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An asymmetrical entangled coherent state: generation scheme and nonclassical properties

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A theoretical scheme is proposed to generate an asymmetrical entangled coherent state from two separate coherent state by similar quantum-optical catalysis. We give the explicit expression of the generated state and discuss its success probability. Some nonclassical properties such as antibunching effect and the negativity of the Wigner function, are studied in detail.

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I. INTRODUCTION

As the representation of an outcome of Schrodinger thought experiment [1], entangled coherent states (ECSs) have attracted wide attention and interest of researchers [2–5]. The ECSs have many potential applications in quantum information processing such as Bell-inequality tests[6, 7], tests for nonlocal realism [8, 9], quantum teleportation [10, 11], quantum computation[12–14], and quantum key distribution [15]. Moreover, many ECSs have realized in the laboratory and numerous implementation schemes have been suggested [16–18]. For example, Howell et al. prepared a two-mode ECS by using a Mach-Zehnder interferometer equipped with a cross-Kerr element in each of two spatially separated modes [19]. The preparation of two spatially separated traveling optical modes is of special interest in recent several decades[20–22].

Actually, the preparation of ECS themselves can be achieved by some conditional measurements [23]. Moreover, there is a number of works adopting the idea of ”conditional measurement”[24–26] to generate quantum states. For instance, Dakna et al. generated a Schrodinger-cat-like state from a single-mode squeezed vacuum state by subtracting photons with low reflectance beam-splitters (BSs) and photon counters [27]. Lvovsky and Mlynek generated a coherent superposition state in the form of $t\left|0\right\rangle+\alpha\left|1\right\rangle$ by using a special ”conditional measurement” scheme, i.e., “quantum-optical catalysis” [28]. The quantum-optical catalysis is simply mixing one photon at the beam splitter and post-select the beam-splitter (BS) output based on detection of one photon. Relative work on quantum-optical catalysis.

Recently, Park and Jeong studied an asymmetric form of the two-mode ECS and test the Bell inequality. They found that the asymmetric ECSs have obvious advantages over the symmetric form of ECSs in testing the Bell-CHSH inequality[29]. Inspired by these ideas, we propose a scheme to generate an asymmetrical entangled coherent state (AECS) by using a similar “quantum-optical catalysis”, where two BSs will be strung together. It seems that we extended the same idea for a single-mode coherent-state superposition [30, 31] to the two-mode version. In addition, we will discuss some nonclassical properties of the generated states.

The paper is organized as follows. In section II, we introduce the generating scheme of the AECS and derive the analytical expression of the AECS as well as the success probability of detection. In Section III, we study the antibunching effect according to one criterion. Then in Section IV, we study the Wigner function and discuss its negativity to show the nonclassicality.

II. ASYMMETRICAL ENTANGLED COHERENT STATE

In this section, we introduce the theoretical scheme of generating an AECS, a new two-mode non-Gaussian quantum state. The success probability is also discussed.

A. Generating scheme of the AECS

As showen in Fig.2, two separate coherent states ($\left|\alpha_a\right\rangle$, $\left|\beta_b\right\rangle$) with amplitude ($\alpha$, β) are injected into a setup, which is similar to that of quantum-optical catalysis. The direct expression of the prepared state $\left|AECS\right\rangle_{ab}$ can be theoretically given by

$$\left|AECS\right\rangle_{ab}=\frac{1}{\sqrt{p_c}}\left\langle 1_c\right|B_2\left|\beta_b\right\rangle\left(B_1\left|\alpha_a\right\rangle\left|1_c\right\rangle\right) \qquad (1)$$

which will be called as “asymmetrical entangled coherent state” (AECS). Here $B_1=e^{\theta_1\left(a^\dagger c-ac^\dagger\right)}$ and $B_2=e^{\theta_2\left(b^\dagger c-bc^\dagger\right)}$ are the respective unitary operators of the two tunable BS_1 and BS_2 in terms of the creation (annihilation) operator $a^\dagger(a)$, $b^\dagger(b)$ and $c^\dagger(c)$ for channels $1,2$ and 3. Consequently, there are the following transformations:

$$\begin{aligned} B_1a^\dagger B_1^\dagger &= a^\dagger t_1-c^\dagger r_1,\ \ B_1c^\dagger B_1^\dagger=a^\dagger r_1+c^\dagger t_1,\\ B_2b^\dagger B_2^\dagger &= b^\dagger t_2-c^\dagger r_2,\ \ B_2c^\dagger B_2^\dagger=b^\dagger r_2+c^\dagger t_2. \end{aligned} \qquad (2)$$