Quantum-optical catalysis by means of a single photon

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Abstract: We convert coherent states of light into nonclassical coherent superpositions of the vacuum and the single-photon states via conditional measurements on a beamsplitter, employing single photons as “catalysts”: they facilitate the conversion without being consumed.

OCIS codes: (270.0270) Quantum optics; (270.5290) Photon statistics; (270.5570) Quantum detectors

Introduction We present new experimental results achieved 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.

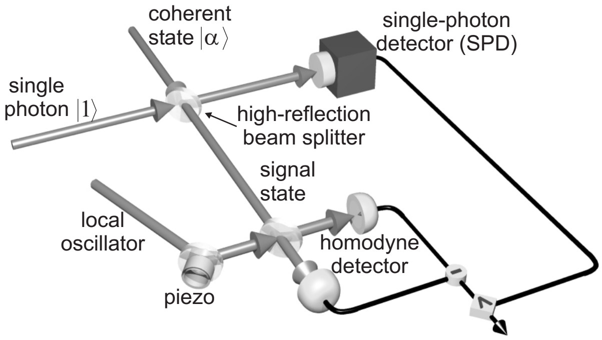

Fig. 1. Scheme of the catalysis experiment. Measurements by the balanced homodyne detector are conditioned on the single-photon detector registering a photon.

We investigate a curious consequence of a well-known property of the simplest quantum-optical device — the beam splitter: its capability to generate an entangled output state with non-classical, but unentangled input [4]. In our experiment the inputs are a single-photon Fock state $|1\rangle$ and a coherent state $|\alpha\rangle$ [Fig. 1]. Performing measurements in one of the output channels causes the entangled beam splitter output state to collapse projecting the other (“signal”) output onto a certain local ensemble. Our goal is to characterize this ensemble in the event the measurement in the first output channel reveals a quantum state *identical* to that in one of the BS inputs, namely, the single-photon state. Contrary to classical intuition we find the signal ensemble to differ from the original (“target”) coherent state: it is approximated by a highly non-classical 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.

Experiment The core of our apparatus consisted of the setup for generating the single-photon Fock state, which was the same as in our previous experiments [1, 2, 5]. A 82-MHz repetition rate train of 1.6-ps pulses generated by a Spectra-Physics Ti:Sapphire laser at 790 nm was frequency doubled and directed into a BBO crystal for down-conversion. The down-conversion occurred in a type-one frequency-degenerate, but spatially non-degenerate configuration. A single-photon detector, placed into one of the emission channels, detected photon-pair creation events. This detector firing ensured that a photon has as well been emitted into the other down-conversion channel, thus preparing single-photon Fock states by conditional measurements. All further measurements were conditioned upon a biphoton production event. We have obtained between 300 and 400 such events in a second.

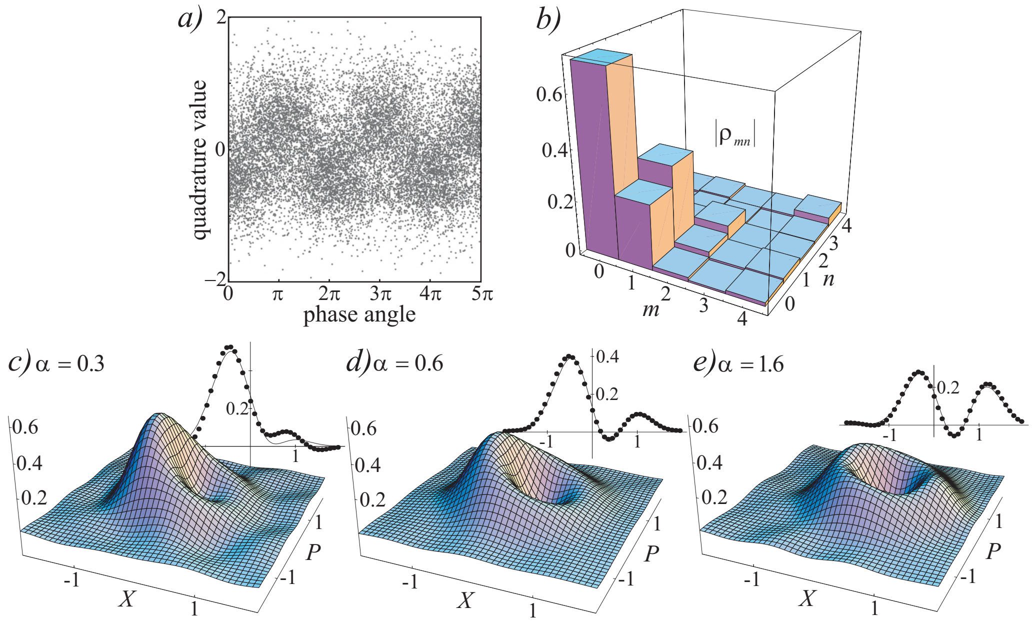

Fig. 2. (a) 14153 raw homodyne detector data; (b) absolute values of the density matrix elements in the Fock representation for $\alpha \approx 0.3$. (c-e): Wigner functions of the signal ensembles obtained for various values of α. Insets show Wigner functions' cross-sections along with theoretical fits.

Pulses containing the conditionally-prepared photon entered an optical arrangement shown in Fig. 1, which had to be maintained interferometrically stable throughout the experimental run. We used a Perkin-Elmer SPCM-AQ-131 single-photon counting module with $\eta_{\mathrm{SPD}} \approx 0.5$ and a beam splitter with a reflectivity of $r^2 = 0.92$. The local oscillator for balanced homodyne detection [3], as well as the target coherent state, have been provided by the master Ti:Sapphire laser. These pulses had to be spatially and temporarily mode matched with each other, as well as with the single-photon pulse emerging from the down-converter.

Results and discussion The raw output data of the pulsed homodyne detector acquired at $t \approx \alpha \approx 0.3$ is shown in Fig. 2(a); they were used to reconstruct the density matrix of the signal ensemble [Fig. 2(b)]. The only non-negligible elements are associated with Fock states $|0\rangle$ and $|1\rangle$; an unproportionaly high fraction of the vacuum state is due to experimental inefficiencies in preparing the single-photon state and its measurements [1].

The reconstructed Wigner functions for the signal states associated with various values of α are shown in Fig. 2(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 $\hat{D}(t\alpha)|1\rangle$ [6]. 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.

A detailed account of this work can be found in Ref. [7]. This experiment can be seen as an implementation of the first of two stages of the non-linear sign shift quantum gate, the basic element of the recent linear-optical quantum computation proposal [8, 9]. Such a gate is another example of quantum optical catalysis: the required modification of the target state is achieved with the two ancilla channels involved remaining in their original quantum states.

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 [10], which is another important element of the Knill *et al.* proposal.

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