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Implementing phase-covariant cloning in circuit quantum electrodynamics

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ABSTRACT

An efficient scheme is proposed to implement phase-covariant quantum cloning by using a superconducting transmon qubit coupled to a microwave cavity resonator in the strong dispersive limit of circuit quantum electrodynamics (QED). By solving the master equation numerically, we plot the Wigner function and Poisson distribution of the cavity mode after each operation in the cloning transformation sequence according to two logic circuits proposed. The visualizations of the quasi-probability distribution in phase-space for the cavity mode and the occupation probability distribution in the Fock basis enable us to penetrate the evolution process of cavity mode during the phase-covariant cloning (PCC) transformation. With the help of numerical simulation method, we find out that the present cloning machine is not the isotropic model because its output fidelity depends on the polar angle and the azimuthal angle of the initial input state on the Bloch sphere. The fidelity for the actual output clone of the present scheme is slightly smaller than one in the theoretical case. The simulation results are consistent with the theoretical ones. This further corroborates our scheme based on circuit QED can implement efficiently PCC transformation.

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1. Introduction

The basic principles of quantum mechanics protect the quantum information from exposure to illegal persons. As mentioned in the no-cloning theorem [1], perfect quantum cloning of arbitrary unknown quantum state is forbidden because of the inherent property of quantum mechanics. This theorem is a consequence of the linearity of quantum mechanics and it is at the basis of the security of quantum communication protocols including quantum key distribution. Quantum key distribution (QKD) is one of the well-known topics of quantum information [2] due to the practical application to quantum communication. However, along with the rapid development of quantum information theory the unknown quantum state can be copied approximately with maximum fidelity and with the copying quality to being independent of initial input state because the no-cloning theorem does not forbid imperfect cloning. The most notable example is the universal quantum cloning machine (UQCM) proposed by Bužek and Hillery [3] in 1996. For the investigation of approximate quantum cloning, it is one of the reasons that from a fundamental research point of view the optimal quantum clones provide insight into the fundamental limits on the manipulation and distribution of quantum information. The other more practical reason is that these clones can be used as very efficient eavesdropping attacks on quantum key distribution protocols [4]. And great effort [5–13] has been devoted to the realization of the optimal approximations to quantum cloning machines (QCMs) motivated by the seminal scheme [3]. Recently, some experiments on quantum cloning have been reported [14–21]. In 2014, a review about various QCMs has been reported by Fan et al. [22]. Bužek and Hillery [3] designed the UQCM which produces two approximate copies from an unknown pure qubit state. The UQCM is a state-independent symmetric cloning. That is to say, all qubit states are cloned with the same fidelity $F = 5/6$.

It is often the case that we possess some a *priori* information about the quantum state but we do not know it exactly. That is why it is important for the study of state-independent cloning. For example, all existing quantum cryptographic experiments are using quantum states that are on the equator, rather than states that span the whole Bloch sphere. Motivated by such a physical implementation of quantum communication ideas, Bruß et al. [6] have presented a PCC with the fidelity 0.854 for the restriction of the input set to the equator of the Bloch sphere. The qubit to be copied lies on the equator, that is to say, the azimuthal angle ϕ on the Bloch sphere can be arbitrary while the polar angle fixed $\theta = \pi/2$ for the qubit. The optimal cloning of equatorial qubits represents an efficient eavesdropping attack on the BB84 quantum key distribution protocol [23]. Using the available *priori* information about the original state to be cloned, it allows us to optimize the cloning process which performs better cloning than the UQCM. Fiurášek [24,25] has generalized the PCC with the prior knowledge of polar angle θ from the full range $[0, \pi]$ and the azimuthal angle ϕ completely unknown, i.e., uniformly distributed between $[0, 2\pi]$. Two optimal 1-to-2 symmetric PCC schemes have been provided [24,25]: one for the states to be copied in the upper hemisphere of the Bloch sphere and the other for those in the lower. Fan et al. [26] have extended the PCC for qubit to one input to many outputs.

We present an efficient scheme for implementation of cloning of qubit states with a *priori* known value of the polar angle by using a superconducting transmon qubit coupled to a waveguide cavity resonator with a highly ideal off-resonant coupling. The information of initial qubit state would be cloned approximately onto a resonator within a higher-dimensional Hilbert space in a cavity, except for onto the transmon qubit by itself. Several proposals exist to use this larger Hilbert space for redundant encoding to allow quantum error correction [27]. Copying an effective two-level system into the large Hilbert space of a continuous variable system, such as that of a harmonic oscillator, may even be more advantageous by allowing for more compact information processing. Recently a proposal [28] has been put forward for encoding, manipulating, and protecting information in photon number parity eigenstates of microwaves dispersively coupled to a superconducting qubit. This provides an exciting new development in the field of coherent state quantum computing. Here, using a three-dimensional circuit QED architecture, we realized a highly ideal strong-dispersive coupling, where the strengths of the off-resonant qubit-cavity interactions were several orders of magnitude greater than the cavity decay rate and higher-order nonlinearities. The strong coupling and coherence possible in this new architecture, along with a new protocol for efficiently transferring qubit states to coherent light states [28], have now enabled Vlastakis et al. [29] to create Schrödinger