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Controllable quantum information network with a superconducting system

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HIGHLIGHTS

- An architecture for quantum information processing is proposed.
- The quantum information transfer between any two selected SQs is implemented.
- This proposal is robust against the decoherence of the system.
- This architecture can be fabricated on a chip down to the micrometer scale.

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ABSTRACT

We propose a controllable and scalable architecture for quantum information processing using a superconducting system network, which is composed of current-biased Josephson junctions (CBJJs) as tunable couplers between the two superconducting transmission line resonators (TLRs), each coupling to multiple superconducting qubits (SQs). We explicitly demonstrate that the entangled state, the phase gate, and the information transfer between any two selected SQs can be implemented, respectively. Lastly, numerical simulation shows that our scheme is robust against the decoherence of the system.

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1. Introduction

Quantum information processing (QIP) is more effective and rapid than classical communication. Quantum networks are the backbone of the QIP. They are distributed quantum many-body systems with controlled information exchange. Similar to classical networks, connecting individual quantum systems by means of modulators creates a quantum network has become a fascinating topic. The different physical systems have been studied for the candidate of quantum computation and quantum information [1–3]. Among the promising quantum systems, each has its own distinct advantages. Such as, ions were trapped by electrical (magnetic) field and manipulated with high precision [4]. The information can be encoded in the internal states as qubits, which exhibit very long coherence times [5]. Through standard state dependent fluorescence techniques, the qubits were measured [6]. Trapped atoms present the weak interaction with the environment, leading to long coherence times [7]. As is known to all, a well-designed quantum network not only requires long coherence time, but also demands scalability, flexible controllability. Fortunately, the superconducting qubits (SQs) exhibit the specific advantages, which can be operated through tunable currents, gate voltage and external flux [8,9]. Recently, the relaxation time $T_1 = 12$ µs and the dephasing time $T_2 = 100$ µs of the SQ have been reported experimentally [10]. Therefore, the SQ systems provide an arena to implement QIP and quantum computation.

Currently, much attention has been paid to study SQ. The coupling between the SQ and the cavity has been studied widely [11]. Then, the coupling between the SQ and the transmission line resonator (TLR) has been proposed in Ref. [12]. This structure is called circuit quantum electrodynamics (QED), which is described by the Jaynes–Cummings model. Experimentally, the strong coupling between a SQ and a TLR has been implemented [13]. Then, the coupling between two SQs with a TLR has been demonstrated [14]; and two-qubit coupling has been realized in this circuit [14]. Wang et al. have realized the deterministic entanglement of photons in two TLRs [15]. Underwood et al. experimentally demonstrated 25 arrays of 12 capacitively coupled TLRs [16]. Theoretically, the coupling between the multiple SQs and a TLR has been proposed [17]. Meanwhile, coupled arrays of a TLR were proposed to study quantum effects such as the quantum phase transition [18], the single photon scattering [19], the single photon transport [20], and the generation of entangled photon pairs [21].

Motivated by these exciting advances, in this paper, we develop an architecture for a controllable and scalable quantum network. In this architecture, the CBJJs act as couplers to induce the coupling of separated TLRs, each coupling to multiple SQs. By adjusting the parameters of each SQ, we can realize the any selected SQ coupling to a TLR. Then, the maximal entangled state (MES) of the any two selected SQs is generated. Moreover, a flexible two-qubit controlling phase gate of the any two selected SQs is realized by means of two single-qubit operations. In addition, we show how to achieve the information transfer between any two selected SQs. More importantly, our proposal can be extended to a large scale quantum system.

The paper is organized as follows. In Section 2, we describe the structure of the quantum networks and give the Hamiltonian for a processing unit of quantum networks. In Section 3, we present the scheme to implement the entanglement of SQs. How to realize a flexible two-qubit controlling phase gate is provided in Section 4. In Section 5, we state quantum information transfer using our scheme. Finally discussions and prospects are made in Section 6.

2. Structure of quantum networks

The schematic of the superconducting quantum network is sketched as Fig. 1(a) (or Fig. 1(c)). This architecture can be described by a Hamiltonian, which is written as

$$\mathscr{H} = \sum H_c^i + H_q + H_T + H_{I1} + H_{I2}, \tag{1}$$

where $H_c^{(i)}$ is the Hamiltonian of the ith SQ, H_q expresses the Hamiltonian of the CBJJ, H_T is the Hamiltonian of the TLR, H_{T1} means the interaction between the SQ and the TLR, and H_{T2} indicates the interaction between the CBJJ and the TLR.