Pis'ma v ZhETF, vol. 117, iss. 11, pp. 865 – 866

Robust and fast quantum state transfer on superconducting circuits

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Submitted 7 April 2023
Resubmitted 20 April 2023
Accepted 28 April 2023

DOI: 10.31857/S1234567823110101, EDN: djrvhp

The Quantum spin chain for QST was first proposed by Bose [1]. In order to achieve perfect transmission with long distance, many kinds of programs have been presented [2–10]. And it is shown that the precise control of coupling strength is a good solution [2–4], but it is challengeable for experiment operations. Therefore, to make the experimental operation as simple as possible, the idea of reducing the ratio of the coupling intensity between the two ends and the chain is put forward [11, 12], where the whole system is simplified into a two-state or three-state system, and then using the characteristics of the energy spectrum, the state is resonately transfered [11, 13]. It is worth noting that in this scheme, high efficiency is accompanied by a small ratio, if high fidelity is obtained, then the transmission time closely associated with the coupling strength will be very long, at the same time, the influence of external factors on the system will enlarge. Therefore, the question of how to shorten the time of state transmission and obtain higher fidelity is our objective.

In this paper, we find another method to achieve state transmission with shorter time and higher fidelity. The idea is to enlarge the proportion of the coupling strength between the two ends and the chain and add alternating on-site potential, which can improve transmission efficiency.

The protocol of description is shown in Fig. 1a, where the coupling strength inside the spin chain is J, and the two relative ends of the chain are connected by the coupling strength g. Thence, the Hamiltonian of the system can be described by

$$\mathcal{H}_1 = \sum_{j=1}^{N} \lambda_j S_j^z + \sum_{j=2}^{N-2} J(S_j^+ S_{j+1}^- + \text{H.c.}) + \\ + g(S_1^+ S_2^- + S_{N-1}^+ S_N^- + \text{H.c.}), \qquad (1)$$

where $\lambda_j = (-1)^j \lambda$ is the on-site potential, and N is the total number of spin qubits. With Jordan–Wigner transformation [14], i.e., $c_j = \exp\left[i\pi(\sum_{l=0}^{j-1} S_l^+ S_l^-)\right] S_j^-$, the Hamiltonian is transformed to

$$\mathcal{H}_1^T = \sum_{j=1}^{N} \lambda_j c_j^\dagger c_j + \sum_{j=2}^{N-2} J(c_j^\dagger c_{j+1} + \text{H.c.}) \\ + g(c_1^\dagger c_2 + c_{N-1}^\dagger c_N + \text{H.c.}). \qquad (2)$$

With the help of "operators" commutation relations, $[\mathcal{H}_1^T, \sum_{j=1}^{N} n_j] = 0$, where $n_j = c_j^\dagger c_j$ is the "particle" number operator, the Hamiltonian of the Eq. (1) is transformed to another Hilbert space consisting of eigenvectors of particle number operators.

In our proposal, there are three parameters $\{J, g, \lambda\}$, which together determine the performance of QST. Our goal is to realize the QST with a longer chain and higher fidelity by searching for appropriate parameters. We display the QST of 9 spin qubits with our scheme. Here and after, setting $J = 1$, we plot the effect of parameters $\{g, \lambda\}$ for QST, as shown in Fig. 1b, and the better results without decoherence and decoherence rate Γ satisfying $\Gamma/J = 10^{-3}$ are displayed. We also extend the length of the chain to 11, and the better results that decoherence rate Γ equals to 0 and satisfies $\Gamma/J = 10^{-3}$ are displayed.

In previous works [11, 13], high-fidelity transmission can be achievable under the restriction condition $J \gg g$, and the long evolution time is accompanied. Besides, if you consider the system's decoherence, the fidelity of the whole operation will be discounted. In our proposal, adding on-site potential to the qubits in the chain, even though g takes a slightly larger value, high-efficiency QST can be achievable within shorter evolution time. More importantly, the scheme is relatively easy to implement in the experiment and details are as follows.

The spin chain is simulated on superconducting circuits, where adjacent transmons are coupled by a large

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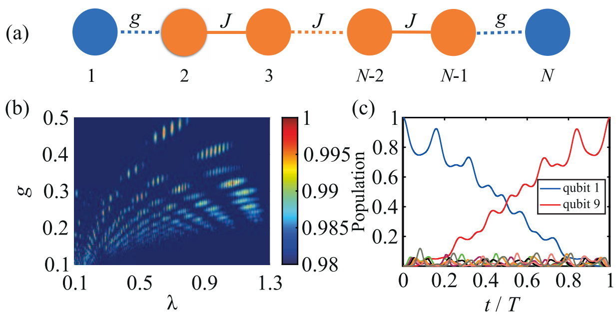

Fig. 1. (Color online) (a) – An illustration of the scheme, a spin chain links the sender (site 1) and the receiver (site N) with coupling strength g, and the coupling strength of the interchain is J, which is set to be 1 in the numerical calculation. (b) – The numerical simulation of large-scale search results in the case $N = 9$. The diagram represents the fidelity distribution on the g-λ plane. (c) – The specific process of state transfer as an example of 9 spin qubits. The system prepares the initial state. After a period of evolution time τ, the state is retrieved from the extreme of the chain with confidence

capacitance. The Hamiltonian of the coupled system can be written as

$$\mathcal{H}_2 = \sum_{l=1}^{N} \frac{\omega_l}{2}\sigma_l^z + \sum_{l=1}^{N-1} \Omega_l(\sigma_l^\dagger \sigma_{l+1} + \text{H.c.}), \tag{3}$$

where ω_l and $\sigma_l^\dagger$ denote the frequency and the creation operator for the lth transmon, respectively, and Ω_l is coupling strength between lth and $(l+1)$th transmons. In accordance with the scheme, tunable coupling strength is necessary and can be achieved by our parametric modulation on the qubits [15]. The representation transformation and rotating-wave approximation is conducted, and then the effective Hamiltonian can be obtained, i.e.

$$\mathcal{H}_2^{\text{eff}} = \sum_{l=1}^{N} \frac{m_l}{2}\sigma_l^z + \sum_{l=1}^{N-1} \Omega_l^{\text{eff}}(\sigma_l^\dagger \sigma_{l+1} + \text{H.c.}), \tag{4}$$

where m_l represents frequency distance between neighboring transmons and external driving, and is determined according to the Hamiltonian to be simulated.

In the case of length for $N = 9$, the coupling strengths of the two ends and the middle are the same separately, that is $\Omega_1 = \Omega_8$, $\Omega_2 = \Omega_3 = ... = \Omega_7$, and $\Omega_1 = 0.31\Omega_2$. And for $N = 11$, the coupling strengths among transmons are identical and remarked as Ω_1. Here, we take the specific values for Ω_2 with respect to 9 transmons and Ω_1 about 11 transmons. With the decoherence rate $\Gamma = 2\pi \times 5$ kHz, numerical simulation in the case $N = 9$ is with fidelity of 99.36 %, and in the case $N = 11$ is 98.62 %, which shows our scheme is robust against decoherence.

In summary, we propose a scheme to implement high-fidelity QST in a spin chain. Our proposal is achieved by modulating coupling strength and adding on-site potential, which effectively reduces the evolution time and has strong robustness against decoherence. In other words, the benefit of our scheme is robust against the decoherence due to shorter time brought by coupling strength. That long distance and high fidelity quantum state transmission will shed light on the realization of a quantum computer in the future.

This is an excerpt of the article “Robust and fast quantum state transfer on superconducting circuits”. Full text of the paper is published in JETP Letters journal. DOI: 10.1134/S0021364023601057

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