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An optical scheme for conditional generation of W state and photon-added coherent state*

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We propose a simple scheme to generate an arbitrary photon-added coherent state of a travelling optical field by combining an array of degenerate parametric amplifiers and corresponding single-photon detectors. Particularly, when the single-photon-added coherent state is observed by developing the novel technique of Zavatta *et al* (2004 Science **306** 660), we can simultaneously obtain the generalized N-qubit W state.

Keywords: photon-added coherent state, W state, parametric down-conversion
PACC: 0367, 4250, 0365

1. Introduction

The generation and engineering of quantum state play a key role in current quantum information science. Over the past decade, various schemes for preparation 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] In 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 types of nonclassical states.[3] Lvovsky and Babichev designed a scheme to prepare the highly nonclassical displaced Fock states of harmonic oscillators by acting upon Fock states with displacement operators.[4] Sanaka[5] and Pegg *et al*[6] 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 of discriminating photon-number state.[7]

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 quantum electrodynamics (QED).[8] In the 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 first visualized the intriguing transition process from classical to purely quantum regimes.[9] 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 op-

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tical N-qubit entangled W state, as an important resource for current quantum information science,[10−14] also can be generated probabilistically in idler channels when we obtain the novel SPACS in output signal channel.

2. Theoretical model

The PACS, first introduced by Agarwal and Tara,[8] is defined as

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

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

$$L_m(x) = \sum_{n=0}^{m} \frac{(-1)^n x^n m!}{(n!)^2 (m-n)!}.$$

Obviously, when $\alpha \to 0$ ($m \to 0$), $|\alpha, m\rangle$ reduces to the Fock (coherent) state. The novel properties of PACS, as an intermediate state between the quantum and classical limits, was studied in detail by Agarwal and Tara.[8] Note that it is quite different from another intermediate state, i.e., the displaced Fock state: $|\mathrm{DFS}\rangle = D(\alpha)|n\rangle = \exp(\hat{a}^\dagger \alpha - \hat{a}\alpha^*)|n\rangle$, which is generated by acting upon Fock states with displacement operators.[4] 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 χ^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 ω_0 the pump frequency, and ω_1, ω_2 the signal and idler frequencies. Under the phase matching condition, the wave vectors of the pump, signal and idler photons are related by $\boldsymbol{k}_0 = \boldsymbol{k}_1 + \boldsymbol{k}_2$ (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

$$\hat{H} = \sum_{i=0}^{2} \hbar\omega_{\mathrm{i}} \Big(\hat{n}_{\mathrm{i}} + \frac{1}{2}\Big) + \hbar g[\hat{a}_1^\dagger \hat{a}_2^\dagger \hat{a}_0 + \hat{a}_1 \hat{a}_2 \hat{a}_0^\dagger], \tag{2}$$

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

For simplicity, we suppose that the signal and idler waves have same polarizations and 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 $\hat{a}_0 \to \mathrm{i}V$ (see Fig.1). Then the Hamiltonian in the interaction picture is: $\hat{H}_{\mathrm{I}} = \mathrm{i}\hbar g V[\hat{a}_1^\dagger \hat{a}_2^\dagger - \hat{a}_1 \hat{a}_2]$. Given an initial state $|\psi(0)\rangle = |\alpha\rangle_{\mathrm{s}}|0\rangle_{\mathrm{i}}$, the output state evolves into

$$\begin{aligned} |\psi(t)\rangle &= \exp[-\mathrm{i}\hat{H}_{\mathrm{I}} t/\hbar]|\psi(0)\rangle \\ &= \exp[\lambda(\hat{a}_1^\dagger \hat{a}_2^\dagger - \hat{a}_1 \hat{a}_2)]|\psi(0)\rangle, \end{aligned} \tag{3}$$

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

$$\begin{aligned} |\psi(t)\rangle \approx\ & |\alpha\rangle_{\mathrm{s}}|0\rangle_{\mathrm{i}} + \lambda|\alpha, 1\rangle_{\mathrm{s}}|1\rangle_{\mathrm{i}} \\ & + \frac{\lambda^2}{2}(\hat{a}_1^\dagger \hat{a}_2^\dagger \hat{a}_1^\dagger \hat{a}_2^\dagger - \hat{a}_1 \hat{a}_2 \hat{a}_1^\dagger \hat{a}_2^\dagger)|\alpha\rangle_{\mathrm{s}}|0\rangle_{\mathrm{i}}\,. \end{aligned} \tag{4}$$

Since $\lambda \ll 1$, we can select the first two terms as the output state, i.e., $|\psi(t)\rangle \approx |\alpha\rangle_{\mathrm{s}}|0\rangle_{\mathrm{i}} + \lambda|\alpha, 1\rangle_{\mathrm{s}}|1\rangle_{\mathrm{i}}$.

So far, the output signal and idler light 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 the output idler channel. Thereby these rare events can stimulate emissions of one photon into the coherent state, which generates the novel SPACS in the signal channel with a success probability being proportional to $|\lambda|^2(1 + |\alpha|^2)$.

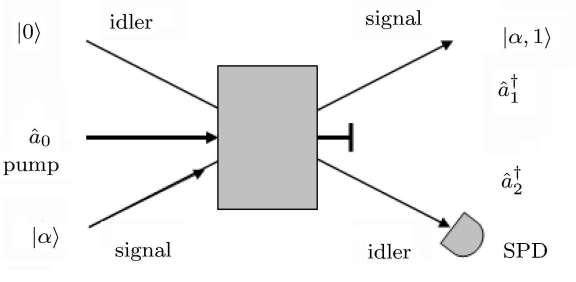


Fig.1. The process of single-photon excitation of the nonlinear crystal in the signal coherent channel. The pump light is the classical coherent light of high intensity $|V|^2$, and the idler input channel is vacuum. When SPD detects one photon, the coherent state will be excited by the entangled photon-pairs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

Note that, recently, Zavatta *et al* first experimentally created the SPACS and then visualized the novel quantum-to-classical transition 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]

3. Preparation of the desired states

Turning to Fig.2, we combine two identical amplifiers by assuming the same low-gain regime, i.e. $g_1 = g_2 = g$ and the same strong classical pumps, i.e. $\mathrm{i}V_1 = \mathrm{i}V_2 = \mathrm{i}V$. Given an initial input state: $|\psi(0)\rangle = |\alpha\rangle_{\mathrm{s}10}|0\rangle_{\mathrm{i}10}|0\rangle_{\mathrm{i}20}$, the output state is

$$\begin{aligned}|\psi(t)\rangle &= \exp[-\mathrm{i}\hat{H}_{\mathrm{I}2}t_2/\hbar]\exp[-\mathrm{i}\hat{H}_{\mathrm{I}1}t_1/\hbar]|\psi(0)\rangle \\ &\approx |\alpha\rangle_{\mathrm{s}2}|0\rangle_{\mathrm{i}1}|0\rangle_{\mathrm{i}2} + \lambda_1|\alpha,1\rangle_{\mathrm{s}2}|1\rangle_{\mathrm{i}1}|0\rangle_{\mathrm{i}2} \\ &\quad + \lambda_2|\alpha,1\rangle_{\mathrm{s}2}|0\rangle_{\mathrm{i}1}|1\rangle_{\mathrm{i}2} \\ &\quad + \lambda_1\lambda_2|\alpha,2\rangle_{\mathrm{s}2}|1\rangle_{\mathrm{i}1}|1\rangle_{\mathrm{i}2}\,. \end{aligned} \tag{5}$$

Here, $\lambda_j = Vgt_j$ $(j = 1, 2)$ denotes different effective time in different crystals. There are three cases based on the results of SPDs in idler channels of the two-body system:

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

Case 2 One of the detectors catches one photon and the other does not. The SPACS can be created in output signal channel in several cases, with a success probability being proportional to: $(|\lambda_1|^2 + |\lambda_2|^2)(1 + |\alpha|^2)$.

Case 3 Both the detectors detect one photon simultaneously. There will be a double-photon-added coherent state (DPACS) $|\alpha, 2\rangle$ in the output signal channel in the quite rare cases, with a success probability being proportional to: $|\lambda_1\lambda_2|^2 2! L_2(-|\alpha|^2)$.

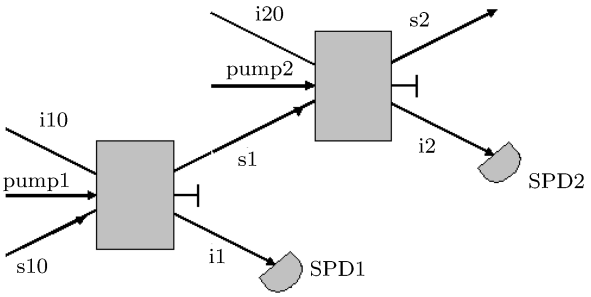


Fig.2. The scheme to generate $|\alpha, 1\rangle$ and $|\alpha, 2\rangle$ by combining two same nonlinear crystals with two same pump lights. Considering the coherent light in signal channel and vacuum in two idler channels input, the desired states will be generated with different probability on conditional 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 crystals as shown in Fig.3.

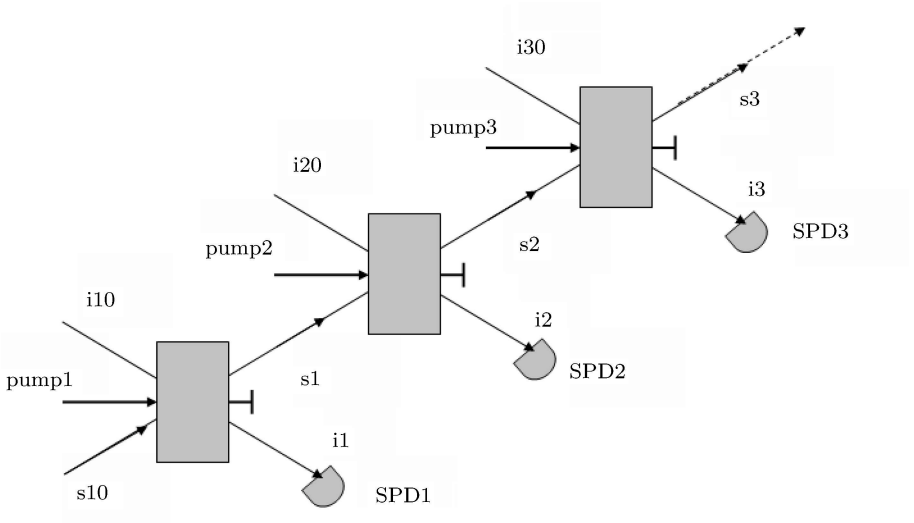


Fig.3. The scheme to generate $|\alpha, m\rangle$ by combining a series of same nonlinear crystals pumped with identical pump lights. With input of the coherent light in signal channel and vacuum in all of the idler channels, arbitrary PACS will be generated with different probabilities in principle based on conditional detections by the corresponding series of SPDs. At the same time, the multi-qubit W state will be produced probabilistically in the output idler channels based on conditional generation of SPACS in the output signal channel.

For an initial input state of the three-body system we have $|\psi(0)\rangle = |\alpha\rangle_{\rm s10}|0\rangle_{\rm i10}|0\rangle_{\rm i20}|0\rangle_{\rm i30}$, and the evolution of the output state is written as

$$\begin{aligned}|\psi(t)\rangle =&\exp[-{\rm i}\hat{H}_{\rm I3}t_3/\hbar]\exp[-{\rm i}\hat{H}_{\rm I2}t_2/\hbar]\exp[-{\rm i}\hat{H}_{\rm I1}t_1/\hbar]|\psi(0)\rangle\\ \approx& |\alpha\rangle_{\rm s3}|0\rangle_{\rm i1}|0\rangle_{\rm i2}|0\rangle_{\rm i3} + \lambda_1|\alpha,1\rangle_{\rm s3}|1\rangle_{\rm i1}|0\rangle_{\rm i2}|0\rangle_{\rm i3} + \lambda_2|\alpha,1\rangle_{\rm s3}|0\rangle_{\rm i1}|1\rangle_{\rm i2}|0\rangle_{\rm i3}\\ &+\lambda_3|\alpha,1\rangle_{\rm s3}|0\rangle_{\rm i1}|0\rangle_{\rm i2}|1\rangle_{\rm i3} + \lambda_1\lambda_2|\alpha,2\rangle_{\rm s3}|1\rangle_{\rm i1}|1\rangle_{\rm i2}|0\rangle_{\rm i3} + \lambda_2\lambda_3|\alpha,2\rangle_{\rm s3}|0\rangle_{\rm i1}|1\rangle_{\rm i2}|1\rangle_{\rm i3}\\ &+\lambda_1\lambda_3|\alpha,2\rangle_{\rm s3}|1\rangle_{\rm i1}|0\rangle_{\rm i2}|1\rangle_{\rm i3} + \lambda_1\lambda_2\lambda_3|\alpha,3\rangle_{\rm s3}|1\rangle_{\rm i1}|1\rangle_{\rm i2}|1\rangle_{\rm i3}. \end{aligned} \tag{6}$$

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

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

Case 2 One SPD can detect one photon and the other two cannot. The SPACS can be generated in the output signal channel with a success probability proportional to $(|\lambda_1|^2 + |\lambda_2|^2 + |\lambda_3|^2)(1 + |\alpha|^2)$.

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

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

We should note that the most interesting thing appears when we obtain the novel state SPACS in the output signal channel, i.e., the final output state will be the following entangled state: $\lambda_1|1\rangle_{\rm i1}|0\rangle_{\rm i2}|0\rangle_{\rm i3} + \lambda_2|0\rangle_{\rm i1}|1\rangle_{\rm i2}|0\rangle_{\rm i3} + \lambda_3|0\rangle_{\rm i1}|0\rangle_{\rm i2}|1\rangle_{\rm i3}$. Given the equal effective time, i.e., $\lambda_1 = \lambda_2 = \lambda_3 = \lambda$, this state can be written as

$$|\psi(t)\rangle_W^3 = \lambda(|1\rangle|0\rangle|0\rangle + |0\rangle|1\rangle|0\rangle + |0\rangle|0\rangle|1\rangle) \tag{7}$$

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

The above proposed generation scheme can be used in the case of $|\alpha, m\rangle$ and N-qubit entanglement in a straightforward way as shown in Fig.3 with a series of such combinations. Assuming a system is composed of N same pump lights and N same amplifiers with the input signal channel for coherent light and the rest idler channels for vacuum light, and the input initial state is $|\psi(0)\rangle = |\alpha\rangle_{\rm s10}|0\rangle_{\rm i10}|0\rangle_{\rm i20}\ldots|0\rangle_{{\rm i}N0}$. After a series of Hamiltonian interaction, the output state of the N-body system reads

$$|\psi(t)\rangle = \prod_{j=1,N} \exp[-{\rm i}\hat{H}_{{\rm I}j}t_j/\hbar]|\psi(0)\rangle \tag{8}$$

with $\hat{H}_{{\rm I}j} = {\rm i}\hbar g V[\hat{a}_{1j}^\dagger\hat{a}_{2j}^\dagger - \hat{a}_{1j}\hat{a}_{2j}]$.

After an evolution time t, the output entangled state of the N-body system can be obtain from Eq.(8). Based on different conditional detections of SPDs, an arbitrary $|\alpha, m\rangle$ can be generated with a success probability proportional to $N|\lambda^m|^2 m!L_m(-|\alpha|^2)$ with $m < N$.

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

$$\begin{aligned}|\psi(t)\rangle_W^N = \frac{1}{\sqrt{N}}(&|1\underbrace{00\cdots0}_{N-1}\rangle + |01\underbrace{00\cdots0}_{N-2}\rangle\\ &+\cdots+|\underbrace{00\cdots0}_{N-1}1\rangle). \end{aligned} \tag{9}$$

For simplicity, we rewrite it as

$$|\psi(t)\rangle_W^N = \frac{1}{\sqrt{N}}|N-1,1\rangle, \tag{10}$$

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 $P_{\rm suc}^W \propto |\lambda|^2(1 + |\alpha|^2)$.

4. Discussion

In this paper, we propose a simple scheme to generate an arbitrary PACS, at the same time, the N-qubit W state can be created based on the detection of the SPACS in output signal channel. The

three-qubit W state, as one of the two inequivalent classes of genuine tripartite entangled states (i.e., the GHZ[17,18] and the W states,[19,20]) shows perfect correlations and violates three-partite Mermin inequality, though its violation is weaker than that for the GHZ state.[21] The most interesting property of W state is that if one particle is measured on the basis of $|0\rangle$,$|1\rangle$, then the state of the remaining two particles is either in a maximally entangled state or in a product state, which has important applications in current quantum information science.

Different from the scheme of generating three-photon polarization-entangled W state proposed by Eibl *et al* based on polarization measurements and type-II spontaneous parametric down-conversion,[21] our scheme needs the type-I parametric down-conversion, the SPDs and the SPACS reconstructions. Therefore, if the efficiency of the SPDs and the reconstruction accuracy of SPACS is high enough, the W state can be generated efficiently. In the elegant experiment of Zavatta *et al*[16] a high-frequency time-resolved balanced homodyne detection was used to reconstruct the Wigner function of SPACS with an overall efficiency of 60%. Therefore 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 are preferable.

Though there are many other simple methods to generate W state, this is the first time to simultaneously optically generate both the PACS and the W state based on conditional detections. Furthermore, it should be emphasized that the probability of W state generation is determined only by the input seed coherent light and the effective interaction time. And higher generation rate can be obtained by, at least theoretically, enhancing the intensity of pump and input coherent lights and strengthening the couplings with the medium. However, there are always some realistic problems related to the imperfection of the elements, which affects the generation efficiency and the fidelity of the desired output state, and many authors have analysed the losses of such optical elements as well as given the suggestions of improving the efficiency and fidelity.[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, and the dead time, during which detectors cannot respond to the incoming photons, may lead to 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,[22] we may gain higher fidelity by lowering the intensity of the input coherent light. The other difficulty comes from the non-ideal BBO crystals. Because photons 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 there are other factors causing losses, e.g., the damping associated with the cascade system due to the environment,[24] the successful probability of the desired states is limited. However, as it is well known that the generation of multi-qubit entanglement is difficult in practice for a long time,[25] our scheme will be experimentally challenging and promising with the development of SPD and homodyne detection techniques.

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