

Quantum technology of non-classical light: new experiments and perspectives

A. I. Lvovsky*, S. A. Babichev, J. Mlynek†
Fachbereich Physik, Universität Konstanz, D-78457 Konstanz, Germany

<http://www.uni-konstanz.de/quantum-optics/quantech/>

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We present new experimental results in the framework of our research program dedicated to developing techniques of synthesis, manipulation and characterization of new quantum states of the light field. The goal of the program is to contribute to the rapidly emerging field of quantum technology by elaborating the basic building blocks for the future quantum information processors based on a particular physical system — nonclassical light.

In our past experiments we have used conditional measurements on biphotons generated by means of parametric down-conversion to produce a pulsed single-photon Fock state in a well-defined transform-limited spatiotemporal mode [1,2]. This state was subjected to quantum reconstruction by means of homodyne tomography, for which a highly-sensitive pulsed, time-domain homodyne detection system was developed [3]. In the present work we use these techniques as *tools* to generate and investigate new, more complex quantum states of light.

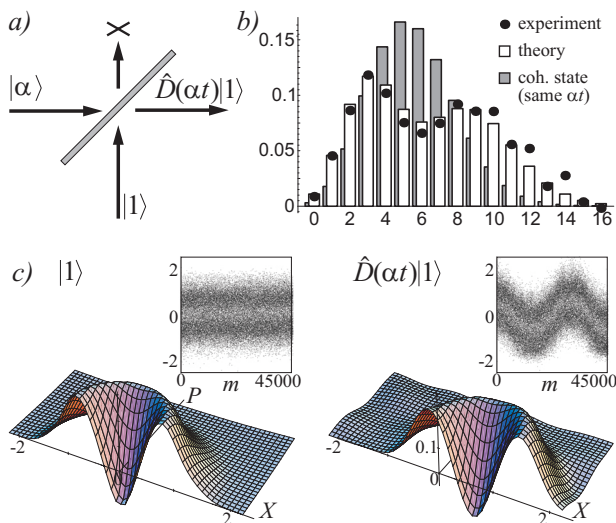


FIG. 1. (a) Preparation of the displaced Fock state. The beam splitter transmission t^2 must be low. (b) A reconstructed density matrix for $\alpha t = 2.4$ exhibits photon number oscillations. (c) Wigner functions of the undisplaced (left) and displaced (right, $\alpha t = 0.6$) Fock states. Quantum efficiency is $\eta = 0.62$.

a. Displaced Fock states [4]. These states obtain from the number states by action of the displacement operator

$\hat{D}(\alpha) \equiv \exp(\alpha\hat{a}^\dagger - \alpha^*\hat{a})$ [5]. They are useful for tomographic reconstruction of random quantum states [6]; yet they have not been synthesized and studied until now.

We have implemented the displacement operator by means of a high-reflection beam splitter (in the actual experiment, a dielectric mirror) off which our single photon was reflected (Fig. 1(a)). A strong coherent laser field entered the beam splitter from the rear, with its tiny fraction being transmitted and displacing the Fock state.

The results of the Displaced Fock state reconstruction are shown in Fig. 1(b,c). The Wigner function exhibits classically impossible negative values in the phase space region around the point $X + iP = \alpha$. The photon number distribution shows two peaks, which is also a well-known nonclassical feature of the displaced Fock states. This experiment presents the first phase-sensitive tomographic reconstruction of a highly non-classical optical state.

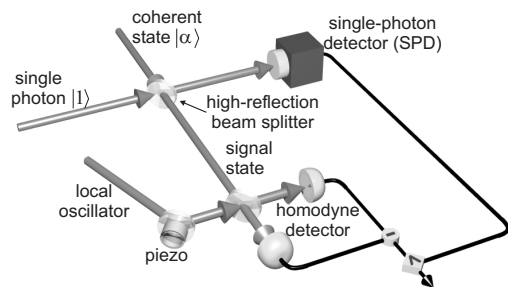


FIG. 2. Scheme of the catalysis experiment. Measurements by the balanced homodyne detector are conditioned on the single-photon detector registering a photon.

b. Quantum-optical catalysis [7]. The beam splitter used in the displaced Fock state preparation had two output channels, one of which (reflection of the coherent state) was discarded. In the following experiment this channel was instead subjected to a quantum measurement via a single-photon detector (SPD). In the event of a “click” this detector triggered a homodyne measurement in the other (signal) channel (Fig. 2). The signal ensemble was thus prepared conditioned on one of the beam splitter output states being the single-photon state, i.e. identical to that in one of the inputs. Contrary to the classical intuition we find the signal ensemble to differ from the original (“target”) coherent state: it is approx-

imated by a coherent superposition $|\psi_s\rangle \propto t|0\rangle + \alpha|1\rangle$. We call the effect of such transformation *quantum-optical catalysis* because of the role of the single photon, which facilitates generation of a non-classical signal ensemble without being affected by this interaction.

This phenomenon can be understood by assuming that both the input coherent excitation α and the beam splitter transmission t^2 are small: $\alpha \sim t \ll 1$. The coherent state can then be approximated as $|\alpha\rangle = |0\rangle + \alpha|1\rangle$. Suppose the SPD registers a photon. Where could this photon have originated from? If it comes from the coherent state, the photon $|1\rangle$ from the Fock state input is likely to have been reflected into the signal channel. If, on the other hand, the photon detected by the SPD originates from the Fock state transmitted through a beam splitter, the quantum state in the signal channel is with a high probability vacuum $|0\rangle$.

The quantum properties of the beam splitter manifest themselves in *fundamental indistinguishability* of these two possibilities. If the two initial states are prepared in identical optical modes, there is no way of telling which one of the initial states the photon in the SPD channel is coming from. As a result, the quantum state in the signal channel is not a statistical mixture of the states $|0\rangle$ and $|1\rangle$ but their coherent superposition.

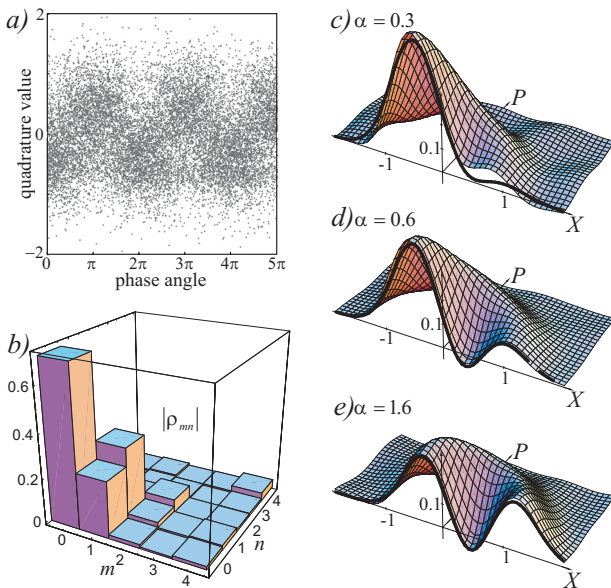


FIG. 3. (a) 14153 raw homodyne detector data. (b) Absolute values of the density matrix elements in the Fock representation for $\alpha \approx 0.3$. (c-e): Quantum catalysis ensembles obtained for various values of α . Heavy lines show theoretical fits to Wigner functions' cross-section.

The density matrix of the signal state measured experimentally at $t \approx \alpha \approx 0.3$ is shown in Fig. 3(b). The only non-negligible elements are associated with Fock states $|0\rangle$ and $|1\rangle$; an unproportionally high fraction of the vacuum state is due to experimental inefficiencies in prepar-

ing the single-photon state and its measurements [1].

The reconstructed Wigner functions for the signal state are shown in Fig. 3(c-e). At large values of α the photon detector will fire with almost every laser pulse and the signal state approaches a displaced Fock state discussed above. For a constant, small t the increase of α thus implements a gradual transition between highly classical ($|0\rangle$) and highly non-classical ($\hat{D}(t\alpha)|1\rangle$) states of light.

The observed effect of quantum optical catalysis is a direct consequence of beam splitter's capability to generate an entangled two-mode state from a non-classical but unentangled input. This experiment can be seen as an implementation of the first of two stages of the nonlinear sign shift quantum gate, the basic element of the recent linear-optical quantum computation proposal [8].

c. Perspectives As shown above, the single-photon state $|1\rangle$ can be used to generate random coherent superpositions of the states $|0\rangle$ and $|1\rangle$. Among our further goals is to extend this technique to the synthesis of *random* single-mode states by means of repeated parametric down-conversion in a chain of nonlinear crystals.

Of special interest is the entangled state $|\Psi^-\rangle = |0, 1\rangle - |1, 0\rangle$ generated by a single photon incident on a 50-% beamsplitter. We plan to characterize this state by means of homodyne tomography and investigate whether this characterization constitutes a demonstration of the state's nonlocality. Just as any other entangled state, $|\Psi^-\rangle$ can be used to implement quantum teleportation [9], which is another important element of the Knill *et al.* proposal.

* email: Alex.Lvovsky@uni-konstanz.de

† Present address: President, Humboldt-Universität zu Berlin, D-10099 Berlin, Germany

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