Front. Phys., 2014, 9(5): 640–645
DOI 10.1007/s11467-014-0435-z

Research article

Entanglement concentration for a non-maximally entangled four-photon cluster state

Xiang Yan, Ya-Fei Yu, Zhi-Ming Zhang†

Laboratory of Nanophotonic Functional Materials and Devices (SIPSE), Laboratory of Quantum Engineering and Quantum Materials, South China Normal University, Guangzhou 510006, China

Corresponding author. E-mail: †*zmzhang@scnu.edu.cn*

Received April 24, 2014; accepted June 4, 2014

We present a scheme for locally concentrating a non-maximally entangled four-photon cluster state into a maximally-entangled four-photon cluster state. This scheme has a high success probability. The controlled-NOT (CNOT) gate is a crucial ingredient in this scheme, and we use a nearly deterministic CNOT gate, which is similar with that first introduced by Nemoto *et al.* (*Phys. Rev. Lett.*, 2004, 93: 250502). This CNOT gate has a simple structure and does not need the strong nonlinearity.

Keywords cluster state, entanglement concentration, controlled-NOT gate

PACS numbers 03.65.Ud, 03.67.Mn, 03.67.-a, 42.50.-p

1 Introduction

Quantum entanglement is an important concept in quantum mechanics. It is a key ingredient in the field of quantum information processing (QIP) [1–7]. For many tasks in QIP, the quantum channels should be preferred in maximally entangled states, so one needs to convert non-maximally entangled states into pure maximally entangled ones. Generally speaking, the non-maximally entangled states usually include two different types. The first type is the mixed state and the second type is the pure less-entangled state. Both of which will make the fidelity of quantum teleportation degraded, quantum dense coding failed, and the quantum cryptography protocol insecure. Many schemes have been proposed to extract maximally-entangled states from non-maximally entangled states, such as entanglement concentration (for pure non-maximally entangled states) [8–10], entanglement purification or distillation (for mixed entangled states) [11–14].

The concentration schemes for two-particle state have been well studied. In a three-particle system [7, 15–17], there are two classes of tripartite-entangled states. They are the Greenberger–Horne–Zeilinger (GHZ) state and the W state. The entanglement concentration for two-particle state is usually suitable for the case of multipartite GHZ state [18–20]. However, these kinds of entanglement concentration cannot deal with the case of a less-entangled W state. In 2003, Cao *et al.* presented an entanglement concentration for a W class state with the help of joint unitary transformation [21]. In 2007, Zhang *et al.* presented an entanglement concentration based on the Bell-state measurement [22]. In 2010, Wang *et al.* presented an entanglement concentration for a W state with linear optics [23]. In 2012, Sheng *et al.* presented two two-step practical entanglement concentration protocols for concentrating an arbitrary three-particle less-entangled W state into a maximally entangled W state assisted with single photons [24] and so on.

Recently, more and more attention has been focused on the cluster states. The cluster states are harder to be destroyed by local operations than two-particle states and three-particle states [25]. A few schemes begin to mention the concentration for cluster states [26–28]. In 2013, Si *et al.* presented an efficient three-step entanglement concentration for an arbitrary four-photon cluster state [26]. Zhao *et al.* presented two-step entanglement concentration for arbitrary electronic cluster state [27], and Choudhury *et al.* presented an entanglement concentration protocol for cluster states [28].

In the present article, we present a scheme for locally concentrating a non-maximally entangled four-photon cluste state into a maximally-entangled four-photon cluster state. We can obtain a maximally-entangled cluster state via local operations and classical communication. The scheme needs some controlled-NOT (CNOT) gates [29] to assist the concentration. It has a high success probability and a simple structure. It only needs the help of the linear optical elements and weak cross-Kerr nonlinearity.

This paper is organized as follows. In Section 2 we introduce the cross-Kerr nonlinear interaction between two light modes and use a nearly deterministic CNOT gate, which is similar with that first introduced by Nemoto *et al.* [30]. In Section 3 we present a scheme for the entanglement concentration of a non-maximally entangled four-photon cluster state. Section 4 includes discussion and conclusions.

2 Cross-Kerr nonlinearity and CNOT gate

We consider the cross-Kerr nonlinear interaction between a signal beam S and a probe beam P. The Hamiltonian for the interaction is [30]

$$\hat{H} = -\hbar\chi\hat{n}_s\hat{n}_p \tag{1}$$

where χ is the coupling strength, $\hat{n}_s$ and $\hat{n}_p$ are the photon number operators of the signal mode and the probe mode, respectively. If the signal mode is in a Fock state $|n\rangle_s$ and the probe mode is in a coherent state $|\alpha\rangle_p$, then the combined system (signal mode + probe mode) evolves as follows:

$$\mathrm{e}^{\mathrm{i}\chi\hat{n}_s\hat{n}_p t}|n\rangle_s|\alpha\rangle_p \rightarrow |n\rangle_s|\alpha\mathrm{e}^{\mathrm{i}n\theta}\rangle_p \tag{2}$$

where $\theta = \chi t$ and t is the interaction time. From Eq. (2) we can see that the state of the signal mode is unaffected, while the state of the probe mode picks up a phase shift which is proportional to the number of photons in the signal mode [31]. The phase shift of the probe mode can be measured by homodyne detection [32]. In this way, we can determine the state of the signal mode without destroying it by measuring the probe mode. This is a kind of non-destructive measurements.

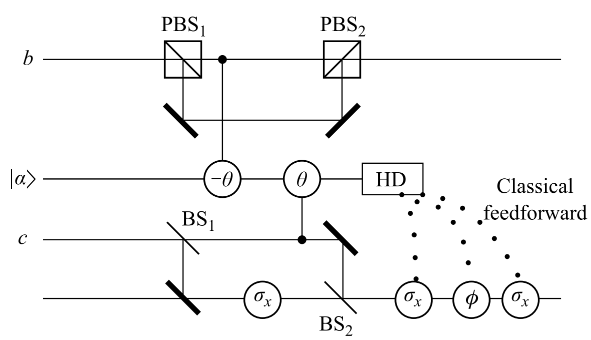

Fig. 1 The controlled-NOT gate. PBS: The polarizing beam splitter which is used to transmit the horizontally and to reflect the vertically polarized photons. θ, $-\theta$: Cross-Kerr nonlinearity. HD: Homodyne detection. The probe light is initially in a coherent state $|\alpha\rangle$.

The CNOT gate with weak cross-Kerr nonlinearity was first introduced by Nemoto *et al.* [30]. Here we use a similar form of it. The CNOT gate is shown in Fig. 1. We suppose that the input photons are prepared in the state

$$|\varphi_1\rangle_{bc} = a|HH\rangle_{bc}+b|HV\rangle_{bc}+c|VH\rangle_{bc}+d|VV\rangle_{bc} \tag{3}$$

where $|a|^2+|b|^2+|c|^2+|d|^2 = 1$, H and V represent horizonal and vertical polarization, respectively. The controlling photon b passes through a balanced Mach–Zehnder (M–Z) interferometer made up of two PBSs, while the target photon c passes through a balanced M–Z interferometer made up of two BSs. The Pauli operator σ_x acts on one arm. The input photons b and c interact with the probe mode (in a coherent state $|\alpha\rangle$) via the cross-Kerr nonlinearities respectively, then the state evolves as follows:

$$\begin{aligned}|\varphi_1\rangle_{bc}\otimes|\alpha\rangle &= (a|HH\rangle_{bc}+b|HV\rangle_{bc}\\ &\quad +c|VH\rangle_{bc}+d|VV\rangle_{bc})\otimes|\alpha\rangle \rightarrow |\phi\rangle\\ &= \sqrt{\frac{R_1T_2}{2}}(a|HH\rangle_{bc}+b|HV\rangle_{bc})|\alpha e^{-i\theta}\rangle\\ &\quad +\sqrt{\frac{T_1R_2}{2}}(c|VV\rangle_{bc}+d|VH\rangle_{bc})|\alpha e^{i\theta}\rangle\\ &\quad +[\sqrt{\frac{T_1R_2}{2}}(a|HV\rangle_{bc}+b|HH\rangle_{bc})\\ &\quad +\sqrt{\frac{R_1T_2}{2}}(c|VH\rangle_{bc}+d|VV\rangle_{bc})]\otimes|\alpha\rangle\end{aligned} \tag{4}$$

where R and T represent reflection and transmission coefficients, respectively. We perform the X homodyne detection on the probe mode. If we find that the probe mode is in the coherent state $|\alpha\mathrm{e}^{\pm\mathrm{i}\theta}\rangle$, we do a feed-forward operation on photon c and obtain the following state:

$$\begin{aligned}|\varphi_2\rangle_{bc} &= \sqrt{R_1T_2}(a|HH\rangle_{bc}+b|HV\rangle_{bc})\\ &\quad +\sqrt{T_1R_2}(c|VV\rangle_{bc}+d|VH\rangle_{bc})\end{aligned} \tag{5}$$

On the other hand, if we find that the probe mode is in the coherent state $|\alpha\rangle$, we carry out a single photon operation σ_x on photon c and obtain the the following state:

$$\begin{aligned}|\varphi_3\rangle_{bc} &= \sqrt{T_1R_2}(a|HH\rangle_{bc}+b|HV\rangle_{bc})\\ &\quad +\sqrt{R_1T_2}(c|VV\rangle_{bc}+d|VH\rangle_{bc})\end{aligned} \tag{6}$$

When the conditions $\sqrt{T_1R_2} = \sqrt{R_1T_2}$ and $T_1 = R_2 = \frac{1}{2}$ are satisfied, we obtain a nearly deterministic CNOT gate, the success probability is $p = 4|T_1R_2| = 1$.

3 Entanglement concentration of a non-maximally entangled four-photon cluster state

In the following, we present the scheme for the concentration process of a non-maximally entangled four-photon cluster state in detail. The schematic diagram is shown in Fig. 2. In the scheme, besides some CNOT gates to assist the concentration, there are also some other ingredients, for example, PBSs and single-photon detectors.

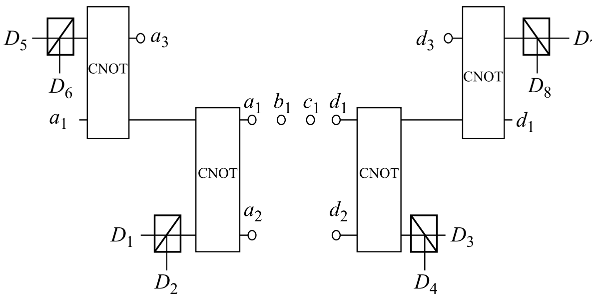

Fig. 2 Schematic diagram of entanglement concentration for a non-maximally entangled four-photon cluster state. CNOT: Controlled-NOT gate. D_i: Single-photon detector.

We suppose that a non-maximally entangled four-photon cluster state in polarization is described as

$$|\varphi\rangle_{a_1b_1c_1d_1} = (a|HHHH\rangle + b|HHVV\rangle + c|VVHH\rangle - d|VVVV\rangle)_{a_1b_1c_1d_1} \quad (7)$$

where $|a|^2+|b|^2+|c|^2+|d|^2=1$. First, we use a photon pair in the state

$$|\varphi\rangle_{a_2d_2} = (a|HH\rangle + b|HV\rangle + c|VH\rangle + d|VV\rangle)_{a_2d_2} \quad (8)$$

Let photons a_1 and a_2 pass through the first CNOT gate, and photons d_1 and d_2 pass through the second CNOT gate, then the following transformation can be accomplished:

$$\begin{aligned}|\varphi\rangle_{a_1b_1c_1d_1}\otimes|\varphi\rangle_{a_2d_2} \rightarrow{}& (ab|HHHHHV\rangle \\ &+ab|HHHVVV\rangle + cd|VHVHHV\rangle \\ &-cd|VHVVVV\rangle)_{a_1a_2b_1c_1d_1d_2} + (ac|HVHHHH\rangle \\ &+ac|VVVHHH\rangle + bd|HVHVVH\rangle \\ &-bd|VVVVVH\rangle)_{a_1a_2b_1c_1d_1d_2} + (bc|HVHVVV\rangle \\ &+bc|VVVHHV\rangle + ad|HVHHHV\rangle \\ &-ad|VVVVVV\rangle)_{a_1a_2b_1c_1d_1d_2} + (a^2|HHHHHH\rangle \\ &+b^2|HHHVVH\rangle) + c^2|VHVHHH\rangle \\ &-d^2|VHVVVH\rangle)_{a_1a_2b_1c_1d_1d_2} \end{aligned} \quad (9)$$

After photons a_2 and d_2 pass through PBS, photon a_2 is detected by single photon detectors D_1 and D_2, while photon d_2 is detected by single photon detectors D_3 and D_4. The above state will collapse into different states depending on which detectors click:

Case 1. If D_1 and D_4 click, the state will collapse into

$$\begin{aligned}|\varphi_1\rangle_{a_1b_1c_1d_1} ={}& \frac{1}{\sqrt{2|ab|^2+2|cd|^2}}[ab(|HHHH\rangle \\ &+|HHVV\rangle) + cd(|VVHH\rangle \\ &-|VVVV\rangle)]_{a_1b_1c_1d_1}\end{aligned} \quad (10)$$

with a success probability of $p_1 = 2|ab|^2+2|cd|^2$.

Case 2. If D_2 and D_3 click, the state will collapse into

$$\begin{aligned}|\varphi_2\rangle_{a_1b_1c_1d_1} ={}& \frac{1}{\sqrt{2|ac|^2+2|bd|^2}}[ac(|HHHH\rangle \\ &+|VVHH\rangle) + bd(|HHVV\rangle \\ &-|VVVV\rangle)]_{a_1b_1c_1d_1}\end{aligned} \quad (11)$$

with a success probability of $p_2 = 2|ac|^2+2|bd|^2$.

Case 3. If D_2 and D_4 click, the state will collapse into

$$\begin{aligned}|\varphi_3\rangle_{a_1b_1c_1d_1} ={}& \frac{1}{\sqrt{2|bc|^2+2|ad|^2}}[bc(|HHVV\rangle \\ &+|VVHH\rangle) + ad(|HHHH\rangle \\ &-|VVVV\rangle)]_{a_1b_1c_1d_1}\end{aligned} \quad (12)$$

with a success probability of $p_3 = 2|bc|^2+2|ad|^2$.

Case 4. If D_1 and D_3 click, the state will collapse into

$$\begin{aligned}|\varphi_4\rangle_{a_1b_1c_1d_1} ={}& \frac{1}{\sqrt{|a|^4+|b|^4+|c|^4+|d|^4}}(a^2|HHHH\rangle \\ &+b^2|HHVV\rangle + c^2|VVHH\rangle \\ &-d^2|VVVV\rangle)_{a_1b_1c_1d_1}\end{aligned} \quad (13)$$

with a success probability of $p_4 = |a|^4+|b|^4+|c|^4+|d|^4$.

Now, let us discuss the concentration process when we have the four-photon state $|\varphi_1\rangle_{a_1b_1c_1d_1}$. We use a photon pair in the polarization state

$$\begin{aligned}|\varphi\rangle_{a_3d_3} ={}& \frac{1}{\sqrt{2|ab|^2+2|cd|^2}}[ab(|HH\rangle + |HV\rangle) \\ &+cd(|VH\rangle + |VV\rangle)]_{a_3b_3}\end{aligned} \quad (14)$$

Let the photons a_1 and a_3 pass through the third CNOT gate, photons d_1 and d_3 pass through the fourth CNOT gate, then the following transformation can be accomplished:

$$\begin{aligned}|\varphi_1\rangle_{a_1b_1c_1d_1}\otimes|\varphi\rangle_{a_3d_3} \rightarrow{}& \frac{1}{2|ab|^2+2|cd|^2}[(ab)^2(|HHHHHV\rangle + |HHHVVV\rangle) + (cd)^2|VHVHHV\rangle \\ &-(cd)^2|VHVVVV\rangle]_{a_1a_3b_1c_1d_1d_3} + \frac{abcd}{2|ab|^2+2|cd|^2}(|HVHHHH\rangle + |VVVHHH\rangle + |HVHVVH\rangle\end{aligned}$$

$$-|VVVVVH\rangle)_{a_1a_3b_1c_1d_1d_3}+\frac{abcd}{2|ab|^2+2|cd|^2}(|HVHVVV\rangle+|VVVHHV\rangle+|HVHHHV\rangle$$
$$-|VVVVVV\rangle)_{a_1a_3b_1c_1d_1d_3}+\frac{1}{2|ab|^2+2|cd|^2}[(ab)^2(|HHHHHH\rangle+|HHHVVH\rangle)$$
$$+(cd)^2(|VHVHHH\rangle-|VHVVVH\rangle)]_{a_1a_3b_1c_1d_1d_3} \quad (15)$$

After photons a_3 and d_3 pass through PBS, if D_6 and $D_7(D_8)$ click, then the original four-photon state is left in the maximally entangled cluster state.

$$|\varphi\rangle_{cluster}=\frac{1}{2}(|HHHH\rangle+|HHVV\rangle+|VVHH\rangle-|VVVV\rangle)_{a_1b_1c_1d_1} \quad (16)$$

with a success probability of

$$p_{cluster}=p_1\otimes\frac{2|abcd|^2}{(|ab|^2+|cd|^2)^2}=\frac{4|abcd|^2}{|ab|^2+|cd|^2} \quad (17)$$

If D_5 and $D_7(D_8)$ clicks, then the original four-photon state is left in

$$|\varphi_{11}\rangle_{a_1b_1c_1d_1}=\frac{1}{\sqrt{2|ab|^4+2|cd|^4}}[(ab)^2(|HHHH\rangle+|HHVV\rangle)+(cd)^2(|VVHH\rangle-|VVVV\rangle)_{a_1b_1c_1d_1}] \quad (18)$$

with a success probability of

$$p_{11}=p_1\otimes\frac{|ab|^4+|cd|^4}{(|ab|^2+|cd|^2)^2}=\frac{2(|ab|^4+|cd|^4)}{|ab|^2+|cd|^2} \quad (19)$$

Moreover, we can concentrate the four-photon into the maximally entangled cluster state from the less-entangled four-photon state $|\varphi_{11}\rangle_{a_1b_1c_1d_1}$ in the next round. With repeating the entanglement concentration process n times, the total success probability of the state $|\varphi_1\rangle_{a_1b_1c_1d_1}$ concentrated into the maximally entangled cluster state is

$$P^a=\sum_{i=1}^{n}P_i^a \quad (20)$$

where

$$P_1^a=\frac{4|abcd|^2}{|ab|^2+|cd|^2},\quad P_2^a=p_{11}\otimes\frac{2|abcd|^4}{(|ab|^4+|cd|^4)^2}=\frac{4|abcd|^4}{(|ab|^2+|cd|^2)(|ab|^4+|cd|^4)}$$
$$P_3^a=p_{11}\otimes\frac{|ab|^8+|cd|^8}{(|ab|^4+|cd|^4)^2}\otimes\frac{2|abcd|^8}{(|ab|^8+|cd|^8)^2}=\frac{4|abcd|^8}{(|ab|^2+|cd|^2)(|ab|^4+|cd|^4)(|ab|^8+|cd|^8)}$$
$$P_n^a=\frac{4|abcd|^{2^n}}{(|ab|^2+|cd|^2)(|ab|^4+|cd|^4)(|ab|^8+|cd|^8)\cdots(|ab|^{2^n}+|cd|^{2^n})} \quad (21)$$

The entanglement concentration processes for the state $|\varphi_2\rangle_{a_1b_1c_1d_1}$ and $|\varphi_3\rangle_{a_1b_1c_1d_1}$ are similar as that for the state $|\varphi_1\rangle_{a_1b_1c_1d_1}$, so with reiteration of the entanglement concentration process n times, the success probability of $|\varphi_2\rangle_{a_1b_1c_1d_1}$ and $|\varphi_3\rangle_{a_1b_1c_1d_1}$ concentrated into the maximally entangled cluster state are

$$P^b=\sum_{i=1}^{n}P_i^b$$
$$P^c=\sum_{i=1}^{n}P_i^c \quad (22)$$

respectively, where

$$P_n^b=\frac{4|abcd|^{2^n}}{(|ac|^2+|bd|^2)(|ac|^4+|bd|^4)(|ac|^8+|bd|^8)\cdots(|ac|^{2^n}+|bd|^{2^n})}$$
$$P_n^c=\frac{4|abcd|^{2^n}}{(|bc|^2+|ad|^2)(|bc|^4+|ad|^4)(|bc|^8+|ad|^8)\cdots(|bc|^{2^n}+|ad|^{2^n})} \quad (23)$$

The state $|\varphi_4\rangle_{a_1b_1c_1d_1}$ has a similar form with the state $|\varphi\rangle_{a_1b_1c_1d_1}$, we only need replace $\frac{a^2}{\sqrt{a^4+b^4+c^4+d^4}}$, $\frac{b^2}{\sqrt{a^4+b^4+c^4+d^4}}$, $\frac{c^2}{\sqrt{a^4+b^4+c^4+d^4}}$ and $\frac{d^2}{\sqrt{a^4+b^4+c^4+d^4}}$ with a', b', c' and d'. Therefore, after reiteration of the entanglement concentration process n times, the success probability of the state $|\varphi_4\rangle_{a_1b_1c_1d_1}$ concentrated into the maximally entangled cluster state is

$$P^d=\sum_{i=1}^{n}P_i^d \quad (24)$$

where

$$P_n^d = \sum_{n=1}^{\infty} \frac{1}{(|a|^4+|b|^4+|c|^4+|d|^4)\cdots(|a|^{2^{n+1}}+|b|^{2^{n+1}}+|c|^{2^{n+1}}+|d|^{2^{n+1}})}$$
$$\times\{\frac{4|abcd|^{2^{2n}}}{(|ab|^{2^{n+1}}+|cd|^{2^{n+1}})(|ab|^{2^{n+2}}+|cd|^{2^{n+2}})\cdots(|ab|^{2^{2n}}+|cd|^{2^{2n}})}$$
$$+\frac{4|abcd|^{2^{2n}}}{(|ac|^{2^{n+1}}+|bd|^{2^{n+1}})(|ac|^{2^{n+2}}+|bd|^{2^{n+2}})\cdots(|ac|^{2^{2n}}+|bd|^{2^{2n}})}$$
$$+\frac{4|abcd|^{2^{2n}}}{(|bc|^{2^{n+1}}+|ad|^{2^{n+1}})(|bc|^{2^{n+2}}+|ad|^{2^{n+2}})\cdots(|bc|^{2^{2n}}+|ad|^{2^{2n}})}\} \tag{25}$$

Therefore, by combining above steps, we obtain the total success probability

$$P_{total} = P^a + P^b + P^c + P^d \tag{26}$$

In Eq. (26), if $a=b=c=d=\frac{1}{2}$, then

$$P_{\rm total} = P^a + P^b + P^c + P^d = \sum_{n=1}^{\infty}\left(\frac{1}{2}\right)^n = 1 \tag{27}$$

We have plotted the total success probability of this entanglement concentration process for the iterating times $n=1,2,3,4,5$, as shown in Fig. 3. We can see that a high success probability can be obtained after reiterating the entanglement concentration process 5 times.

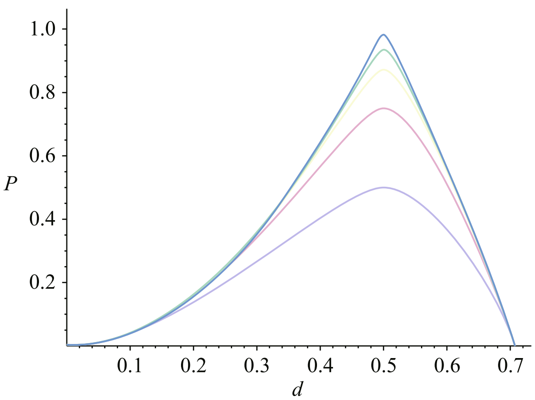

Fig. 3 The total success probability P of obtaining a maximally-entangled cluster state after iterating entanglement concentration process $n=1,2,3,4,5$ times (in the bottom-up order). Here $a=b=\frac{1}{2}$, $d\in(0,\frac{\sqrt{2}}{2})$.

4 Discussion and conclusions

By far, we have fully presented our scheme. Let us discuss its feasibility. Our scheme is based on the cross-Kerr nonlinearity. We know that the natural cross-Kerr nonlinearities are extremely weak. However, Nemoto *et al.* [30] have shown that weak cross-Kerr nonlinearities can be used for quantum information processing. After their work, a series of studies have been done on the cross-Kerr nonlinearity [33–34]. In our scheme, we need to differentiate the coherent states $|\alpha e^{i\theta}\rangle$ and $|\alpha e^{-i\theta}\rangle$. However, in general, they are not completely orthogonal, and cannot be distinguished determinately [35]. For a measurement of the momentum quadrature, the probability of misidentifying them is given by $P_{\rm error} = {\rm erfc}(\sqrt{2}\alpha\sin\theta)$. $P_{\rm error}$ is small when $\alpha\sin\theta$ is large. For a smallθ, as long as α is large enough, we can differentiate the states $|\alpha e^{i\theta}\rangle$ and $|\alpha e^{-i\theta}\rangle$ with a small error probability. For example, for $\alpha\sin\theta=\frac{\pi}{2}$, the error probability will be in the order of 10^{-3}, and $P_{\rm error}$ decreases rapidly with increasing $\alpha\sin\theta$. This scheme is also influenced by the quantum controlled-NOT gates, and we have used a nearly deterministic controlled-NOT gate.

There is a work by another group (Si *et al.* [26]) which also reports on a concentration scheme for cluster states in an optical set-up. This work uses a single photon resource to assist the protocol and also uses linear optical elements and a weak cross-Kerr nonlinearity. Let us discuss the differences between our scheme from their's and the advantages of our scheme. We use an almost deterministic controlled-NOT gate with weak cross-Kerr nonlinearity without Toffoli gates which are not completely deterministic. In addition, we use two-photon less-entangled states to assist the entanglement concentration. All of this can simplify the process of entanglement concentration. It has a high success probability which is larger than that in Si *et al.*'s scheme.

In summary, we have proposed a scheme for local concentrating a non-maximally entangled four-photon cluster state into a maximally-entangled four-photon cluster state. The scheme is based on linear optical elements, cross-Kerr nonlinearity, and homodyne measurement. The key ingredient of the scheme is a controlled-NOT gate, and we use a nearly deterministic CNOT gate which is similar with that first introduced by Nemoto *et al.* [30]. And we can accomplish concentrating process only via local operations and classical communication.

Acknowledgements This work was supported by the Major Research Plan of the National Natural Science Foundation of China (Grant No. 91121023), the National Natural Science Foundation of China (Grant No. 60978009), the National Basic Research Program of China (973 Program) (Grant Nos. 2011CBA00200 and 2013CB921804), and the Program for Changjiang Scholars and Innovative Research Team in University (Grant No. IRT1243).

References

1. H. Jeong and M. S. Kim, Efficient quantum computation using coherent states, *Phys. Rev. A*, 2002, 65(4): 042305
2. T. C. Ralph, A. Gilchrist, G. J. Milburn, W. Munro, and S. Glancy, Quantum computation with optical coherent states, *Phys. Rev. A*, 2003, 68(4): 042319
3. S. J. van Enk and O. Hirota, Entangled coherent states: Teleportation and decoherence, *Phys. Rev. A*, 2001, 64(2): 022313
4. H. Jeong, M. S. Kim, and J. Lee, Quantum-information processing for a coherent superposition state via a mixedentangled coherent channel, *Phys. Rev. A*, 2001, 64(5): 052308
5. D. Gottesman and J. Preskill, Secure quantum key distribution using squeezed states, *Phys. Rev. A*, 2001, 63(2): 022309
6. N. J. Cerf, M. Lévy, and G. Assche, Quantum distribution of Gaussian keys using squeezed states, *Phys. Rev. A*, 2001, 63(5): 052311
7. W. Dür, G. Vidal, and J. I. Cirac, Three qubits can be entangled in two inequivalent ways, *Phys. Rev. A*, 2000, 62(6): 062314
8. C. Bennett, G. Brassard, S. Popescu, B. Schumacher, J. Smolin, and W. Wootters, Purification of noisy entanglement and faithful teleportation via noisy channels, *Phys. Rev. Lett.*, 1996, 76(5): 722
9. Z. Zhao, J. W. Pan, and M. S. Zhan, Practical scheme for entanglement concentration, *Phys. Rev. A*, 2001, 64(1): 014301
10. L. Ye and G. C. Guo, Scheme for entanglement concentration of atomic entangled states in cavity QED, *Phys. Lett. A*, 2004, 327(4): 284
11. C. Bennett, G. Brassard, S. Popescu, B. Schumacher, J. Smolin, and W. Wootters, Purification of noisy entanglement and faithful teleportation via noisy channels, *Phys. Rev. Lett.*, 1996, 76(5): 722
12. M. Yang and Z. L. Cao, Entanglement distillation for W class states, *Physica A*, 2004, 337(1-2): 141
13. M. Yang, W. Song, and Z. L. Cao, Entanglement distillation for atomic states via cavity QED, *Physica A*, 2004, 341: 251
14. J. W. Pan, C. Simon, C. Brukner, and A. Zeilinger, Entanglement purification for quantum communication, *Nature*, 2001, 410(6832): 1067
15. H. F. Wang, S. Zhang, and K. H. Yeon, Linear optical scheme for entanglement concentration of two partially entangled three-photon W states, *Eur. Phys. J. D*, 2010, 56(2): 271
16. L. L. Sun, H. F. Wang, S. Zhang, and K. H. Yeon, Entanglement concentration of partially entangled three-photon W states with weak cross-Kerr nonlinearity, *J. Opt. Soc. Am. B*, 2012, 29(4): 630
17. Y. B. Sheng, L. Zhou, and S. M. Zhao, Efficient two-step entanglement concentration for arbitrary W states, *Phys. Rev. A*, 2012, 85(4): 042302
18. C. H. Bennett, H. J. Bernstein, S. Popescu, and B. Schumacher, Concentrating partial entanglement by local operations, *Phys. Rev. A*, 1996, 53(4): 2046
19. Z. Zhao, J. W. Pan, and M. S. Zhan, Practical scheme for entanglement concentration, *Phys. Rev. A*, 2001, 64(1): 014301
20. Y. B. Sheng, F. G. Deng, and H. Y. Zhou, Nonlocal entanglement concentration scheme for partially entangled multipartite systems with nonlinear optics, *Phys. Rev. A*, 2008, 77(6): 062325
21. Z. L. Cao and M. Yang, Entanglement distillation for three-particle W class states, *J. Phys. B*, 2003, 36(21): 4245
22. L. H. Zhang, M. Yang, and Z. L. Cao, Entanglement concentration for unknown W class states, *Physica A*, 2007, 374(2): 611
23. H. F. Wang, S. Zhang, and K. H. Yeon, Linear optical scheme for entanglement concentration of two partially entangled three-photon W states, *Eur. Phys. J. D*, 2010, 56(2): 271
24. Y. B. Sheng, L. Zhou, and S. M. Zhao, Efficient two-step entanglement concentration for arbitrary W states, *Phys. Rev. A*, 2012, 85(4): 042302
25. W. Dür and H. J. Briegel, Stability of macroscopic entanglement under decoherence, *Phys. Rev. Lett.*, 2004, 92(18): 180403
26. B. Si, S. L. Su, L. L. Sun, L. Y. Cheng, H. F. Wang, and S. Zhang, Efficient three-step entanglement concentration for an arbitrary four-photon cluster state, *Chin. Phys. B*, 2013, 22(3): 030305
27. S. Y. Zhao, J. Liu, L. Zhou, and Y. B. Sheng, Two-step entanglement concentration for arbitrary electronic cluster state, *Quantum Inf. Process.*, 2013, 12(12): 3633
28. B. S. Choudhury and A. Dhara, An entanglement concentration protocol for cluster states, *Quantum Inf. Process.*, 2013, 12(7): 2577
29. Q. Lin and J. Li, Quantum control gates with weak cross-Kerr nonlinearity, *Phys. Rev. A*, 2009, 79(2): 022301
30. K. Nemoto and W. J. Munro, Nearly deterministic linear optical controlled-NOT gate, *Phys. Rev. Lett.*, 2004, 93(25): 250502
31. P. Kok, W. J. Munro, K. Nemoto, T. C. Ralph, J. P. Dowling, and G. J. Milburn, Linear optical quantum computing with photonic qubits, *Rev. Mod. Phys.*, 2007, 79(1): 135
32. B. Yurke, Wideband photon counting and homodyne detection, *Phys. Rev. A*, 1985, 32(1): 311
33. J. H. Shapiro, Single-photon Kerr nonlinearities do not help quantum computation, *Phys. Rev. A*, 2006, 73: 062305
34. J. H. Shapiro and M. Razavi, Continuous-time cross-phase modulation and quantum computation, *New. J. Phys.*, 2007, 9: 16
35. W. J. Munro, Kae Nemoto, T. P. Spiller, S. D. Barrett, P ieter Kok, and R. G. Beausoleil, Efficient optical quantum information processing, *J. Opt. B*, 2005, 7(7): S135