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Generation of three-photon polarization-entangled decoherence-free states

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ABSTRACT

We present a generation proposal of three-photon polarization-entangled decoherence-free states, which are immune to the collective decoherence. Based on weak cross-Kerr nonlinearities, the polarization and spacial entanglement gates are realized, and thus three-photon polarization-entangled decoherence-free states can be produced. According to the outcomes of Homodyne measurement performed in the spacial entanglement gate, one Swap gate is inserted into two paths of the photon 1 to swap its spacial modes, by means of classical feed forward. In addition, in the process for realizing two entanglement gates, unitary transformation operations are performed on the appropriate photons conditioned on the different phase shifts occurred on the coherent states, aiming to obtain the same state under two scenarios of the different path compositions of photons. At the output ports of the circuit, three-photon polarization-entangled decoherence-free states which can be utilized to represent two logical qubits, $|0\rangle_L$ and $|1\rangle_L$ are achieved. Apart from Kerr media, only simple linear optical elements and the classical feed forward techniques are necessary in this proposal, facilitating its practical implementation.

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1. Introduction

Due to the existence of the unwanted interaction between the system and environment, the quantum superposition and coherence are destructed, and as a result the quantum information carried by the system is destroyed. Unfortunately, the environment-induced decoherence cannot be avoided, so it requires the researchers to consider how to solve or alleviate its disadvantageous effects [1–5].

Numerous methods are adopted to overcome the effects resulting from the environment-induced decoherence. Apparently, there is not a simple, single and universal method to repair the system damaged by the completely arbitrary decoherence. Exploiting the idea of classical redundant coding, the method of quantum error correction codes is proposed, where the auxiliary qubits are utilized to detect the occurred errors, by which the appropriate operations are performed to correct the errors induced by decoherence [6–8]. Defeating comparatively slowly decoherence effects, rapidly and actively switching is performed to decouple the interaction between the system and environment by means of dynamical decoupling controls [9–14]. In the method applying the feedback control, the suitable operations are executed to protect coherence of the system based on the obtained measurement information [15–19]. Different from the above methods, the method of decoherence-free subspaces is a passive process to overcome the detrimental effects induced by the collective decoherence which means that each component qubit undergoes the identical decoherence in the system. In these subspaces, for certain symmetrical decoherence mechanism, the system state in one subspace cannot be changed into another subspace no matter how strong decoherence, where the encoded quantum information keeps invariant while the quantum state may be changed [20–24]. Under the circumstance of no shared reference frames or polarization rotation of photons via optical fibers, the decoherence-free subspace method is especially applicable.

In the absence of decoherence-free subspaces, there maybe exist decoherence-free subsystems for encoding quantum information against collective decoherence [25]. As for a two-qubit system, only one decoherence-free state presents, so it cannot be used to protect the quantum information of an arbitrary logical qubit. In three-qubit systems, there is no way to construct decoherence-free subspaces and thus realize universal quantum computation under the collective decoherence, while some of them can be utilized to construct decoherence-free subsystems, the minimal decoherence-free subsystems, intending to keep the quantum information from the interference of the collective decoherence [20,25,26]. Firstly, in nuclear magnetic resonance system, the three-qubit decoherence-free state was investigated and demonstrated [27,24]. In theory, Shao et al. [28] presented a scheme for preparing the three-qubit decoherence-free states employing the spin systems by means of Zeno-like measurements [29].

Especially for optical systems, the encoding in decoherence-free subsystems attracts the extensively attention, aiming to transmit quantum information from one person to another person without being affected by the collective decoherence. For the long-distance quantum communication, without controversy, photons are the optimal quantum information carriers, with the merits of high transmission velocity, low decoherence, and the mature relevant techniques in classical applications.

By virtue of spontaneous parametric down-conversion, the singlet state $|\psi^-\rangle = \frac{1}{\sqrt{2}}(|HV\rangle - |VH\rangle)$ was firstly verified experimentally [30]. As mentioned above, it is the smallest but unique decoherence-free state in the optical systems. Furthermore, its experimental preparation with the linear optics standard model [31] and property investigation in the condition of the collective and noncollective decoherence were presented [32]. Thus far, there are few schemes for preparing three-photon polarization-entangled decoherence-free states.

In this proposal, we focus on the generation of three-photon polarization-entangled decoherence-free states. With the assistance of weak cross-Kerr nonlinearities, we firstly present a feasible proposal for preparing the decoherence-free states in Section 2. In Section 3, we calculate the efficiency and analyze feasibility of this proposal. In Section 4, a summary on our work is presented.

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