Annals of Physics 385 (2017) 86–94

Contents lists available at ScienceDirect

Annals of Physics

journal homepage: www.elsevier.com/locate/aop

Hyperentanglement concentration of nonlocal two-photon six-qubit systems with linear optics

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HIGHLIGHTS

- A linear hyperentanglement concentration protocol is proposed for photon systems.
- Parity-check gates on one degree of freedom (DOF) will not affect the other two DOFs.
- Polarization, spatial-mode, and time-bin DOFs are manipulated with linear optics.
- Nonlocal maximally hyperentangled two-photon six-qubit systems are obtained.
- Entanglement of multiphoton systems in three DOFs can be improved with this method.

ARTICLE INFO

Article history:
Received 16 February 2017
Accepted 24 July 2017
Available online 1 August 2017

Keywords:
Hyperentanglement concentration
Photon system
Polarization-spatial-time-bin hyperentanglement
Linear optics
Quantum communication

ABSTRACT

Hyperentanglement, the entangled states in the multiple degrees of freedom (DOFs) of a photon system simultaneously, has attracted much attention recently as it can increase the capacity of quantum communication largely. Here we present the first scheme for concentrating the nonlocal two-photon six-qubit systems entangled in polarization, spatial-mode, and time-bin DOFs with linear optics. We construct the parity-check gates for the quantum states of nonlocal photon systems in all the three DOFs with linear-optical elements. Fortunately, our parity-check gate for one DOF does not affect the quantum states in the other two DOFs, which makes our hyperentanglement concentration protocol (hyper-ECP) can be implemented conveniently for polarization–spatial–time-bin partially hyperentangled states. This hyper-ECP is practical

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http://dx.doi.org/10.1016/j.aop.2017.07.013

as it requires only linear-optical elements, and it can be directly generalized to improve the entanglement of nonlocal multi-photon systems entangled in three DOFs in the long-distance high-capacity quantum communication.

1. Introduction

Recently, hyperentanglement, which contains entangled states in the multiple degrees of freedom (DOFs) of a photon system simultaneously [1–8], has attracted a great deal of attention as it can increase both the capacity and the security of quantum communication largely because the entanglement in all DOFs of photons can be used to carry information, especially with the complete hyperentangled Bell-state analysis [9–13]. It can accomplish the hyperteleportation of an unknown quantum state in more than one DOF [9,10], and this task has been demonstrated probabilistically in experiment [14]. It can be used to complete hyperentanglement swapping [9,10] and quantum repeaters [15]. It can also be used to beat the channel capacity limit for linear photonic superdense coding [16], achieve the deterministic entanglement purification [17–19], and assist the Bell-state analysis of polarization DOF [17,18,20–22]. To date, several kinds of hyperentanglement have been produced in experiment, such as energy–momentum-polarization hyperentangled Bell states, spatial–polarization hyperentangled Bell states, polarization–spatial–time–energy hyperentangled Bell states, and two longitudinal momentum–polarization hyperentangled states.

In high-capacity quantum communication, hyperentanglement distillation is an important technique for depressing the effect of channel noise, including the hyperentanglement concentration protocols (hyper-ECPs) [23–30] for partially hyperentangled pure states and the hyperentanglement purification protocols [31–34] for mixed hyperentangled states, similar to the entanglement concentration [35–42] and entanglement purification [17–19,43–45] of photon systems in one DOF. In the past few years, many interesting hyper-ECPs have been presented for nonlocal hyperentangled photon systems, and they are implemented by either linear-optical elements [23,25,26] or nonlinear-optical elements [24,27–30]. In 2013, Ren et al. [23] presented some hyper-ECPs for two-photon four-qubit hyperentangled states in the polarization and spatial-mode DOFs with linear optics. In 2015, Li and Ghose presented two hyper-ECPs for time-bin–polarization hyperentangled Bell states with linear optics [26]. Recently, the hyper-ECP with nonlinear-optical elements has also been proposed for increasing its success probability [24,27–30].

The previous schemes for hyperentanglement concentration have been proposed to deal with the states that entangled in two DOFs of photon systems. Different from these previous hyper-ECPs, here we investigate the possibility of concentrating the nonlocal photon systems entangled in all the polarization, spatial-mode, and time-bin DOFs with linear optics for the first time. We present three parity-check gates for the nonlocal photon systems entangled in all the three DOFs with linear-optical elements, where the parity-check gate for one DOF will not affect the quantum states in the other two DOFs. With the three parity-check gates, the maximally entangled state in one DOF can be obtained conveniently without affecting the states in the other two DOFs, and the maximally hyperentangled state can be obtained by performing the three parity-check gates on the three DOFs of nonlocal photon systems. This hyper-ECP has a maximal success probability without using the unbalanced interferometer on the time-bin DOF, and it can be directly generalized to concentrate the N-photon polarization–spatial–time-bin hyperentangled Greenberger–Horne–Zeilinger (GHZ) states. As it requires only linear-optical elements, our hyper-ECP is practical and useful for improving the hyperentanglement in high-capacity long-distance quantum communication.

2. Hyper-ECP for two-photon six-qubit hyperentangled Bell state

The two-photon six-qubit maximally hyperentangled Bell state in the polarization, spatial-mode, and time-bin DOFs is described as:

$$|\phi\rangle_{ab} = \frac{1}{2\sqrt{2}}(|HH\rangle + |VV\rangle)_{ab} \otimes (|a_1b_1\rangle + |a_2b_2\rangle) \otimes (|SS\rangle + |LL\rangle)_{ab}. \quad (1)$$