Generation of continuous-variable quadripartite square cluster state and its entanglement improvement via quantum feedback

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Abstract: In this paper, we investigate the generation of continuous-variable quadripartite square cluster state of optical fields and discuss the enhancement of the multipartite entanglement of the cluster state via quantum feedback. We show that the quadripartite square cluster state can be generated via concurrent OPO processes and the loss of the cavity will degrade the quantum correlations of the cluster state. By introducing appropriate feedback loops, we find that the entanglement and the purity of the cluster state can be improved significantly.

Keywords: quantum optics; continuous variable cluster state; feedback

0 Introduction

Entanglement, as one of the most striking features of quantum mechanics, has become an essential resource for quantum information processing [1]. Now, it has been proven that continuous variable (CV) entanglement of optical fields is very important for performing CV quantum communication and computation [2], due to the fact that the CV optical entanglement can be easily generated and detected relatively. Recently, CV cluster states [3], as a kind of CV multipartite entangled states, have attracted much research interest. It was predicted that the quantum correlations exhibited the CV cluster state are robust against the noisy environment, compared to the CV Greenberger-Horne-Zeilinger (GHZ) state [4]. Moreover, it has also been shown that CV cluster states can be utilized to building the so-called one-way quantum computation which is a promising form of quantum computing [5] and the CV-cluster-states-based one-way quantum computation can perform universal quantum computing provided that at least one non-Gaussian detection operation is used [6]. Recently, several proposals have been put forward for generating CV clusters states [7-13]. For example, Su *et al.* [13] experimentally produced the CV quadripartite cluster state with squeezed beams of light with beam splitters. However, due to the effects of noisy environment, the multipartite entanglement contained in the cluster states are unavoidably decreased, which severely limits the related applications of the CV cluster states in quantum processing. Therefore, how to suppress the decoherence and enhance the multipartite entanglement of the CV cluster states becomes a practical research issue.

Nowadays, quantum feedback has become a quite efficient way to control quantum systems [14-18]. By using the theory of quantum-limited feedback introduced by Wiseman and Milburn [19], controlling noise in an open system on a quantum level has been considered extensively [20-25]. Typically, Wiseman and Milburn showed that the homodyne-mediated feedback can enhance intracavity squeezing of a degenerate OPO. It was also shown that the CV entanglement generated via a non-degenerate OPO can be enhanced significantly by adding an appropriate feedback loops. Experimentally, the feedback-enhanced squeezing from OPO has been realized very recently [26].

In this paper, we investigate the generation of CV quadripartite square cluster state of optical

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fields and discuss the feedback-induced enhancement of the multipartite entanglement of the cluster state. We show that the quadripartite square cluster state can be generated via concurrent OPO processes. It is found that the loss of the cavity will degrade the multipartite entanglement of the cluster state. By introducing appropriate feedback loops, we find that the multipartite entanglement and the purity of the quadripartite cluster state can be improved significantly. This paper is arranged as follows: in Section 2, the generation of the quadripartite square cluster state and its properties of the quantum correlations are investigated. In Section 3, we discuss the enhancement of the entanglement and purity of the cluster state by quantum feedback. In the last Section 4, we give our main summery.

1 Generation of quadripartite square cluster state

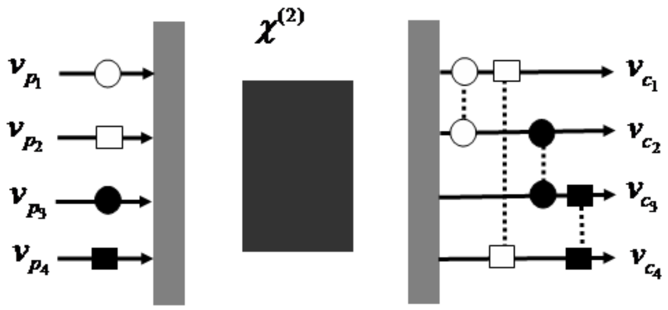

Fig. 1 The schematic plot of a $\chi^{(2)}$ nonlinear crystal inside a driven optical cavity for the generation of the CV quadripartite square cluster state. The frequencies of the pumping lasers are denoted by v_{p_j} $(j=1,2,3,4)$ and the four cavity modes with frequencies v_{c_j} can be generated via concurrent OPO processes in the cavity. The squares and circles stand for the different frequencies of the cavity modes.

As shown in Fig.1, we consider an optical cavity which contains a $\chi^{(2)}$ nonlinear crystal and the optical cavity is driven by the four pumping lasers with frequencies v_{p_j} and initial phases θ_j. Then, the four cavity modes at frequencies v_{c_j} can be generated via the concurrent NOPO processes occurring in the crystal. By adjusting the frequencies of the lasers to meet $v_{p_1}=v_{c_1}+v_{c_2}$, $v_{p_2}=v_{c_1}+v_{c_4}$, $v_{p_3}=v_{c_2}+v_{c_3}$, $v_{p_4}=v_{c_3}+v_{c_4}$ and choosing the initial phases as $\theta_1=-\pi/2$, $\theta_2=0$, $\theta_3=\pi$, $\theta_4=\pi/2$, the Hamiltonian of the system is given by

$$H_c=\alpha i(-c_1c_2-ic_1c_4+ic_2c_3+c_3c_4)+H.c., \tag{1}$$

where the annihilation operators c_j denotes the cavity modes and the coupling strength $\alpha=\alpha_p\chi^{(2)}$ with α_p being the identical amplitudes of the pumping fields. By taking into account the dissipation of the cavity, the master equation of the cavity system is given by

$$\frac{d}{dt}\rho=-i\left[H_c,\rho\right]+\left(L_{c_1}+L_{c_2}+L_{c_3}+L_{c_4}\right)\rho, \tag{2}$$

where the damping term

$$L_{c_j}\rho=\frac{\kappa}{2}\left(2c_j\rho c_j^{\dagger}-c_j^{\dagger}c_j\rho-\rho c_j^{\dagger}c_j\right), \tag{3}$$

with the damping rate κ.

With the above master equation, one can determine the evolution of the quantum state of the cavity fields. At First, let us briefly discuss how one could distinguish that a given state belongs to the class of cluster states. Simply, a given state is quantified as a cluster state if the quadrature correlations are such that in the limit of infinite squeezing, the state becomes zero eigenstate of a set of quadrature combinations [3]

$$(p_j - \sum_{i \in N_j} x_i) \to 0, \tag{4}$$

where x_j and p_j are the position and momentum quadrature operators of the cavity modes c_j, defined as $x_j = \left(c_j + c_j^+\right)/\sqrt{2}$ and $p_j = -i\left(c_j + c_j^+\right)/\sqrt{2}$, and x_i are the position operator of the modes c_i which are the nearest neighbors N_j of the modes c_j. In what follows, we quantify a given state as a cluster state by evaluating the variances of linear combinations of the momentum and position operators of the involved field modes. If the variances vanish in the limit of the infinite squeezing, according to the above definition, then a given state is a cluster state. According to Eq. (3), we can find that the variances $V(g_j) = \left\langle g_j^2 \right\rangle - \left\langle g_j \right\rangle^2$, with the combined operators g_j defined as $g_1 = p_1 + x_3 + \sqrt{2}x_4$, $g_2 = p_2 - \sqrt{2}x_3 - x_4$, $g_3 = p_1 + x_3 - \sqrt{2}x_2$, and $g_4 = p_4 + \sqrt{2}x_1 - x_2$, are equal and they are given by

$$V(g_j) = \frac{8\beta e^{-(4\beta+\kappa)t} + 2\kappa}{4\beta + \kappa}, \tag{5}$$

where $\beta = \alpha/\sqrt{2}$. Ideally, if we neglect the dissipation rate of the cavity ($\kappa = 0$), from Eq. (5) one can find that the variances $V(g_j)$ approaches zero in the long-time limit, namely

$$V(g_j) \to 0. \tag{6}$$

Therefore, according to the definition in Eq.(4), we see that the four cavity fields are indeed prepared into a quadripartite square cluster state, as shown in Fig.2.

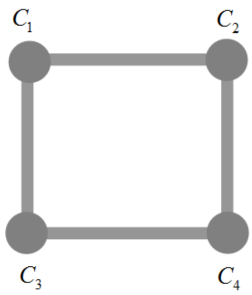

Fig.2 The CV quadripartite square cluster state. Each circle stands for a cavity mode and each line represents the bipartite entanglement between two cavity modes

Realistically, due to the cavity loss $\kappa \neq 0$, the variances in the long-time scale are

$$V(g_j) = \frac{2\kappa}{4\beta + \kappa}. \tag{7}$$

With the steady-state condition $\kappa > 4\beta$, the variances satisfy

$$1 < V(g_j) < 2\,, \tag{8}$$

which indicates that the quadripartite square cluster state in the cavity has the finite variances below the quantum limit 2. Therefore, we show that by the concurrent NOPO processes, the quadripartite cluster state can be generated in the four cavity modes and moreover the intra-cavity quantum correlations of the cluster state are severely limited by the unavoidable cavity loss.

2 Quantum correlations improved by quantum feedback

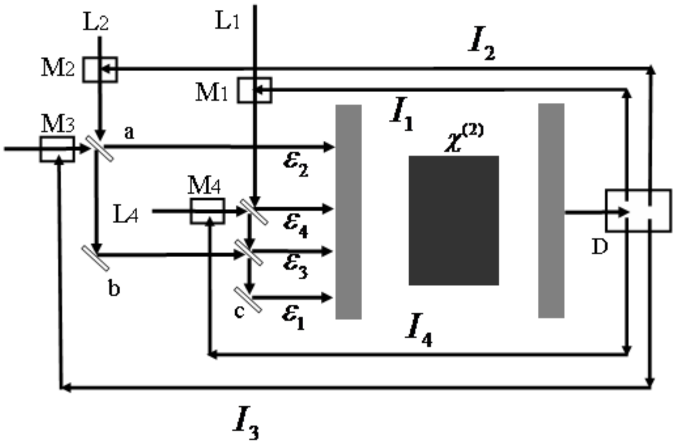

Fig.3. The feedback loops are used to enhance the quantum correlations of the quadripartite square cluster state. From the detection region (D), the currents I_j are fed back to the modulators M_j to modulate the amplitudes of the lasers L_j. The output beams from the beam splitters with the amplitudes ε_j are used to drive the cavity fields c_j.

In this section, we focus on the improvement of the quantum correlations of the above cluster state via quantum feedback. To introduce the feedback loop, as shown in Fig.3, other four laser fields (labeled by L_j) with the amplitudes α_j are used and injected into the balanced (1:1) beam splitters (BS). The beam splitters (BS) a and c lead to $3\pi/2$ phase shifts of the corresponding reflected beams and the BS b leads to the phase shift of π. In this way, the output beams from the beam splitters are used to drive the cavity modes and the amplitudes ε_j of, which are given by are $\varepsilon_1 = (\alpha_1 + \alpha_2 + i\alpha_3 + i\alpha_4)/2$, $\varepsilon_2 = (\alpha_2 - i\alpha_3)/\sqrt{2}$, $\varepsilon_3 = (i\alpha_1 - i\alpha_2 + \alpha_3 - \alpha_4)/2$, and $\varepsilon_4 = (i\alpha_1 + \alpha_4)/\sqrt{2}$. So, the Hamiltonian of the system in the absence of the feedback loop reads

$$\begin{aligned} H_1 &= H_c + (\varepsilon_1 c_1 + \varepsilon_2 c_2 + \varepsilon_3 c_3 + \varepsilon_4 c_4 + H.c.) \\ &= H_c + \alpha_1(x_1 - y_3 - \sqrt{2}y_4) + \alpha_2(x_1 + \sqrt{2}x_2 + y_3) \\ &\quad + \alpha_3(-y_1 + \sqrt{2}y_2 + x_3) + \alpha_4(-y_1 - x_3 + \sqrt{2}x_4). \end{aligned} \tag{9}$$

Now we discuss the feedback scheme based on the homodyne-mediated feedback theory of Wiseman and Milburn [19], which mainly involves, in the homodyne measurement process, the current of the homodyne measurement and the way in which the current is fed back to control the system. Here we use four feedback loops to couple the system, as shown Fig.3, to control the entanglement of the system. In the detection region, through the homodyne measurement on the output fields from the cavity we can obtain the currents $I_1=(I_1^{y_1}+I_1^{x_3}+\sqrt{2}I_1^{x_4})/2$, $I_2=(I_2^{y_1}+\sqrt{2}I_2^{y_2}-I_2^{x_3})/2$, $I_3=(I_3^{x_1}-\sqrt{2}I_3^{x_2}+I_3^{y_3})/2$, and $I_4=(I_4^{x_1}-I_4^{y_3}+\sqrt{2}I_4^{y_4})/2$, where $I_i^{x_j}(t)=\langle x_j\rangle+\zeta_i^j/\sqrt{\kappa\eta}$ and $I_i^{y_j}(t)=\langle y_j\rangle+\zeta_i^j/\sqrt{\kappa\eta}$. Here ζ_i^j are measurement-induced white noises and η is the detect efficiency. Then, the currents are fed back via the feedback loops to the modulators M_j to modulate the lasers and control the system. In this way, the feedback Hamiltonian can be found to be

$$
\begin{aligned}
H_f=&\lambda_1 I_1^{(y_1+x_3+\sqrt{2}x_4)}(t-\tau)(x_1-y_3-\sqrt{2}y_4)\\
&+\lambda_2 I_2^{(y_1+\sqrt{2}y_2-x_3)}(t-\tau)(x_1+\sqrt{2}x_2+y_3)\\
&+\lambda_3 I_3^{(x_1-\sqrt{2}x_2+y_3)}(t-\tau)(-y_1+\sqrt{2}y_2+x_3)\\
&+\lambda_4 I_4^{(x_1-y_3+\sqrt{2}y_4)}(t-\tau)(-y_1-x_3+\sqrt{2}x_4),
\end{aligned}
\tag{10}
$$

where τ is feedback loop delay time and λ_j are proportional to the feedback strength. By considering the Markovian feedback, namely the delay time $\tau=0$, which means that once the measurement results is recorded and it immediately influences the system. In this situation, the noises have the correlations $\langle\zeta_j^i(t)\zeta_{j'}^{i'}(t')\rangle=\frac{1}{2}\delta_{ii'}\delta_{jj'}\delta_{tt'}$. Following the method proposed by Wiseman and Milburn [19], the feedback-included master equation is found to be

$$
\frac{d}{dt}\rho=-i[H_1,\rho]+\sum_{j=1}^{4}\left(L_{c_j}\rho+L_{f_j}\rho\right), \tag{11}
$$

where

$$
L_{f_j}\rho=\hat{K}_j\left(d_j\rho+\rho d_j^{+}\right)+\frac{1}{2\kappa\eta}\hat{K}_j^2\rho. \tag{12}
$$

Here the super-operator $\hat{K}_j$ is defined as the $\hat{K}_j\rho=-i\left[F_j,\rho\right]$ as,

$F_1=\lambda_1(x_1-y_3-\sqrt{2}y_4)$, $F_2=\lambda_2(x_1+\sqrt{2}x_2+y_3)$, $F_3=\lambda_3(-y_1+\sqrt{2}y_2+x_3)$, $F_4=\lambda_4(-y_1-x_3+\sqrt{2}x_4)$,where the combined operators are given by $d_1=\left(-ic_1+c_3+\sqrt{2}c_4\right)/2$, $d_2=\left(-ic_1-\sqrt{2}ic_2-c_3\right)/2$ $d_3=\left(c_1-\sqrt{2}c_2-ic_3\right)/2$, and $d_4=\left(c_1+ic_3-\sqrt{2}ic_4\right)/2$.

After obtaining the explicit master equation, we can discuss the properties of the quantum correlations in the system under the influence of the feedback. According to the above master equation, it is not difficult to find the variances of the operators g_j, given by

$$
V(g_j)=\frac{2\left(1-e^{-(4\beta+\kappa+2\lambda)t}\right)\left(\lambda^2-4\beta\kappa\eta\right)}{\kappa\eta\left(4\beta+\kappa+2\lambda\right)}+2. \tag{13}
$$

For check, one can see that the above equation reduces to Eq. (5) without the feedback when the feedback strength $\lambda = 0$. In addition, the purity P of the cavity state ρ can be obtained as

$$P = Tr(\rho^2) = \frac{1}{16[(m+\frac{1}{2})^2 - n^2]^2}, \tag{14}$$

where

$$m = \frac{1}{4\kappa\eta\left(4\beta-\kappa\right)\left(4\beta+\kappa+2\lambda\right)} \times [\left(4\beta-\kappa\right)\left(16\beta\kappa\eta-\lambda^2\right)e^{-(4\beta+\kappa+2\lambda)t}$$
$$+4\beta\kappa\eta\left(4\beta+\kappa+2\lambda\right)e^{(4\beta-\kappa)t} - \left(32\beta^2\kappa\eta+8\beta\lambda\kappa\eta-4\beta\lambda^2+\kappa\lambda^2\right)],$$
$$n = \frac{1}{4\kappa\eta\left(4\beta-\kappa\right)\left(4\beta+\kappa+2\lambda\right)} \times [\left(4\beta-\kappa\right)\left(4\beta\kappa\eta-\lambda^2\right)e^{-(4\beta+\kappa+2\lambda)t}$$
$$-4\beta\kappa\eta\left(4\beta+\kappa+2\lambda\right)e^{(4\beta-\kappa)t} + \left(8\beta\kappa^2\eta+8\beta\lambda\kappa\eta+4\beta\lambda^2-\kappa\lambda^2\right)]. \tag{15}$$

From Eq.(15), one can find that the condition for achieving the steady state of the system is obtained as

$$\kappa > 4\beta \quad \text{and} \quad -\frac{4\beta+\kappa}{2} < \lambda < 0 .$$

In the steady-state regime, the steady variances and the purity can be found as

$$V^{\infty}(g_j) = \frac{2(\kappa^2\eta + 2\lambda\kappa\eta + \lambda^2)}{\kappa\eta(4\beta+\kappa+2\lambda)}, \tag{16}$$

$$P(\infty) = [\frac{\eta(\kappa-4\beta)(4\beta+\kappa+2\lambda)}{\kappa^2\eta+2\lambda\kappa\eta+\lambda^2}]^2 = 4(1-\frac{4\beta}{\kappa})^2 \frac{1}{V^2(\infty)}. \tag{17}$$

From Eq.(16), we can find that the steady variances becomes minimal (quantum squeezing becomes maximal)

$$\begin{aligned} V_{\min}^{\infty}(g_j) &= \frac{1}{\eta\kappa}(\sqrt{(4\beta+\kappa)^2 - 16\beta\kappa\eta} - (4\beta+\kappa) + 2\eta\kappa) \\ &= 2(\frac{\lambda_0}{\eta\kappa}+1), \end{aligned} \tag{18}$$

when the feedback strength $\lambda = \lambda_0 = \frac{\sqrt{(4\beta+\kappa)^2 - 16\beta\kappa\eta} - (4\beta+\kappa)}{2}$. Evidently, when the feedback strength $|\lambda| \le |\lambda_0|$, the quantum correlations are improved with the increase of $|\lambda|$, while the quantum correlations decrease as the feedback strength increases in the range of $|\lambda_0| < |\lambda| < \frac{4\beta+\kappa}{2}$. When $|\lambda| = \frac{8\eta\beta\kappa}{4\beta+\kappa}$, we have $V^{\infty}(g_i) = V_0^{\infty}(g_i)$, where $V_0^{\infty}(g_i)$ denotes the steady squeezing in the absence of the feedback. Therefore, only the feedback strength $0 < |\lambda| < \frac{8\eta\beta\kappa}{4\beta+\kappa}$ the squeezing will be increased by the feedback. Ideally, for the perfect detection ($\eta = 1$) and near the threshold $4\beta \to \kappa$, the steady-state variance

$$V^{\infty}\left(g_j\right)\rightarrow 0, \qquad (19)$$

with the feedback strength $\lambda \rightarrow -4\beta$. This means that the feedback can lead the cavity state to be in a cluster state with the perfect correlations. In addition, one can find from Eq.(17) that the maximal purity $P_{\max}(\infty)=[\frac{\eta(\kappa-4\beta)}{(\lambda_0+\kappa\eta)}]^2$ for the feedback strength $\lambda=\lambda_0$. When the strength $-\frac{\kappa+4\beta}{2}<\lambda<\lambda_0$ the purity increases as the feedback strength λ increases. For $\eta=1$ and $\lambda=-4\beta$, we have $P(\infty)=1$, meaning the pure the quantum state can be resulted by the feedback. Therefore, here we see explicitly that the feedback can not only enhance the quantum correlations of the quadripartite cluster state in the cavity but also improve the purity of the cluster state. This is clearly shown in Fig.4 where the dependence of the steady variances and purity of the quadripartite square cluster state on the feedback strength is plotted. From it we see that the steady-state squeezing and purity are improved by the feedback when the feedback strength is chosen appropriately.

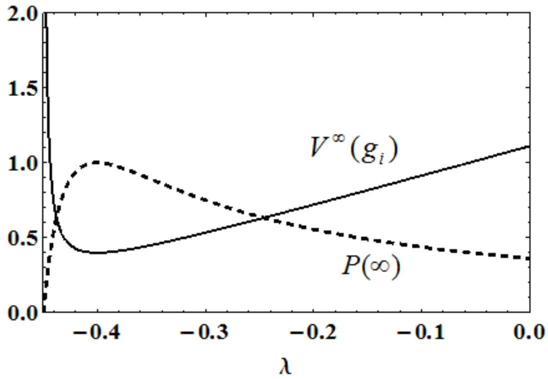

Fig.4. The dependence of the steady-state variances $V^{\infty}(g_i)$ and the purity $P(\infty)$ on the feedback strength λ for $\beta=0.1$, $\kappa=0.5$, and $\eta=1$.

In Fig.5, the temporal evolution of the variances $V(g_j)$ in presence of the feedback is plotted. It shows that the squeezing can be enhanced by the feedback in the long-time regime. In addition, the time for achieving the steady-state of the system is prolonged when the feedback is involved. In Fig.6, the effect of the detection efficiency η on the variance is also plotted. From it we see that the increase of the detection efficiency can enhance the improvement of the squeezing.

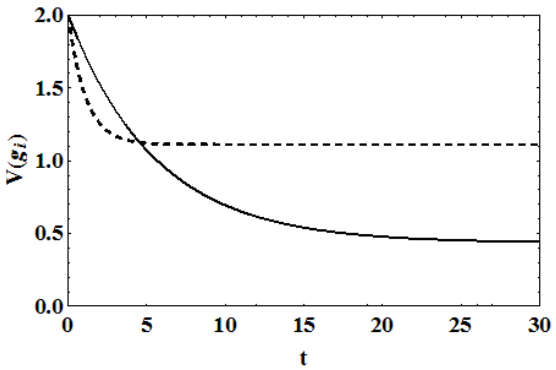

Fig.5. The time evolution of the variances $V(g_i)$ for $\beta=0.1$, $\kappa=0.5$, $\eta=1$, and $\lambda=-0.36$ (solid line), $\lambda=0$ (dashed line).

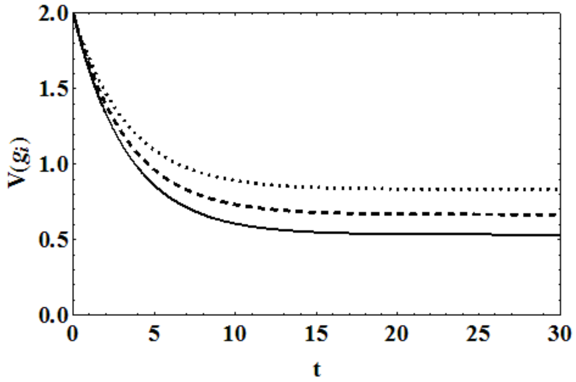

Fig.6. The time evolution of the variances $V(g_i)$ for $\beta=0.1$, $\kappa=0.5$, $\lambda=-0.3$, $\eta=0.8$ (dotted line), $\eta=0.9$ (dashed line), $\eta=1$ (solid line).

In Fig.7, the time evolution of the purity P of the CV quadripartite cluster state in the presence of the feedback is plotted. It is clearly shown that the purity is enhanced by feedback in the long-time scale.

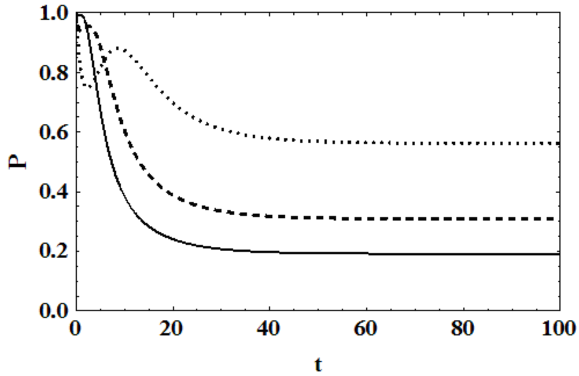

Fig.7. The time evolution of the purity P for $\beta=0.1$, $\kappa=0.5$, $\eta=1$, and $\lambda=-0.1$ (solid line), $\lambda=-0.2$ (dashed line), $\lambda=-0.3$ (dotted line).

3 Conclusions

In conclusions, we investigate the generation of quadripartite square cluster state of optical fields and discuss the use of the quantum feedback to enhance the multipartite entanglement of the cluster state. It is shown explicitly that the quadripartite square cluster state can be generated via concurrent OPO processes and further the loss of the cavity will degrade the multipartite entanglement of the cluster state. By introducing appropriate feedback loops, we find that the multipartite entanglement and the purity of the quadripartite cluster state can be improved significantly.

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四模连续变量方形簇态的制备及基于量子反馈的纠缠增强

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摘要：本文研究了在光场中制备四模连续变量方型簇态的方法，并讨论了如何利用量子反馈来增强簇态的多模纠缠。结果表明，四模方型簇态可以通过并行光学参量振荡过程产生，并且腔的损耗可以降低簇态的量子关联。同时，通过引入合适的反馈回路，可以明显提高簇态的纠缠和纯度。

关键词：量子光学；连续变量簇态；反馈
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