Quantum tomography of the single-photon Fock state

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Abstract: We have reconstructed the quantum state of an optical single-photon Fock state using pulsed homodyne tomography. The reconstructed angle-averaged Wigner function shows a strong dip reaching a classically impossible negative value.

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The single photon Fock state is one of the most fundamental states of the light field. It is highly non-classical and reveals the wave-particle duality of light most strikingly. Its marginal distributions are of non-Gaussian shape and its Wigner function exhibits a strong negativity around the origin of phase space. Although the reconstruction of the Fock state has already been performed for the motional state of trapped beryllium ions [1], in the optical domain this task has not been resolved so far, the main difficulty being the lack of coherent single-photon sources.

We present results of applying the technique of optical homodyne tomography [2] to the single photon Fock state prepared by conditional measurements on a photon pair produced in parametric down-conversion.

In our experimental setup (Fig.1) we employ a mode-locked Ti:Sapphire-laser in combination with a pulse picker to obtain transform-limited 1.6-ps pulses at 790 nm. Most of the radiation is single-pass frequency doubled in an LBO-crystal yielding 100 µW at 395 nm, which is then passed on to a BBO crystal for down-conversion. The down-
converter is operated in a type I frequency degenerate, but spatially non-degenerate configuration. A single photon counter is placed in one of the emission channels – labeled trigger – to detect photon pair creation events and to trigger the readout of a homodyne system placed in the other emission channel – labeled signal. In this way only those pulses are selected for homodyne measurements where a photon has been emitted into the signal channel, thus preparing single photon Fock states by conditional measurements.

We use a small fraction of the original optical pulses from the pulse picker – split off before the frequency-doubler – as local oscillator for the homodyne system. These pulses have to be temporally and spatially mode-matched to the mode of the photons in the signal channel. In order to be able to resolve the quantum noises of individual laser pulses, we have developed a homodyne design with ultra-low electronic noise (1000 electrons per pulse), high subtraction efficiency (> 83 dB), and high frequency bandwidth (DC – 2 MHz).

Our experimental results are shown in Fig. 2. In a 14-hour experimental run we have obtained two phase-randomized sets of quadrature values, 12000 for the Fock state and 200000 for the vacuum state (for comparison and calibration). The statistical distribution of the raw Fock state homodyne data was then used to reconstruct the Wigner function (Fig. 2). The reconstructed Wigner function exhibits a dip at the center reaching a classically impossible negative value.
From a fit of the marginal distribution, a measurement efficiency of 55% is deduced. The losses are determined by a number of factors including transverse and longitudinal mode matching of the local oscillator and the signal mode, detector inefficiencies and losses in the signal arm as well as state preparation inefficiencies due to e.g. dark counts of the trigger detector.

Further work will focus on achieving a better measurement efficiency and reconstructing other highly non-classical states of the light field.