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Statistics of states generated by quantum-scissors device*

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Generating desired states is a prerequisite in quantum information. Some desired states can be generated by a quantum-scissors device (QSD). We present a detailed analysis of the properties of the generated states, including average photon numbers and intensity gains. The theoretical analysis shows that there is a nondeterministic amplification in terms of the average photon number under the condition that the average photon number of the input state is less than 1. In contrast to the input states, the generated states show the nonclassical property described by the negativity of the Wigner function. Furthermore, we generalize the QSD to truncate arbitrary photon number terms of the input states, which may be useful in high-dimensional quantum information processing.

Keywords: quantum state generation, nondeterministic amplification, nonclassical property, generalized quantum-scissors

PACS: 03.65.–w, 03.67.–a, 89.70.–a, 41.85.–p **DOI:** 10.1088/1674-1056/28/3/030302

1. Introduction

The quantum properties of light have attracted increasing attention from scientists.[1–5] Photons are natural information carriers (a quantum bus) in a quantum network, connecting remote quantum computer nodes via quantum emitters, due to their weak interaction with their environment.[6–9] This makes photons one of the most promising candidates for building a quantum computer.[10,11] In order to realize universal quantum information processing (QIP),[12] the generation of desired states is a prerequisite. Arguably, one of the main methods in the field of quantum optics is utilizing nonlinear interactions at the few-photon level, which would be able, e.g., to generate various highly nonclassical states of light and implement advanced schemes for QIP.[13–15] Unfortunately, the nonlinear coupling between single photons mediated by common material media is extremely weak, so other approaches have to be pursued. Besides, the nonclassicality of photon states has recently been a topic of great interest both theoretically and experimentally, as it represents a test ground to address many important questions such as the quantum-to-classical transition.[16,17] One of the most promising techniques appears to be the measurement induced strategy. In other words, using passive linear optics, ancillary single photons, and photon counting measurements, one can generate some desired states. This strategy is commonly adopted for building effective nonlinearities in linear quantum optical gates.[18–21] Among them, an interesting scheme is based on quantum scissors devices (QSDs).[18] By exploiting the QSD, one can generate an arbitrary running-wave superposition of the vacuum and one-particle states, $\alpha|0\rangle+\beta|1\rangle$. The QSD is also generalized to generate not only qubits but also qudits of any dimension.[22,23]

Quantum mechanics imposes that any amplifier that works independently on the phase of the input signal has to introduce some excess noise.[24,25] The impossibility of such a noiseless amplifier stems from the unitarity and linearity of quantum evolution, which leads to a famous theorem named the no-cloning theorem.[26,27] A possible way to circumvent this limitation is to interrupt such evolution via a measurement, providing a random outcome able to herald a successful- and noiseless-amplification event.[28,29] It has been shown that QSD can be used as a nondeterministic optical noiseless amplifier.[30,31]

Since the QSD has a lot of potential applications,[32,33] it is worthwhile to further study the statistics of states generated by a QSD. In this paper, we view the QSD as a black box and feed several different input states, e.g., Fock states, coherent states, and thermal states. The output states and their statistics are investigated, especially the average photon number and intensity gain. We find that there is nondeterministic amplification for some special input states, whose average photon numbers are less than 1. However, it is impossible that the average photon numbers of the output states exceed 1. We analyze the nonclassical property of the generated states using the Wigner function, and also generalize the QSD to truncate some special terms of the input states and show the potential applications in QIP.

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The paper is organized as follows. In Section 2, we outline the setup of the QSD and view it as a black box. We find that it truncates the input states and retains the portion where the photon number is less than 1 under the conditional detection. Subsequently, we present in Section 3 a detailed study of the output states and their statistics, such as average photon number, intensity gain, and nonclassical properties in the case of different input states, including Fock states, coherent states, and thermal states. In addition, we study the generalized QSD in Section 4. Conclusions are summarized in Section 5.

2. Setup description

Figure 1 shows a sketch of the experimental setup of the original QSD. The setup consists of two beam splitters. Thus, there are three channels, which are described by modes a, b, and c in terms of their respective creation (annihilation) operators $a^\dagger(a)$, $b^\dagger(b)$, and $c^\dagger(c)$. We inject the input states in the input port of channel c and the auxiliary states in the input ports of channel a and b, then perform a measurement at the output ports of channel b and c. Finally, we obtain the generated states at the output port of channel a. Equivalently, the QSD leaves only one input port and one output port, if we choose fixed auxiliary states and outcomes of measurement. Thus, we can view the QSD as a black box with one input port and one output port. Injecting an appropriate input state into the input port, one can generate a new quantum state at the output port.

The action of the beam splitter (BS) is described by the unitary operator

$$R_{ab} = \exp\left[\mathrm{i}\theta(a^\dagger b + a b^\dagger)\right], \tag{1}$$

and $t = \cos\theta$ and $r = \sin\theta$ are the BS transmission and reflection coefficient, respectively.[34]

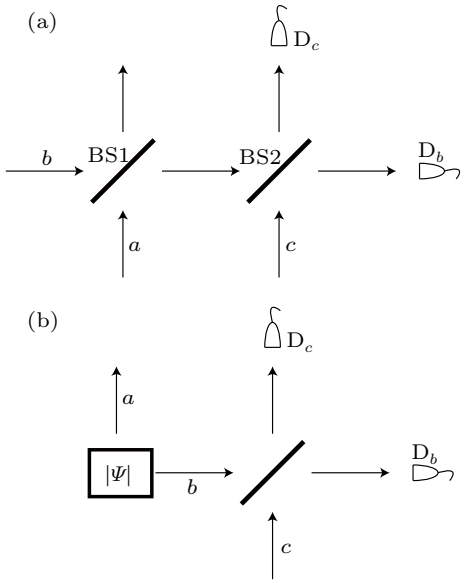


Fig. 1. Experimental setup. (a) The primitive QSD and (b) the generalized QSD.

We assume the scheme sketch in Fig. 1(a) has an input state given by

$$\rho_{abc}^{\mathrm{in}} = \rho_a \otimes \rho_b \otimes \rho_c = |1\rangle\langle 1| \otimes |0\rangle\langle 0| \otimes \sum_{m,n} \rho_{m,n} |m\rangle\langle n|. \tag{2}$$

After running through BS1 and BS2, we obtain the output state

$$\rho_{abc}^{\mathrm{out}} = R_{bc} R_{ab} \rho_{abc}^{\mathrm{in}} R_{ab}^\dagger R_{bc}^\dagger. \tag{3}$$

Here, we assume that θ_1 of BS1 and θ_2 of BS2 are the free parameters to be adjusted for the achievement of desired states. By measuring the field modes b and c, we synthesize the projection of the field mode a in some desired states. Here, we choose the situation that the photon detectors D_b and D_c register one and zero photons, respectively. Finally, we obtain the output state of field mode a

$$\begin{aligned}
\rho_a^{\mathrm{out}} \propto\ & \langle 1|_b \langle 0|_c R_{bc} R_{ab} \rho_{abc}^{\mathrm{in}} R_{ab}^\dagger R_{bc}^\dagger |1\rangle_b |0\rangle_c \\
=\ & \rho_{00} (\sin(\theta_1)\cos(\theta_2))^2 |0\rangle\langle 0| \\
& + \rho_{01} \sin(\theta_2)\sin(\theta_1)\cos(\theta_2)\cos(\theta_1) |0\rangle\langle 1| \\
& + \rho_{10} \sin(\theta_2)\sin(\theta_1)\cos(\theta_2)\cos(\theta_1) |1\rangle\langle 0| \\
& + \rho_{11} (\sin(\theta_2)\cos(\theta_1))^2 |1\rangle\langle 1|.
\end{aligned} \tag{4}$$

For the case of both $50-50$ symmetric BSs, it follows that $\theta = \frac{\pi}{4}$ and $t = r = \frac{1}{\sqrt{2}}$. We obtain the output states conditioned on this detection

$$\rho_a^{\mathrm{out}} \propto \rho_{00} |0\rangle\langle 0| + \rho_{01} |0\rangle\langle 1| + \rho_{10} |1\rangle\langle 0| + \rho_{11} |1\rangle\langle 1|. \tag{5}$$

3. Statistics of generated states

The setup can be viewed as a black box: feed in an input state ρ_c^{in} and generate an output state ρ_a^{out}. It should be pointed out that the process is probabilistic. Only in the case where the conditional detection occurs can we obtain the desired states. Thus, some statistical properties of the output states, such as average photon numbers, intensity gains, and nonclassial properties, should be studied. Here, we define the intensity gain as

$$g = \frac{\langle \hat{n} \rangle_{\mathrm{out}}}{\langle \hat{n} \rangle_{\mathrm{in}}}, \tag{6}$$

where $\langle \hat{n} \rangle_{\mathrm{in/out}} = \mathrm{Tr}[\hat{n}\rho_{\mathrm{in/out}}]$ are the average photon number of the input or output states, respectively. If $g > 1$, the signal is amplified, otherwise the signal is attenuated.

The negative Wigner function is evidence of the nonclassicality of a quantum state.[28,35,36] For a single-mode density operator ρ, the Wigner function in the coherent state representation z can be expressed as[37]

$$W(\beta) = \frac{2\mathrm{e}^{2|\beta|^2}}{\pi} \int \frac{\mathrm{d}^2 z}{\pi} \langle -z|\rho|z\rangle \mathrm{e}^{-2(z\beta^* - z^*\beta)}, \tag{7}$$

where $\beta = (q + \mathrm{i}p)/\sqrt{2}$. Therefore, we easily obtain the Wigner function of both input states and output states and estimate whether or not the states have nonclassical properties.

3.1. Fock states

For the Fock state $|N\rangle$ which is the eigenstate of number operator $\hat{n}$, the probability distribution that n photons are present is $p(n) = \delta_{n,N}$. If $N > 1$ or 0, we obtain nothing at the output port because of the zero probability of the conditional detection. Only in the case of $N = 1$ does the QSD generate Fock state $|1\rangle$. This is equivalent to performing a photon counting measurement between BS1 and BS2 and the outcome is no photon in the detection. It is worth noting that it seems unnecessary or excessive using a QSD. However, it has an advantage over detecting photons, as practical detectors are imperfect. A click on the detector is more reliable than no response. Thus, this case can be used as quantum nondemolition measurement.[37] The conditional detection indicates that there is a photon in mode a. Moreover, if there is exactly one single photon in mode a, then its polarization state is unperturbed by the measurement.

3.2. Coherent states

The coherent state, $|\alpha\rangle$, has a Poissonian photon number probability distribution, $p(n) = \mathrm{e}^{-|\alpha|^2}|\alpha|^{2n}/n!$. Injecting this state into the QSD, we obtain the output state as

$$|\psi\rangle_{\mathrm{co}}^{\mathrm{out}} = \frac{k}{\sqrt{k^2+|\alpha|^2}}|0\rangle + \frac{\alpha}{\sqrt{k^2+|\alpha|^2}}|1\rangle, \tag{8}$$

where $k = \dfrac{\tan(\theta_1)}{\tan(\theta_2)}$. This is a superposition of vacuum and one-photon states, which is the main problem discussed in Ref. [18]. In the original quantum scissors, $\theta_1 = \theta_2 = \frac{\pi}{4}$ are used and suitable coherent states are needed for generating the desired superposition states of vacuum and one-photon. Here, we allow the adjustment of the reflection and transmission coefficients of BS1 and BS2, which makes the setup more flexible to generate desired states.

It is easy to calculate the average photon number and we have

$$\langle\hat{n}\rangle_{\mathrm{co}}^{\mathrm{in}} = |\alpha|^2 \tag{9}$$

for the input coherent state, and

$$\langle\hat{n}\rangle_{\mathrm{co}}^{\mathrm{out}} = \frac{|\alpha|^2}{k^2+|\alpha|^2} \tag{10}$$

for the output state. Using the definition of the intensity gain, we obtain

$$g = \frac{1}{k^2+|\alpha|^2}. \tag{11}$$

For the original quantum scissors, $k = 1$, and thus it is impossible for g to exceed unity, which means no amplification. However, by adjusting the BS reflection and transmission coefficients, it is possible to amplify the signal.[30] For the purpose of amplification, we have the requirement on k and α which reads

$$\frac{1}{k^2+|\alpha|^2} > 1. \tag{12}$$

Since $k > 0$, we obtain the necessary condition as $|\alpha|^2 < 1$. In other words, if the input state is a weak coherent state, there exists nondeterministic amplification by using a QSD with proper θ_1 and θ_2. In Fig. 2, we plot the intensity gain as a function of k and α. The intensity gain decreases monotonically on k with fixed α. In the case of $|\alpha| = 1$, g cannot exceed 1, which means no amplification. If $|\alpha| < 1$, g can be greater than 1, and the smaller k is, the higher g we have.

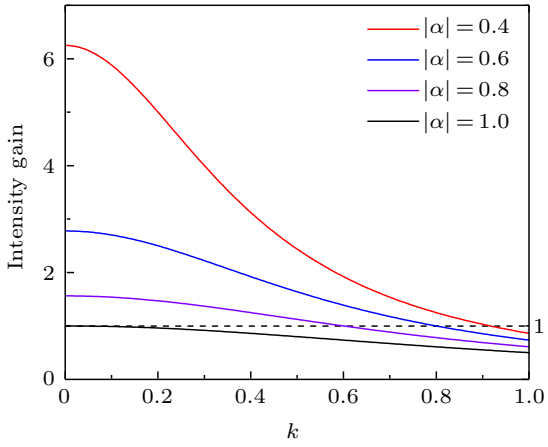


Fig. 2. Intensity gain for coherent state as a function of k with $|\alpha| = 0.4$, 0.6, 0.8, and 1.0. Here, the amplification (i.e., $g > 1$) occurs only for $|\alpha| < 1$.

For strong coherent states, there is a roundabout method.[30,31] Using beam splitters, we can split strong coherent states into N beams of weak coherent states under the condition that N is large enough. Before coherent addition, the QSD is used on each beam of weak coherent state. Finally, the strong coherent states are amplified with nonzero probability.

Using Eq. (7), we obtain $W_{\mathrm{co}}^{\mathrm{in}}(\beta) = \frac{2}{\pi}\exp(-2|\alpha-\beta|^2)$ for the input coherent state and

$$\begin{aligned} W_{\mathrm{co}}^{\mathrm{out}}(\beta) = {} & \frac{k^2}{k^2+|\alpha|^2}\frac{2}{\pi}\exp(-2|\beta|^2) \\ & + \frac{|\alpha|^2}{k^2+|\alpha|^2}\frac{2}{\pi}(4|\beta|^2-1)\exp(-2|\beta|^2) \\ & - \left(\frac{k\alpha^*}{k^2+|\alpha|^2}\beta^* + \frac{k\alpha}{k^2+|\alpha|^2}\beta\right)\frac{4}{\pi}\exp(-2|\beta|^2) \end{aligned} \tag{13}$$

for the generated state. Here, we plot the Wigner functions of the input state and output generated state in Fig. 3. As we all know, the coherent state is a Gaussian state, whose Wigner function has no negative region. However, the output generated states have lost the Gaussian characters because of the non-Gaussian forms of their Wigner functions. Furthermore, the Wigner function will exhibit negativity in some region satisfying the following condition:

$$k^2 + |\alpha|^2(4|\beta|^2-1) - 4k\Re(\alpha\beta) < 0,$$

where $\Re(z)$ denotes the real part of z. This is a nonclassical property, which cannot appear in the classical distribution.

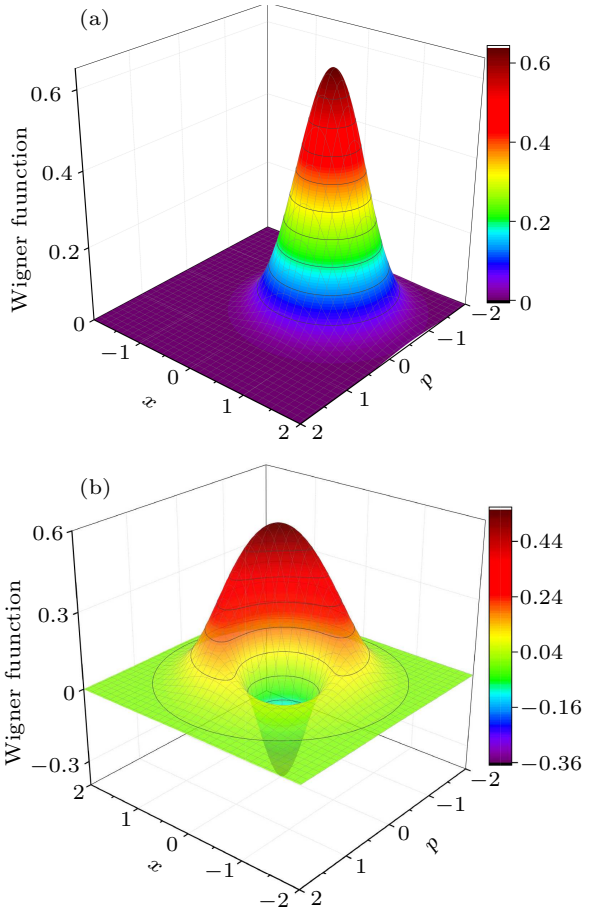


Fig. 3. Wigner function. (a) Wigner function of the input coherent state with $\alpha = \frac{1}{2}(1+\mathrm{i})$. (b) Wigner function of the generated state with $\alpha = \frac{1}{2}(1+\mathrm{i})$ and $k = 0.5$. It is obvious that the Wigner function of the generated state has a negative region which shows the nonclassical properties.

3.3. Thermal states

The thermal state is the equilibrium state for a field coupled to a reservoir at a finite temperature and is mixed with a density operator that is diagonal in the number-state basis. It is given by

$$\rho_{\mathrm{th}} = \sum_{n=0}^{\infty} \frac{\bar{n}^n}{(\bar{n}+1)^{n+1}} |n\rangle\langle n|, \tag{14}$$

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

$$\rho_{\mathrm{th}}^{\mathrm{out}} \propto \frac{k^2}{(\bar{n}+1)} |0\rangle\langle 0| + \frac{\bar{n}}{(\bar{n}+1)^2} |1\rangle\langle 1|. \tag{15}$$

The output state is a mixed state of vacuum and one-particle states with the average photon number $\langle\hat{n}\rangle_{\mathrm{th}}^{\mathrm{out}} = \dfrac{\bar{n}}{k^2(\bar{n}+1)+\bar{n}}$. Thus, the intensity gain reads

$$g = \frac{1}{k^2(\bar{n}+1)+\bar{n}}. \tag{16}$$

Like the coherent states, there exists nondeterministic amplification in the case $\bar{n} < 1$. We have plotted the intensity gain as a function of k with fixed $\bar{n}$ in Fig. 4.

It is straightforward to calculate the forms of the Wigner function for the input state

$$W_{\mathrm{th}}^{\mathrm{in}}(\beta) = \frac{2}{\pi(2\bar{n}+1)} \exp\left(\frac{-2|\beta|^2}{2\bar{n}+1}\right), \tag{17}$$

and for the output state

$$W_{\mathrm{th}}^{\mathrm{out}}(\beta) = \frac{k^2(\bar{n}+1)}{k^2(\bar{n}+1)+\bar{n}} \frac{2}{\pi} \exp(-2|\beta|^2) + \frac{\bar{n}}{k^2(\bar{n}+1)+\bar{n}} \frac{2}{\pi} (4|\beta|^2 - 1) \exp(-2|\beta|^2). \tag{18}$$

In Fig. 5, we plot the Wigner function of the thermal state and the generated state. The negative region is found for the output state.

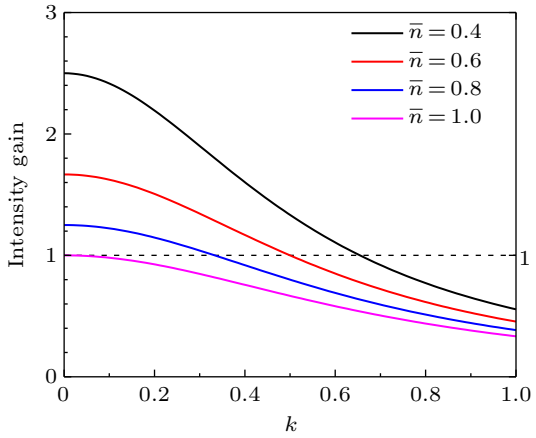


Fig. 4. Intensity gain for thermal states as a function of k for $\bar{n} = 0.4$, 0.6, 0.8, and 1.0. Similarly, the amplification occurs only for $\bar{n} < 1$.

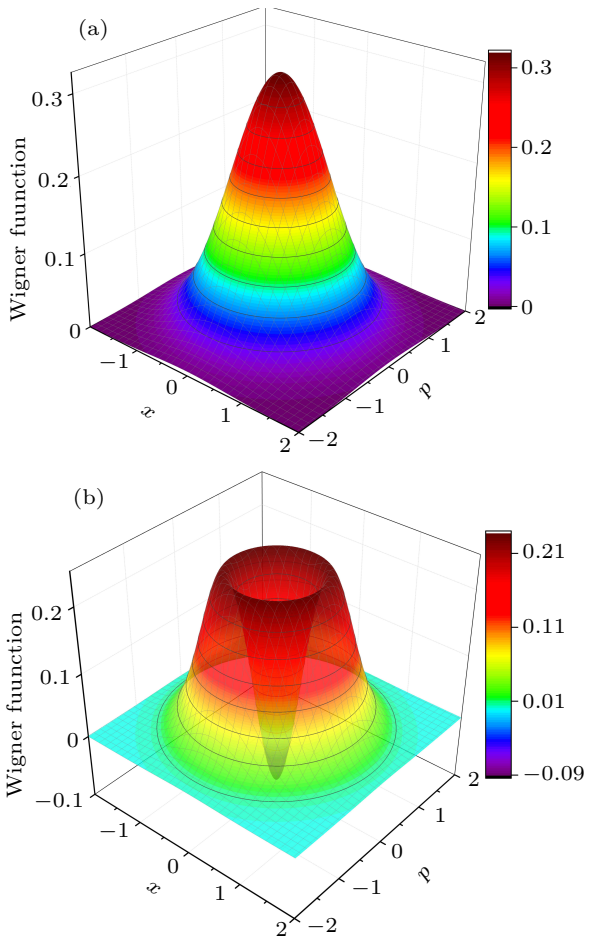


Fig. 5. Wigner function. (a) Wigner function of the input thermal state with $\bar{n} = 0.5$. (b) Wigner function of the generated state with $\bar{n} = 0.5$ and $k = 0.5$. It is obvious that the Wigner function of the generated state has a negative region which shows the non-classical properties.

4. Generalized QSD

In the original quantum scissors, a single photon $|1\rangle$ in mode a is injected into BS1; a single photon is detected in D_b and no count is registered in D_c. Then the output state in mode a, $|\psi\rangle_a^{\text{out}}$, is the truncation of the input state's Fock expansion to the first two terms, without higher number terms. Actually, this is an interesting extension of teleportation, since using BS1 we obtain the Einstein–Podolsky–Rosen (EPR) pair. However, if the source state lives in the Hilbert space of higher dimension than the EPR pair, all the higher dimensional terms present in the source will be "cut off" from the teleported ensemble. To put it simply, the higher number terms cannot appear at the output port because there will never be more than one photon in the original EPR state.

It is natural to consider whether we can extend the QSD to truncate other terms. Here, we show that this task is achievable and that we can truncate arbitrary terms of the input states. We first consider truncating two arbitrary terms of the input state, but the generalization is straightforward. In order to carry out that task, we assume that we already have a state

$$|\Psi\rangle = \frac{1}{\sqrt{2}}\left(|p\rangle_a|q\rangle_b + |q\rangle_a|p\rangle_b\right) \tag{19}$$

instead of state $|\psi\rangle = \frac{1}{\sqrt{2}}(|0\rangle_a|1\rangle_b + |1\rangle_a|0\rangle_b)$, generated by BS1. p and q are nonnegative integers and we assume $p < q$. Figure 1(b) shows a sketch of the generalized QSD. The state $|\Psi\rangle$ can be generated using linear optical elements.[38–41] After obtaining $|\Psi\rangle$, we inject the mode b into BS2 to interfere with the input state following the conditional detection, where $p+q$ photons are detected in D_b and no count is registered in D_c. Finally, we obtain the output state

$$\begin{aligned}\rho_a^{\text{out}} \propto\ & \rho_{pp}t_2^{2q}r_2^{2p}|p\rangle\langle p| + \rho_{pq}t_2^{q+p}(\mathrm{i}r_2)^p(-\mathrm{i}r_2)^q|p\rangle\langle q| \\ & + \rho_{qp}t_2^{q+p}(\mathrm{i}r_2)^q(-\mathrm{i}r_2)^p|q\rangle\langle p| + \rho_{qq}t_2^{2p}r_2^{2p}|q\rangle\langle q|. \end{aligned} \tag{20}$$

Choosing $t_2 = r_2 = \frac{1}{\sqrt{2}}$ and the proper phase shifter, we obtain the output state

$$\rho_a^{\text{out}} = \frac{1}{\mathscr{N}}\left[\rho_{pp}|p\rangle\langle p| + \rho_{pq}|p\rangle\langle q| + \rho_{qp}|q\rangle\langle p| + \rho_{qq}|q\rangle\langle q|\right], \tag{21}$$

where $\mathscr{N}$ is the normalization coefficient. This means that we have truncated the input states onto the subspace spanned by $|p\rangle$ and $|q\rangle$. If the input state has terms $|p\rangle$ and $|q\rangle$, then it will be truncated and teleported to the output port, which shows nonlocality.

For the more general situation, we need

$$|\Psi\rangle = \frac{1}{\mathscr{N}}\sum_{k\in\mathscr{D}}|k\rangle_a|m-k\rangle_b, \tag{22}$$

where $\mathscr{N}$ is the normalization coefficient, k and m are positive integers, and $\mathscr{D}$ is the set that we want to truncate. This device may have some important applications in high-dimensional QIP, where we may need to transform qudits to qubits in some computation tasks.

5. Conclusion

So far, we have not discussed the probability of success of the QSD. It depends on the input states and the coefficients of the beam splitters. For the original QSD, the success probability is

$$Pro = \rho_{00}(\sin\theta_1)^2(\cos\theta_2)^2 + \rho_{11}(\sin\theta_2)^2(\cos\theta_1)^2. \tag{23}$$

For the generalized QSD, the success probability is

$$Pro = \sum_{k\in\mathscr{D}}\rho_{kk}(\sin\theta_2)^{2k}(\cos\theta_2)^{2(m-k)}. \tag{24}$$

For large k, the success probability may be very small, and this is the disadvantage of a QSD. However, we can still obtain the optimal truncation with maximum success probability by choosing proper coefficients of the beam splitters.

In summary, QSDs are very useful technology to realize some processes that are forbidden with unitary operations. And a large class of nonclassical states can be generated by exploiting QSDs. We have presented a comprehensive study of the QSD and the generated states for different input states. We have analyzed the average photon number, intensity gain, and nonclassical properties of the generated states. We find that there exists nondeterministic amplification using a QSD under the condition that the average photon number of the input state is less than 1. We also show the nonclassical properties of the output states using the Wigner function. What is more, we generalize the QSD and it can truncate arbitrary terms of the input states. This generalized QSD may be useful in QIP.

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