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Nonclassical properties and entanglement of non-Gaussian entangled states generated via multiple-photon subtraction on two-mode squeezed coherent states

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ABSTRACT

We investigate how the photon-subtraction operation affects the quantum optical nonclassicalities and the entanglement of photon-subtracted two-mode squeezed coherent states (PS-TMSCS). For such non-Gaussian entangled states, the normalization factor and Mandel Q parameter, as well as, the quantity of the Hillery–Zubairy inequality are analytically derived, and they are all periodic functions of the compound phase $\chi = \phi_1 + \phi_2 - \theta$ involved in the TMSCS. We show that the fields in such states exhibit remarkable sub-Poissonian photon statistics, especially at the optimal phase $\chi = 0$. The Wigner function of the PS-TMSCS is modulated by a factor which is related to two-variable Hermite polynomials. And the shape of the Wigner function is phase-sensitive, which is different from that of the TMSCS. As characterized by the Hillery–Zubairy entanglement criterion, we show that the quantity of Hillery–Zubairy E gets more negative not only for a larger value of r but also for greater values of photon subtraction numbers (m, n) at the optimal compound phase = 0.

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1. Introduction

With the rapid development of quantum information theory, non-Gaussian states have been received much attention. This is mainly because their strongly nonclassical properties, such as the entanglement and clear negativity of the Wigner function, which are important for the improvement of the efficiency in the implementation of the quantum information processing [1–10]. One of the most promising approaches to generate non-Gaussian and negative Wigner function states of light is through photon subtraction or addition. Agarwal and Tara [11] theoretically studied the nonclassical properties of photon-added coherent states, which was implemented [12] via a nondegenerate parametric amplifier with small coupling strength. The photon subtraction was implemented [13] with a beam splitter of high transmissivity. For a review on quantum-state engineering with photon addition and subtraction, we refer to Refs. [9,10].

Particularly, two-mode squeezed states are important entangled resources in quantum teleportation and computation. They have received more attention from both experimentalists and theoreticians. In order to increase the quantum entanglement, theoretical and experimental efforts focus on photon-subtracted or -added two-mode squeezed states [14–20]. Ourjoumtsev et al. [17] demonstrated experimentally that the entanglement of Gaussian entangled states can be increased by subtracting one photon from two-mode squeezed vacuum states. This is indeed true, and the deep reason behind this phenomenon may be that Gaussian states are extremal for entanglement in continuous-variable systems according to the Giedke–Wolf–Cirac theorem [21]. Therefore, non-Gaussian states, such as photon-subtracted states, are always more entangled than Gaussian states. For multiple-photon added or subtracted two-mode squeezed vacuum state, the optimal enhancement is obtained when the same number of operations is applied to both modes, where both addition and subtraction give the same entanglement enhancement [20]. Recently, Lee et al. [22] proposed that a coherent superposition of photon subtraction and addition to enhance quantum entanglement of two-mode squeezed vacuum state. On the other hand, the Dell'Anno–De Siena–Illuminati non-Gaussian teleportation [23,24], which shows that a general class of entangled two-mode non-Gaussian states, the squeezed Bell states, that include photon-subtracted squeezed states as particular cases, are optimal in yielding the best output fidelity of quantum teleportation in the standard continuous-variable protocol of Vaidman [25], Braunstein and Kimble [26], and are always better than the corresponding Gaussian states. Moreover, Adesso et al. have showed that non-Gaussian states are

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optimal for quantum estimation with respect to Gaussian states [27].

Besides the entanglement, the quantum optical nonclassicalities based on the diagonal coherent state representation [28], such as non-classical photon statistics, negative Wigner functions are also important nonclassical features displayed by some quantum states. Recently, it is demonstrated that the negative Wigner function is a useful resource for quantum computation [29]. The entanglement and the optical nonclassicalities of multiple-photon added two-mode squeezed thermal states have also been analyzed [30,31] by Mandel parameter, cross-correlation function, and Wigner functions. In our previous work, we have studied the nonclassical photon statistics of the multiple-photon-subtracted two-mode squeezed coherent states (PS-TMSCS) [32], and showed that the photon statistical properties are sensitive to the compound phase involved in the TMSCS. And the photon subtraction operations applied to both modes can enhance the cross-correlation and anti-bunching effects of result states. In this work, we further investigate its entanglement and other optical nonclassicalities. Particularly, we shall present how the three phases involved in the TMSCS affects those nonclassical properties.

This paper is organized as follows. In Section 2, by the generating function of two-variable Hermite polynomials, we derive the normalization factor of the PS-TMSCS, which is related to a two-variable Hermite polynomials of the complex squeezing parameter r and displacement parameters λ_1 and λ_2. Our numerical analyses show that when $m \neq 0$ and $n \neq 0$, as well as $|\lambda_1| \neq 0$, and $|\lambda_2| \neq 0$, are all satisfied, is $N_{m,n}$ a periodic function of the compound phase $\chi = \phi_1 + \phi_2 - \theta$. In Section 3, based on the normalization factor, we explore how the photon subtraction affects the quantum optical nonclassicalities, such as sub-Poissonian statistical properties and the negative Wigner function of the PS-TMSCS. In Section 4, as characterized by the Hillery–Zubairy entanglement criterion, we investigate the entanglement of the PS-TMSCS. Our main results are summarized in Section 5.

2. PS-TMSCS and its normalization factor

Let us first review the PS-TMSCS. It is well known that the general TMSCS is generated performing the two mode squeezing operator on an initial two-mode vacuum state first and followed by the two-mode displacement operator, i.e.,

$$|\xi, \lambda_1, \lambda_2\rangle = D(\lambda_1, \lambda_2) S_2(\xi)|0, 0\rangle, \tag{1}$$

where $S_2(\xi)$ and $D(\lambda_1, \lambda_2)$ are the two-mode squeezing and displacement operators, respectively, defined by

$$\begin{aligned} S_2(\xi) &= \exp[\xi a^\dagger b^\dagger - \xi^* ab], \\ D(\lambda_1, \lambda_2) &= \exp[\lambda_1 a^\dagger - \lambda_1^* a + \lambda_2 b^\dagger - \lambda_2^* b], \end{aligned} \tag{2}$$

in which $a^\dagger$ and $b^\dagger$ (a and b) are photon creation (annihilation) operators in each mode, while

$$\xi = re^{i\theta}, \quad \lambda_1 = |\lambda_1| e^{i\phi_1}, \quad \lambda_2 = |\lambda_2| e^{i\phi_2} \tag{3}$$

are complex parameters.

Theoretically, the normalized PS-TMSCS can be generated by simultaneously operating photon annihilation operators a and b on a TMSCS [32], i.e.,

$$|\xi\rangle_{ps} = N_{m,n}^{-1/2} a^m b^n |\xi, \lambda_1, \lambda_2\rangle, \tag{4}$$

where $N_{m,n}$ is the normalization constant (see Appendix A in detail)

$$N_{m,n} = \sum_{l=0}^{m}\sum_{k=0}^{n} \frac{(\sinh r)^{2(l+k)}(m!n!)^2}{l!k!|\lambda_1|^{2l-2m}|\lambda_2|^{2k-2n}} \times \left| \sum_{f=0}^{\min(m-l,n-k)} \frac{(2|\lambda_1\lambda_2|e^{i\chi})^{-f}(\sinh 2r)^f}{f!(m-l-f)!(n-k-f)!} \right|^2 \tag{5}$$

where the compound phase χ is defined by

$$\chi = \phi_1 + \phi_2 - \theta. \tag{6}$$

Obviously, $N_{m,n}$ is a periodic function of χ involved in the TMSCS with a period 2π. Eq. (5) shows that only when $m \neq 0$ and $n \neq 0$, as well as $|\lambda_1| \neq 0$ and $|\lambda_2| \neq 0$, are all satisfied, is $N_{m,n}$ a periodic function of the compound phase χ involved in the TMSCS with a period 2π.

For the PS-TMSCS state given by Eq. (4), we can obtain the expectation value of a general product of operators by the same approach as deriving Eq. (5)

$$\langle a^{\dagger p} a^q b^{\dagger h} b^j \rangle = \frac{1}{N_{m,n}} \langle \xi | a^{\dagger m} b^{\dagger n} a^{\dagger p} a^q b^{\dagger h} b^j a^m b^n |\xi\rangle = \frac{N_{m+q,m+p,n+j,n+h}}{N_{m,n}}, \tag{7}$$

where we set

$$\begin{aligned} N_{m+q,m+p,n+j,n+h} &= e^{i(q-p)\phi_1 + i(j-h)\phi_2} |\lambda_1|^{p+q} |\lambda_2|^{j+h} (m+q)!(n+j)! \\ &\times \sum_{l=0}^{\min[m+q,m+p]} \sum_{k=0}^{\min[n+j,n+h]} \frac{(\sinh r)^{2(l+k)}(m+p)!(n+h)!}{l!k!|\lambda_1|^{2l-2m}|\lambda_2|^{2k-2n}} \\ &\times \sum_{f=0}^{\min[m+q-l,n+j-k]} \frac{(f!)^{-1}(2e^{i\chi}|\lambda_1\lambda_2|)^{-f}\sinh^f 2r}{(m+q-l-f)!(n+j-k-f)!} \\ &\times \sum_{s=0}^{\min[m+p-l,n+h-k]} \frac{(s!)^{-1}(2e^{-i\chi}|\lambda_1\lambda_2|)^{-s}\sinh^s 2r}{(m+p-l-s)!(n+h-k-s)!} \end{aligned} \tag{8}$$

When $p = q$ and $h = j$ are satisfied, Eq. (8) actually reduces to Eq. (5), i.e., $N_{m+q,m+p,n+j,n+h} \equiv N_{m+p,n+h}$. Eqs. (5) and (7) are important for further studying nonclassical properties of the PS-TMSCS. Particularly, with the help of Eqs. (5) and (7), its is convenient to explore some quantum optical nonclassicalities that are expressed in terms of expectation values of field operators, such as sub-Poissonian statistics, the cross-correlation, anti-bunching effects, squeezing properties, as well as the entanglement characterized by some inseparability criteria.

3. Quantum optical nonclassicalities of the PS-TMSCS

The quantum optical concept of nonclassicality, based on the diagonal coherent state representation, and the notion of entanglement, are two such important nonclassical features displayed by some quantum states. Whereas the former has played an important role from the early days of quantum optics, the latter has received enormous attention more recently, with the development of the theory of quantum information. In this section, based on the normalization factor of the PS-TMSCS, we shall investigate how photon subtraction operations affect the quantum optical nonclassicality, such as sub-Poissonian statistics and the negative of Wigner functions.

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