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Nonlocal hyperconcentration on entangled photons using photonic module system

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Entanglement distribution will inevitably be affected by the channel and environment noise. Thus distillation of maximal entanglement nonlocally becomes a crucial goal in quantum information. Here we illustrate that maximal hyperentanglement on nonlocal photons could be distilled using the photonic module and cavity quantum electrodynamics, where the photons are simultaneously entangled in polarization and spatial-mode degrees of freedom. The construction of the photonic module in a photonic band-gap structure is presented, and the operation of the module is utilized to implement the photonic nondestructive parity checks on the two degrees of freedom. We first propose a hyperconcentration protocol using two identical partially hyperentangled initial states with unknown coefficients to distill a maximally hyperentangled state probabilistically, and further propose a protocol by the assistance of an ancillary single photon prepared according to the known coefficients of the initial state. In the two protocols, the total success probability can be improved greatly by introducing the iteration mechanism, and only one of the remote parties is required to perform the parity checks in each round of iteration.

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Estimates on the system requirements and recent experimental results indicate that our proposal is realizable with existing or near-further technologies.

1. Introduction

Entanglement is an essential resource in a variety of quantum information applications [1–3]. Compared with other systems, photons are considered as the most promising candidate for quantum information carrier since photonic qubits are easy to be manipulated and robust against decoherence. Hence, nonlocally distributed maximally entangled photon systems are often used as quantum channels in quantum communication and distributed quantum computation. However, entangled photons are usually prepared locally and they will inevitably suffer from the channel and environment noise in a practical transmission or storage process. Due to the interaction with the noise, the purity and the degree of nonlocal entanglement will degrade, which will affect the efficiency and security of quantum information proposals.

One of the effective ways to improve the low-quality entanglement is quantum entanglement concentration which is to distill the maximally entangled states from a partially entangled pure state ensemble. Since Bennett et al. [4] proposed the first entanglement concentration protocol (ECP) based on the Schmidt projection method, a number of interesting works on this topic have been reported. For entangled photon systems, practical schemes for the concentration of partially entangled photon pairs have been proposed [5–7] and experimentally demonstrated [8,9] using linear optics. An efficient ECP using cross-Kerr nonlinearities was proposed by Sheng et al. [10]. All these protocols were proposed based on the polarization entanglement of photon systems, and two identical partially entangled initial states are required to distill a maximally entangled state probabilistically. Later, single-photon-assisted ECPs for entangled photon systems were proposed [11–13], which require only one partially entangled state to complete the task of entanglement concentration. The precondition of the protocols is that the coefficients of the initial state should be accurately known to the remote parties beforehand. Moreover, entanglement concentration has also been widely studied in atomic systems [14–18], which exhibit potential applications in quantum repeaters and networks. Recently, Wang et al. [19] investigated the entanglement concentration process of valley qubits by exploiting the optical excitation selection rules in graphene quantum dots, which provides a fast, all-optical manipulation of on-chip qubits and gives an effective way for quantum information processing (QIP) in graphene-based solid systems.

Usually, quantum information can be encoded on different degrees of freedom (DOFs) of photons [20]. In case the photons are simultaneously entangled in more than one DOF, the capacity of optical QIP could be enlarged using such hyperentangled systems [21–23]. So far, hyperentanglement has been adapted for use in various quantum information applications, such as quantum key distribution [24], quantum entanglement purification [25–28], Bell-state analysis [29–33], quantum repeaters [34], and so on. An interesting scheme was recently presented by using the hyperentanglement to realize the deterministic entanglement distillation, which can benefit the secure double-server blind quantum computation in a noise environment [35]. However, hyperentangled photonic systems also suffer from the noise, which will decrease the entanglement on each DOF. In parallel, the concentration of hyperentanglement has attracted much attention in recently years. In 2013, Ren et al. [36] proposed a hyperentanglement concentration (hyperconcentration) protocol for two-photon four-qubit states using linear optics. There are four hyperconcentration protocols introduced in Ref. [36] with two methods. The parameter-splitting method used to concentrate the photon systems in the partially hyperentangled states with known parameters is the optimal one with simple linear optical elements. Later, they proposed another hyperconcentration protocol assisted by