Scheme for conditional generation of photon-added coherent state and optical entangled $W$ state

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We propose a simple scheme to generate an arbitrary photon-added coherent state of a travelling optical field by using only a set of degenerate parametric amplifiers and single-photon detectors. Particularly, when the single-photon-added coherent state (SPACS) is observed by following, e.g., the novel technique of Zavatta et al. (Science 306, 660 (2004)), we also obtain the generalized optical entangled $W$ state. Finally, a qualitative analysis of possible losses in our scheme is given.

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I INTRODUCTION

The generation and engineering of quantum state play a key role in current quantum information science. Over the past decade, various schemes of preparations of different kinds of nonclassical or entangled quantum states have been probed by using, e.g., the versatile nonlinear medium or the conditional measurement technique at the output ports of beam splitters (BS) [1]. For some elegant examples, Sanders proposed a scheme to produce an entangled coherent state by using a nonlinear Kerr medium in one arm of an interferometer [2]; Dakna et al. proposed a method relying on an alternate application of coherent displacement and photon adding or subtracting via conditional measurements on BS for the generation of several different types of nonclassical states [3]; Lvovsky et al. designed a scheme to prepare the highly nonclassical displaced Fock states of harmonic oscillators by acting upon Fock states with displacement operators [4]; Sanaka and Pegg et al. demonstrated the production of nonclassical Fock state of light or its finite superpositions by using the effective nonlinearity of BS or truncating a classical coherent state; and the three- or four-photon states also were achieved by using correlated photon pairs produced by parametric down conversion and single-photon detector (SPD) with the capability to discriminate photon-number state [5].

Recently, Agarwal and Tara formulated an interesting new nonclassical quantum state, i.e., the photon-added coherent state (PACS), which exhibits the intermediate properties between the classical coherent state and the quantum Fock state, and also gave a possible scheme to produce this state via cavity QED [6]. In their remarkable experiment, comprised of type-I beta-barium borate (BBO) crystal, SPD and balanced homodyne detector, Zavatta et al. obtained the novel single-photon-added coherent state (SPACS) and then firstly visualized the intriguing transition process from classical to purely

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quantum regimes \[ \lambda \]. In this paper, following these important pioneering works, we propose a simple but new scheme to produce an arbitrary PACS by combining an array of parametric amplifiers and corresponding SPDs. Particularly, the generalized optical \( N \)-qubit entangled \( W \) state, as an important resource for current quantum information science \[10, 11, 12, 13, 14\], also can be generated probabilistically in idler channels when we get the novel SPACS in output signal channel.

II THE THEORETICAL MODEL

The PACS \( |\alpha, m\rangle \), firstly introduced by Agarwal and Tara \[8\], is defined as

\[
|\alpha, m\rangle = \frac{\hat{a}^m \alpha}{|m!L_m(|\alpha|^2)|^{1/2}},
\]

where \( \hat{a}(\hat{a}^\dagger) \) is the photon annihilation (creation) operator, \( m \) is an integer, \( L_m(x) \) is the Laguerre polynomial of order \( m \) defined by \( L_m(x) = \sum_{n=0}^{\infty} \frac{(-1)^n x^n m^n}{(m+n)!} \). Obviously, when \( \alpha \to 0 \) or \( m \to 0 \), \( |\alpha, m\rangle \) reduces to the Fock or coherent state respectively. The novel properties of PACS, as an intermediate state between the quantum and classical limits, was studied in detail by Agarwal et al. \[8\]. Note that it is quite different from another intermediate state, i.e., the displaced Fock state: \( |DFS\rangle = D(\alpha)|n\rangle = \exp(\hat{a}^\dagger \alpha - \alpha^* \hat{a})|n\rangle \), which is generated by acting upon Fock states with displacement operators \[8\].

The PACS is, however, obtained via successive one-photon excitations on a classical coherent light.

Now we consider the parametric down-conversion process (type-I BBO crystal) as an optical parametric amplifier, in which one photon incident on the dielectric with \( \chi^2 \) nonlinearity breaks up into two new photons of lower frequencies. In the steady state, we always have \( \omega_0 = \omega_1 + \omega_2 \), with \( \omega_0 \) the pump frequency, and \( \omega_1, \omega_2 \) the signal and idler frequencies. Under the phase matching condition, the wave vectors of the pump, signal and idler photons are related by \( \vec{k}_0 = \vec{k}_1 + \vec{k}_2 \) (momentum conservation). The signal and idler photons appear simultaneously within the resolving time of the detectors and the associated electronics \[15\]. The Hamiltonian of this process can be written as:

\[
\hat{H} = \sum_{i=0}^{2} \hbar \omega_i (\hat{n}_i + \frac{1}{2}) + \hbar g [\hat{a}_1^\dagger \hat{a}_2^\dagger \hat{a}_0 + \hat{a}_1 \hat{a}_2 \hat{a}_0^\dagger],
\]

where the real mode coupling constant \( g \) contains the nonlinear susceptibility \( \chi^2 \). Besides, \( [\hat{n}_1 + \hat{n}_2 + 2 \hat{n}_0, \hat{H}] = 0 \), which indicates the conversion of one pump photon into one signal and one idler photon.

For simplicity, we suppose that signal and idler waves have the same polarizations and that their directions are well defined by apertures. Also the incident pump field is intense and the pump mode \( \hat{a}_0 \) can be treated classically as a field with complex amplitude \( \hat{a}_0 \to iV \) (see Fig.1). Then the Hamiltonian in the interaction picture is: \( \hat{H}_I = i\hbar g V [\hat{a}_1^\dagger \hat{a}_2^\dagger \hat{a}_0 - \hat{a}_1 \hat{a}_2] \) and, for an initial state: \( |\psi(0)\rangle = |\alpha\rangle_s |0\rangle_i \), after an interaction time \( t \), the output state evolves into

\[
|\psi(t)\rangle = \exp[-i\hat{H}_I t/\hbar]|\psi(0)\rangle = \exp[\lambda(\hat{a}_1^\dagger \hat{a}_2^\dagger \hat{a}_0^\dagger \hat{a}_1 \hat{a}_2 - \hat{a}_1 \hat{a}_2 \hat{a}_1^\dagger \hat{a}_2^\dagger)]|\psi(0)\rangle,
\]

where \( \lambda = Vgt \), as an effective interaction time. For short times \( t \) compared with average time interval between successive down-conversions, by expansion of the exponential we have (assuming \( \lambda \ll 1 \))

\[
|\psi(t)\rangle \approx |\alpha\rangle_s |0\rangle_i + \lambda |\alpha, 1\rangle_s |1\rangle_i + \frac{\lambda^2}{2} (\hat{a}_1^\dagger \hat{a}_2^\dagger \hat{a}_0^\dagger \hat{a}_1 \hat{a}_2 - \hat{a}_1 \hat{a}_2 \hat{a}_1^\dagger \hat{a}_2^\dagger)|\alpha\rangle_s |0\rangle_i.
\]
Since $\lambda \ll 1$, we can select the first two terms as the output state, i.e., $|\psi(t)\rangle \approx |\alpha\rangle_s|0\rangle_i + \lambda|\alpha, 1\rangle_s|1\rangle_i$.

So far, the output signal and idler lights are entangled with each other in the frequency domain $^{15}$. From the above we can see that the signal channel mostly contains the original coherent state, except for the few cases when single photon is detected in output idler channel. Thereby these rare events can stimulate emissions of one photon into the coherent state, which then generates the novel SPACS in the signal channel with a success probability being proportional to $|\lambda|^2(1 + |\alpha|^2)$.

![Diagram](image)

**FIG. 1:** The process of single-photon excitation of the nonlinear crystal in the signal coherent channel. The pump light is the classical coherent light of high intensity $|V|^2$, and the idler input channel is vacuum. SPD is the single photon detector placed in the idler channel. When SPD detects one photon, the coherent state will be excited by the entangled photon-pairs in the signal channel.

Note that, recently, Zavatta et al. first experimentally created the SPACS and then visualized the novel quantum-classical transition process via the technique of single-photon detection and balanced homodyne detection $^{9, 16}$. Here we select the one-photon excitation term to avoid higher-order ones which cannot be discriminated by the SPD in the elegant experiment of Zavatta et al. $^{16}$.

### III PREPARATION OF THE DESIRED STATES

Turning to Fig.2, we combine two identical optical parametric amplifiers by assuming the same low-gain regime, i.e., $g_1 = g_2 = g$ and the same strong classical pumps, i.e., $iV_1 = iV_2 = iV$. Therefore, for an initial input state: $|\psi(0)\rangle = |\alpha\rangle_s|0\rangle_i|0\rangle_s|0\rangle_i$, after some evolution time $t$, the output state becomes

$$
|\psi(t)\rangle = \exp[-i\hat{H}_{12}t_2/\hbar]exp[-i\hat{H}_{11}t_1/\hbar]|\psi(0)\rangle
$$

$$
\approx |\alpha\rangle_s^2|0\rangle_i|0\rangle_s + \lambda_1|\alpha, 1\rangle_s|1\rangle_i|0\rangle_s + \lambda_2|\alpha, 1\rangle_s|0\rangle_i|1\rangle_s + \lambda_1\lambda_2|\alpha, 2\rangle_s|1\rangle_i|1\rangle_s.
$$

(5)

Here, $\lambda_j = Vgt_j$ $(j = 1, 2)$, denoting different effective time for different crystals. For this, there are three cases based on the results of SPDs in idler channels:

Case 1: Neither of two detectors catches one photon. The initial input coherent state just appears in output signal channel most of the time.

Case 2: One of the detectors catches one photon. The initial input coherent state just appears in output signal channel in several cases with a success probability being proportional to: $(|\lambda_1|^2 + |\lambda_2|^2)(1 + |\alpha|^2)$.
The initial input state of the three-body system:

FIG. 2: The scheme to generate pump lights. Given the coherent light in signal channel and vacuum in two idler channels input, the desired states will be generated with different probability on conditional detections of SPD1 and SPD2.

In short, the states $|\alpha, 1\rangle$, $|\alpha, 2\rangle$ can be probabilistically prepared via the conditional SPDs technique.

Similarly we can combine three identical optical parametric amplifiers as in Fig.3, and now, for an initial input state of the three-body system: $|\psi(0)\rangle = |\alpha\rangle_{s10}|0\rangle_{i10}|0\rangle_{i20}|0\rangle_{i30}$, after an interaction time $t$, the output state of the system is written as

$$|\psi(t)\rangle = \exp[-i\hat{H}_{t3}t_3/\hbar]\exp[-i\hat{H}_{t2}t_2/\hbar]\exp[-i\hat{H}_{t1}t_1/\hbar]|\psi(0)\rangle$$

$$\approx |\alpha\rangle_{s3}|0\rangle_{i1}|0\rangle_{i2}|0\rangle_{i3} + \lambda_1|\alpha, 1\rangle_{s3}|1\rangle_{i1}|0\rangle_{i2}|0\rangle_{i3} + \lambda_2|\alpha, 1\rangle_{s3}|0\rangle_{i1}|1\rangle_{i2}|0\rangle_{i3} + \lambda_3|\alpha, 1\rangle_{s3}|0\rangle_{i1}|0\rangle_{i2}|1\rangle_{i3}$$

$$+ \lambda_1\lambda_2|\alpha, 2\rangle_{s3}|1\rangle_{i1}|1\rangle_{i2}|0\rangle_{i3} + \lambda_2\lambda_3|\alpha, 2\rangle_{s3}|0\rangle_{i1}|1\rangle_{i2}|1\rangle_{i3} + \lambda_1\lambda_3|\alpha, 2\rangle_{s3}|1\rangle_{i1}|0\rangle_{i2}|1\rangle_{i3}$$

$$+ \lambda_1\lambda_2\lambda_3|\alpha, 3\rangle_{s3}|1\rangle_{i1}|1\rangle_{i2}|1\rangle_{i3},$$

(6)

in which, $\lambda_j = V g t_j (j = 1, 2, 3)$, denoting different evolution times for different nonlinear crystals.

From the above output state of the three-body system, we can probabilistically get the PACS in output signal channel on conditional detections of the single-photon in three idler channels, i.e.,

Case 1: Neither of three SPDs detects one photon. Again we get a coherent output signal $|\alpha\rangle_{s3}$.

Case 2: When one SPD detects one photon and the other two cannot. The SPACS can be generated in output signal channel with a success probability being proportional to: $|\lambda_1\lambda_2|^2L_2(-|\alpha|^2)$.

Case 3: When two SPDs detect one photon simultaneously and the third cannot. Now we get the DPACS $|\alpha, 2\rangle_{s3}$ in output signal channel but with a success probability being proportional to: $|\lambda_1\lambda_2|^2 + |\lambda_2\lambda_3|^2 + |\lambda_1\lambda_3|^2)2!L_2(-|\alpha|^2)$.

Case 4: When the three SPDs all detect one photon instantaneously. There will be a triple-photon-added coherent state (TPACS) $|\alpha, 3\rangle_{s3}$ appearing in output signal channel with a success probability being proportional to: $|\lambda_1\lambda_2\lambda_3|^2L_3(-|\alpha|^2)$.

We should note that the most interesting thing comes when we get the novel state SPACS in output
FIG. 3: The scheme to generate $|\alpha, m\rangle$ by combining a series of same nonlinear crystals with all the pump lights equal. Given the coherent light in signal channel and vacuum in all of the idler channels input, arbitrary PACS will be generated with different probability in principle on conditional detections by the corresponding series of SPDs. In addition, the multi-qubit $W$ state will be produced probabilistically in output idler channels on conditional generation of SPACS in output signal channel.

signal channel, i.e., the final output state will be the following entangled state:

$$\lambda_1 |1\rangle_i |0\rangle_{i2} |0\rangle_{i3} + \lambda_2 |0\rangle_{i1} |1\rangle_{i2} |0\rangle_{i3} + \lambda_3 |0\rangle_{i1} |0\rangle_{i2} |1\rangle_{i3},$$  \hspace{1cm} (7)

for the equal effective time, i.e., $\lambda_1 = \lambda_2 = \lambda_3 = \lambda$, this state can be written as

$$|\psi(t)\rangle_W^3 = \lambda (|1\rangle |0\rangle |0\rangle + |0\rangle |1\rangle |0\rangle + |0\rangle |0\rangle |1\rangle),$$  \hspace{1cm} (8)

with the success probability $P_{\text{suc}}^W \propto |\lambda|^2 (1 + |\alpha|^2)$. Obviously, if we choose a proper effective interaction time, i.e., $\lambda = \frac{1}{\sqrt{3}}$, we can obtain an interesting entangled state which takes the same form as the familiar three-qubit entangled $W$ state: $|W\rangle = \frac{1}{\sqrt{3}}(|100\rangle + |010\rangle + |001\rangle)$.

The proposed generation scheme can be used to the case of $|\alpha, m\rangle$ and $N$-qubit entanglement in a straightforward way. The scheme is as Figure 3 shows with a series of such combinations. Assuming a system composed of $N$ same pump lights and $N$ same amplifiers with the input signal channel coherent light and the rest idler channels vacuum light, the input initial state reads:

$$|\psi(0)\rangle = |\alpha\rangle_{s10} |0\rangle_{i10} |0\rangle_{i20} \ldots |0\rangle_{iN0}.$$  \hspace{1cm} (9)

After a series of Hamiltonian interaction, the output state of the $N$-body system reads:

$$|\psi(t)\rangle = \prod_{j=1,N} \exp[-i\hat{H}_{1j}t_j/\hbar]|\psi(0)\rangle,$$  \hspace{1cm} (10)

where

$$\hat{H}_{1j} = i\hbar gV[\hat{a}_j^{\dagger}\hat{a}_j^{\dagger} - \hat{a}_{1j}\hat{a}_{2j}].$$  \hspace{1cm} (11)

After an evolution time $t$, the output entangled state of the $N$-body system can be got from the Eq.(10). Based on different conditional detections of SPDs in the idler channels, arbitrary $|\alpha, m\rangle$ can
be generated with the success probability being proportional to $N|\lambda|^2m!L_m(-|\alpha|^2)$ with $m < N$, $t_j = \frac{1}{\lambda}$, in which $t_j$ is the real interaction time with each medium.

At the same time, the $N$-qubit $W$ state in the idler channels will be produced on conditional generation of the SPACS in the output signal channel. When we choose $\lambda = \frac{1}{\sqrt{N}}$, we can get:

$$|\psi(t)\rangle_W^N = \frac{1}{\sqrt{N}}(10\ldots0_N - 1 + |010\ldots0_N - 2 + \cdots + |0\ldots01_N - 11\rangle).$$  \hspace{1cm} (12)

For simplicity, we rewrite it as

$$|\psi(t)\rangle_W^N = \frac{1}{\sqrt{N}}|N - 1, 1\rangle,$$  \hspace{1cm} (13)

where $|N - 1, 1\rangle$ denotes all the totally symmetric states involving $N - 1$ zeros and 1 one. It follows that, the success probability of $N$-qubit $W$ state is: $P_{\text{su}}^W \propto |\lambda|^2(1 + |\alpha|^2)$.

**IV DISCUSSIONS**

We propose a simple scheme to generate an arbitrary PACS, at the same time, the optical entangled $W$ state can be created on the detection of the SPACS in output signal channel. In addition, if the TPACS $|\alpha, 2\rangle$ can be efficiently detected, one also can get the entangled $W$ state with a quadratic damping probability. The three-qubit $W$ state, as one of the two inequivalent classes of genuine tripartite entangled state (i.e., the GHZ \cite{17, 18} and the $W$ states \cite{19, 20}), shows perfect correlations and violates a three-partite Mermin inequality, though its violation is weaker than that for the GHZ state \cite{21}. The most interesting properties of $W$ state is that if one particle is measured in basis of $|0\rangle, |1\rangle$, then the state of remained two particles is either in a maximally entangled state or in a product state, which has important applications in current quantum information science.

Differing from the scheme of generating three-photon polarization-entangled $W$ state proposed by Eibl \textit{et al.} based on polarization measurements and type-II spontaneous parametric down-conversion \cite{21}, our scheme needs the technique of SPDs and the SPACS reconstructions. Therefore, if the efficiency of the SPDs and the reconstruction accuracy of SPACS is high enough, the optical entangled $W$ state can be generated efficiently. In the elegant experiment of Zavatta \textit{et al.} \cite{16}, a high-frequency time-resolved balanced homodyne detection was used to reconstruct the Wigner function of SPACS with an overall efficiency of 60%. Hence we can use this homodyne technique to enhance the efficiency of $W$ state generation. Besides, since the $W$ state can be created whenever one SPD catches one photon, the SPDs with high quantum efficiency should be used to get a high generation rate.

It should be emphasized that the probability of $W$ state generation is independent of crystal numbers $N$, and is determined only by the input seed coherent light and the effective interaction time. And higher generation rate can be got by, at least theoretically, enhancing the intensity of pump light and input coherent light and enlarging the couplings with the medium. However, there are always some realistic problems related to the imperfection of the elements itself which affects the generation efficiency and the fidelity of the desired output state, and many authors analyzed the losses of such optical elements as well as the suggestions of improving the efficiency and fidelity \cite{22, 23}.

One of the difficulties consists in the requirement of high quantum efficiency of photon-counting detectors. The practical limitations of the detectors including the nonzero dark count rates causing
false alarm even without a photon in signal mode, the dead time, during which detectors cannot respond to the incoming photons, may result in the non-unit quantum efficiency. In practice, we should choose the detector which bears lower dark count rate and shorter resolution time on the premise of same efficiency. Besides, taking into account of the detailed analysis about the dependence of fidelity on the coherent light intensity \[ \text{[22]} \], we can get higher fidelity by lowering the intensity of the input coherent light. The other difficulty comes from the non-ideal BBO crystals. Because the photon may have finite bandwidth due to the finite crystal size and the spatial location of the idler-signal photons in the radiation cone of the crystal output, narrow spatial and frequency filters should be placed in the idler mode before the detector. Since the mode-locked laser, used as the pump of BBO crystal in Zavatta et al. experiment \[ \text{[9, 10]} \], can provide a quadratic conversion rate higher than 50% in market, we may select it to enhance the efficiency.

Since there are other factors causing losses in practice, i.e., the damping associated with the cascaded system due to the environment \[ \text{[24]} \], etc., the problem is more complex and therefore the successful probability of the desired states is limited. However, as it is known to all that the generation of multi-qubit entanglement is difficult in practice for a long time \[ \text{[25]} \], our scheme will be experimentally challenging and promising with the development of SPD and homodyne detection techniques.

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