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Thermal state truncation by using quantum-scissors device

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ABSTRACT

A non-Gaussian state being a mixture of the vacuum and single-photon states can be generated by truncating a thermal state in a quantum-scissors device of Pegg et al. (1998) [12]. In contrast to the thermal state, the generated state shows nonclassical property including the negativity of Wigner function. Besides, signal amplification and signal-to-noise ratio enhancement can be achieved.

1. Introduction

The generation of quantum states is a prerequisite for universal quantum information processing (QIP) [1]. Quantum states are usually classified into discrete-variable (DV) and continuous-variable (CV) descriptions [2]. In the CV quantum regime, there are two classes of quantum states that play an important role in QIP: Gaussian and non-Gaussian states, referring to their character of wave function or Wigner function [3,4]. In general, Gaussian states are relatively easy to generate and manipulate using current standard optical technology [5].

However, in the recent several decades, some probabilistic schemes are proposed to generate and manipulate non-Gaussian states [6–8]. Many schemes work in postselection [9], that is, the generated state is accepted conditionally on a measurement outcome. The typical examples include photon addition and subtraction [10], and noise addition [11] . Among them, an interesting scheme was based on the quantum-scissors devices (QSD). In 1998, Pegg, Phillips and Barnett proposed this quantum state truncation scheme, which change an optical state $\gamma_0|0\rangle + \gamma_1|1\rangle + \gamma_2|2\rangle + \cdots$ into qubit optical state $\gamma_0|0\rangle + \gamma_1|1\rangle$. The device is then called a quantum-scissors device, while the effect is referred to as optical state truncation via projection synthesis. This quantum mechanical phenomenon was actually a nonlocal effect relying on entanglement because no light from the input mode can reach the output mode [12]. After its proposal, an experiment of quantum scissors was realized by Babichew, Ries and Lvovsky [13] by applying the experimentally feasible proposal of Ref. [14–16]. The QSD was also applied and generalized to generate not only qubits but also qutrits [17] and qudits [18,19] of any dimension. Similar quantum state can be also generated via a four-wave mixing process in a cavity [20].

Following these works on QSD, Ferreyrol et al. implemented a nondeterministic optical noiseless amplifier for a coherent state [21]. Moreover, heralded noiseless linear amplifications were designed and realized [22–24]. Recently, an experimental demonstration of a practical nondeterministic quantum optical amplification scheme was presented to achieve amplification of known sets of coherent states with high fidelity [25]. By the way, many systems transmitting signals using quantum states could benefit from amplification. In fact, any attempt to amplify signal must introduce noise inevitably. In other words, perfect deterministic amplification of an unknown quantum signal is impossible. In addition, Miranowicz et al. studied the phase-space interference of quantum states optically truncated by QSD [26].

Inspired by the above works, we generate a non-Gaussian mixed state by using a Gaussian thermal state as the input state of the QSD in this paper. This process transform an input thermal state into an incoherent mixture of only zero-photon and single-photon components. The success probability of such event is studied. Some properties of the generated state, such as signal

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amplification, signal-to-noise ratio and the negativity of the Wigner function, are investigated in detail. The paper is organized as follows. In Section 2, we outline the framework of QSD and introduce the scheme of thermal state truncation. Quantum state is derived explicitly and the probability is discussed. Subsequently, some statistical properties, such as average photon number, intensity gain, signal-to-noise ratio, are investigated in Section 3. In addition, we study the Wigner function and the parity for the output state in Section 4. Conclusions are summarized in Section 5.

2. Thermal state truncation scheme

In this section, we outline the basic framework of quantum-scissors device and introduce our scheme of thermal state truncation.

2.1. Framework of quantum-scissors device

QSD mainly includes two beam splitters (BSs) and three channels, as shown in Fig. 1. Three channels are described by the optical modes a, b, and c in terms of their respective creation (annihilation) operators $a^{\dagger}(a)$, $b^{\dagger}(b)$ and $c^{\dagger}(c)$. Since every channel have an input port and an output port, the QSD have six ports. The interaction including several key stages as follows. Firstly, the channel a and the channel c are correlated through an asymmetrical beam splitter (A-BS), whose operation can be described by the unitary operator $B_1 = e^{\theta\left(a^{\dagger}c - ac^{\dagger}\right)}$ with the transmissivity $T = \cos^2\theta$. After that, the channel b and the channel c are then correlated through another symmetrical beam splitter (S-BS, also 50:50 BS), whose operation can be described by the unitary operator $B_2 = e^{\frac{\pi}{4}\left(b^{\dagger}c - bc^{\dagger}\right)}$. Moreover, among these six ports, four ports are fixed with special processes as follows: (1) injecting the auxiliary single-photon $|1\rangle$ in the input port of channel a; (2) injecting the auxiliary zero-photon $|0\rangle$ in the input port of channel c; (3) detecting the single-photon $|1\rangle$ in the output port of channel b; and (4) detecting the zero-photon $|0\rangle$ in the output port of channel c.

QSD leaves only one input port (i.e., the input port in channel b) and one output port (i.e., the output port in channel a). Injecting an appropriate input state in the input port, one can generate a new quantum state in the output port. Many previous theoretical and experimental schemes have used the pure states as the input states to generated quantum states. Here, our proposed scheme use a mixed state as the input state to generate quantum state.

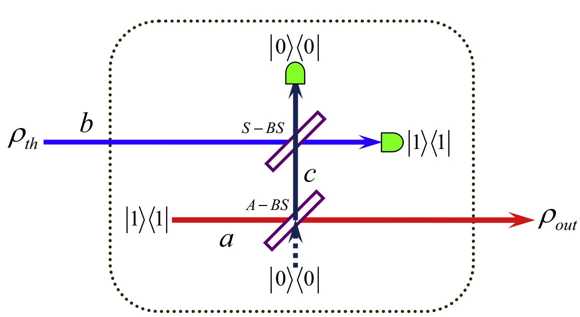

Fig. 1. Conceptual scheme of "quantum scissors device" (QSD) for thermal state truncation. The auxiliary single-photon $|1\rangle\langle 1|$ in channel a and the auxiliary zero-photon $|0\rangle\langle 0|$ in channel c generates an entangled state between the modes a and c after passing through an asymmetrical beam splitter (A-BS) with the transmissivity T. The input mode b (accompanied by the input thermal state ρ_{th}) is then combined with c in a (50:50) symmetrical beam splitter (S-BS). A successful heralded truncation (accompanied by the output generated state ρ_{out}) in the output a mode is flagged by a single-photon event in the output b mode detection and no photons on the output c mode detection.

2.2. Thermal state truncation

Using a mixed state (i.e., thermal state) as the input state, we shall generate another mixed state in our present protocol. The input thermal state is given by

$$\rho_{th} = \sum_{n=0}^{\infty} \frac{\bar{n}^n}{\left(\bar{n}+1\right)^{n+1}} \left| n \right\rangle \left\langle n \right|, \tag{1}$$

where $\bar{n}$ is the average number of the thermal photons [27]. Therefore, the output generated state can be expressed as

$$\rho_{out} = \frac{1}{p_d} \left\langle 0_c \right| \left\langle 1_b \right| B_2 \{\rho_{th} \otimes [B_1 (\left| 1_a \right\rangle \left\langle 1_a \right| \otimes \left| 0_c \right\rangle \left\langle 0_c \right|) B_1^{\dagger}]\} B_2^{\dagger} \left| 1_b \right\rangle \left| 0_c \right\rangle \tag{2}$$

where p_d is the success probability.

The explicit density operator in Eq. (2) can further be expressed as

$$\rho_{out} = p_0 \left|0\right\rangle\left\langle 0\right| + p_1 \left|1\right\rangle\left\langle 1\right|, \tag{3}$$

where $p_0 = \left(1-T\right)\left(\bar{n}+1\right)/\left(\bar{n}+1-T\right)$ and $p_1 = \bar{n}T/\left(\bar{n}+1-T\right)$ are, respectively, the zero-photon distribution probability and the one-photon distribution probability. Obviously, the output state is an incoherent mixture of a vacuum state $|0\rangle\langle 0|$ and a one-photon state $|1\rangle\langle 1|$ with certain ratio coefficients p_0, p_1. If T=0, then $\rho_{out} \to \left|0\right\rangle\left\langle 0\right|$; while for T=1, then $\rho_{out} \to \left|1\right\rangle\left\langle 1\right|$.

From another point of view, the output generated state in Eq. (3) remains only the first two terms of the input thermal state in Eq. (1), which can also be considered as an truncation from the input thermal state. However, the corresponding coefficients of these terms are changed. Moreover, the output generated state carry the information of the input thermal state because it also depend on the thermal parameter $\bar{n}$. Since no light from the input port reaches the output port, this process also mark the nonlocal quantum effect of the operation for the quantum scissors.

From present protocol, we easily obtain p_d as follows

$$p_d = \frac{\bar{n}+1-T}{2\left(\bar{n}+1\right)^2}. \tag{4}$$

For a given $\bar{n}$, it can be shown that p_d is a linear decreasing function of T.

In Fig. 2, we plot p_d as a function of T for different $\bar{n}$. For instance, when $\bar{n} = 1$, we have $p_d|_{\bar{n}=1} = 0.25 - 0.125\,T$ (see the green line in Fig. 2); when $\bar{n} = 0$, we have $p_d|_{\bar{n}=0} = 0.5 - 0.5\,T$ (see the black line in Fig. 2). The results on the success probability provide a theoretical reference for experimental realization.

3. Statistical properties of the generated state

By adjusting the interaction parameters, i.e., the thermal parameter $\bar{n}$ of the input state and the transmission parameter T of the A-BS, one can obtain different output states with different figures of merits. Some statistical properties, such as average photon number, intensity gain and signal-to-noise ratio, are studied in this section. As the reference, we will compare the properties of the output state with those of the input state.

3.1. Average photon number and intensity gain

Using the definition of the average photon number, we have $\left\langle \hat{n} \right\rangle_{\rho_{th}} = \bar{n}$ for the input thermal state and