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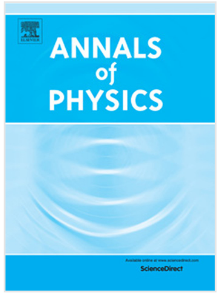

Refined hyperentanglement purification of two-photon systems for high-capacity quantum communication with cavity-assisted interaction

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Refined hyperentanglement purification of two-photon systems for high-capacity quantum communication with cavity-assisted interaction

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Hyperentanglement, defined as the entanglement in multiple degrees of freedom (DOFs) of a photonic quantum system, has attracted much attention recently as it can improve the channel capacity of quantum communication largely. Here we present a refined hyperentanglement purification protocol (hyper-EPP) for two-photon systems in mixed hyperentangled states in both the spatial-mode and polarization DOFs, assisted by cavity quantum electrodynamics. By means of the spatial (polarization) quantum state transfer process, the quantum states that are discarded in the previous hyper-EPPs can be preserved. That is, the spatial (polarization) state of a four-photon system with high fidelity can be transformed into another four-photon system with low fidelity, not disturbing its polarization (spatial) state, which makes this hyper-EPP take the advantage of possessing a higher efficiency.

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I. INTRODUCTION

Quantum entanglement is a key resource in quantum information processing, especially in quantum communication, such as quantum teleportation [1], quantum dense coding [2], quantum key distribution [3, 4], quantum secret sharing [5], and quantum secure direct communication [6–8]. In a secure quantum communication, the remote parties usually require the maximally entangled states to set up their quantum channel. However, the maximally entangled quantum systems can only be produced locally and they will inevitably suffer from environment noise in the process for distribution [9], which will decrease the quality of entanglement and make the quantum communication insecure. Quantum repeaters are required to link two remote quantum nodes in long-distance quantum communication and quantum communication network [10]. The basic idea of a quantum repeater is to divide the total transmission line into segments with a shorter length at the order of the attenuation length [10–12], and then entanglement purification and entanglement swapping can be used to depress the effect of noise and extend the entanglement to a longer distance, respectively.

Entanglement purification is used to distill some high-fidelity maximally entangled quantum systems from an ensemble in a mixed state [13–20]. In 1996, Bennett et al. [13] proposed the first entanglement purification protocol (EPP) to purify a Werner state, resorting to quantum controlled-NOT gates and bilateral rotations. In 2001, Pan, Simon, and Zellinger [14] proposed an EPP for ideal entanglement sources with two polarizing beam splitters (PBSs). In 2002, Simon and Pan [15] proposed an EPP for two entangled photons with two parameter down-conversion (PDC) sources and two PBSs. In 2010, Sheng and Deng [16] proposed the concept of deterministic entanglement purification for two-photon entangled systems, and they presented a two-step deterministic EPP for polarization entanglement with the hyperentanglement in both the spatial mode and the frequency degrees of freedom (DOFs) of photon pairs. Subsequently, Sheng and Deng [17] proposed a one-step deterministic EPP for polarization entanglement with only the spatial entanglement of photon pairs, resorting to linear-optical elements and a PDC entanglement source, and they gave the physical interpretation for one-step deterministic EPP with the density matrix theory. Meanwhile, Li [18] independently presented the one-step deterministic EPP with a simpler optical circuit. In 2011, Deng [19] extended the deterministic EPP for multiple photon systems with the spatial entanglement or the frequency entanglement. In 2014, Sheng and Zhou [20] also described another good deterministic EPP for polarization entanglement assisted by time-bin entanglement. The deterministic EPPs [16–20] are far different from the conventional EPPs [13–15] as they work in a completely deterministic way, not in a probabilistic way, and they can reduce the quantum resource sacrificed largely, which make them very useful in practial quantum repeaters. In 2011, Wang et al. proposed an interesting EPP [21] using cross-Kerr nonlinearity by identifying the intensity of probe coherent beams and another EPP [22] for electron-spin entangled states using quantum-dot spin and microcavity coupled systems.

Hyperentanglement, defined as the entanglement in several DOFs of a quantum system [23–25], has attracted much

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