ, originally proposed by Wigner to study quantum corrections to classical statistical physics [6], is, along with its value at the origin,

$$W_{\hat{\rho}}(\alpha) = \frac{1}{\pi} Tr\left[D^{\dagger}(\alpha)\rho D(\alpha)(-1)^{N}\right] \tag{1}$$

$$W(0) = \frac{1}{\pi}\sum_{n}^{\infty}(-1)^{n}\rho_{nn}, \tag{2}$$

where $D(\alpha)$ and N are the displacement and number operator respectively, and $\alpha = p + iq$, where p and q are the real phase and amplitude phase space coördinates. Hence, photon statistics yield the Wigner function of an optical mode at the origin of the phase space. In order to reconstruct the Wigner function over the whole phase space, we can displace the quantum state by interfering it with a local oscillator of a given amplitude,$\alpha \gg 1$, at a highly unbalanced , $t \ll 1$, beamsplitter [7], thereby getting $W_{displaced}(0; -t\alpha) \simeq W(-t\alpha)$.
The experiment builds on our previous demonstration of coherent-state tomography [8] with the addition of a heralded single-photon source, Fig.1. A stable frequency-doubled 532 nm Nd: YAG laser(1 kHz FWHM) pumped a type-II PPKTP crystal in a doubly resonant optical parametric oscillator (OPO) whose cavity was Pound-Drever-Hall (PDH) locked at exactly half the pump frequency. This created frequency-degenerate, cross-polarized signal(S) and idler(I) photon pairs. The Idler photon was filtered by an interference filter and a PDH locked filter cavity and detected by a superconducting transition edge sensor (TES), capable of resolving up to 5 photons at high quantum efficiency [9]. The signal photon was interfered with a phase-/amplitude-modulated displacement field provided by the fundamental frequency of the pump laser. The unbalanced beamsplitter ($r^2 = 0.97$) output was sent to another TES and PNR detection statistics were digitized and recorded. The reconstructed is displayed on Fig.2. We calibrated our displacements to coherent-state Poisson statistics on the TES and were limited up to $|t\alpha| = 0.7961$ due to TES photon flux limitations. All experimental losses due to imperfect mode matching, optical losses, and the quantum efficiency of the TES system cause mixing of the vacuum state $|0\rangle$ with the single-photon state $|1\rangle$, which reduces negativity of the single-photon Wigner function from the ideal value of -$\frac{1}{\pi}$. The effect of all losses on measured state can be expressed in overall measurement efficiency, η of the signal channel. The resulting Wigner function is

$$W(\alpha) = \eta W_{|1\rangle\langle 1|}(\alpha) + (1-\eta)W_{|0\rangle\langle 0|}(\alpha) \tag{3}$$

In conclusion, we have shown clear negativity in the single-photon Fock Wigner function with no loss corrections. In the future, we will multiplex several TES channels which will allow us to access higher displacements.

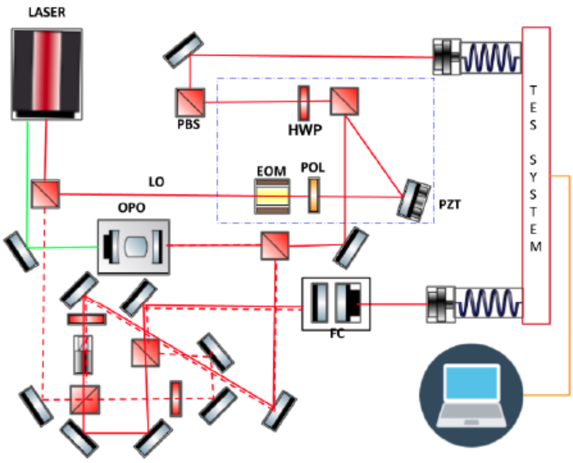

Fig. 1: Schematic of the experimental setup. POL: Polarizer. PZT: Piezoelectric transducer. EOM: Electro-optic modulator. HWP: Half-wave plate. FC: Filter Cavity. Dotted lines denote the locking (on/off) beam paths.

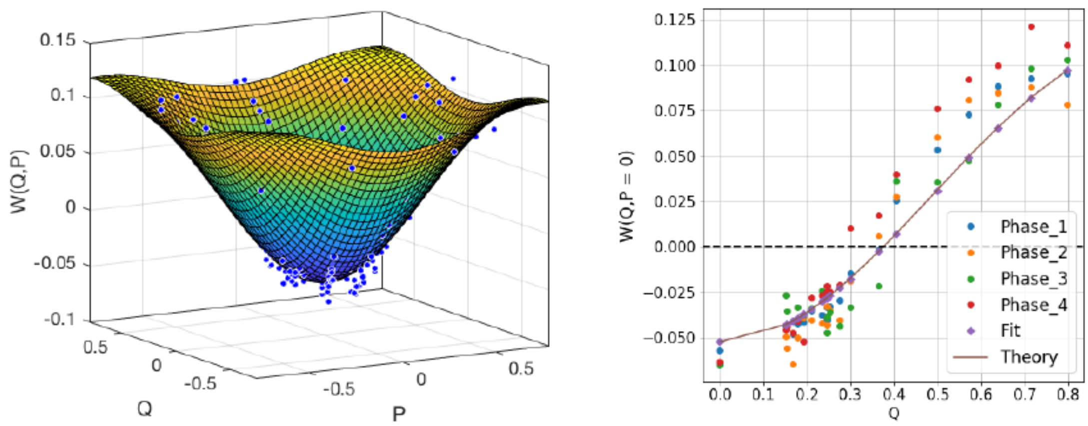

Fig. 2: Left, Experimental data (blue points) and Wigner function fit yielding $\eta = 0.58(2)$, from 10 phases and 20 amplitudes. Right, experimental data for Wigner function (4 phases shown), solid line is the Wigner function fit.

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