Two-Qubit Gate Operation Applied on Nearest Neighboring Qubits in a Neutral Atom Quantum Computer

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We have discussed a design of a neutral atom quantum computer with an on-demand interaction [1]. In this contribution, we propose a feasible experiment towards a two-qubit gate operation that is less demanding than our original proposal, although the gate operation is limited between two neighboring atoms. We evaluate the process of a two-qubit gate operation that is applied on a nearest neighboring trapped atoms and estimate the upper bound of the gate operation time and corresponding gate fidelity.

I. INTRODUCTION

Trapped neutral atoms system might be one of the promising candidates for implementing a scalable quantum computer [2, 3], since neutral atoms have advantage of an intrinsically weaker interaction with the environment; however, two-qubit gate operation is yet a serious challenge in the system. A one-qubit gate operation has been already demonstrated with a two-photon Raman transition [4, 5], which is a well-established technique today. Several proposal have been proposed to implement a two-qubit gate operation, but a quantum gate between two individually addressed atoms has not been demonstrated. Mandel *et all.* [6, 7] have been demonstrated a two-qubit gate operation using hyperfine state dependent optical lattice potentials. A drawback of this implementation is that the gate applies on all the nearest neighbor pairs in the optical lattice simultaneously. We recently proposed a method to apply a two-qubit gate operation on a selected pair of atoms [1] employing the method which demonstrated by Mandel *et all.* In this proposal, an array of apertures are punched in a thin substrate made of silicon. To each aperture, an optical fiber is attached through which two laser beams are fed: one is used to produce near field Fresnel diffraction (NFFD) for trapping atoms, while the other is used to control the hyperfine qubit states of the atom through two-photon Raman transition for applying one-qubit gate operation. Two selected atoms are sent to a one-dimensional optical lattice by manipulating the size of apertures. The collision in the subspace $|0\rangle|1\rangle$ is introduced by controlling the polarization of the counterpropagating laser beams, with which the optical lattice is produced, so that this particular component acquires an extra dynamical phase. Subsequently, the polarizations are reversed and the atoms are sent back to their initial positions in the optical lattice. Finally the atoms are transferred from the optical lattice to the initial Fresnel traps. The most challenging part in the proposal is the aperture size control within microseconds that is circumvented in this new design, which makes the method more friendly to experimentalists; although it is less strong since the two-qubit gate operation can just be applied on the nearest neighboring trapped atoms.

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II. PROPOSAL

There is a thin substrate made of silicon with an array of apertures on it. Two laser beams incident on the screen through an optical fiber which is attached to each aperture. One is used for trapping atom and the other one is used for the one-qubit gate operation. The near field Fresnel diffraction (NFFD) potential is produced by passing laser beam through an aperture with a radius comparable to the wavelength of the laser beam, so that each trap holds a single atom [8]. For definiteness, we assume the NFFD potential is adjusted so that only one atom is trapped by the each trap potential. One-qubit gate operation is implemented by making use of the two-photon Raman transition [4, 5]. Since each lattice site is equipped with its own gate control laser beam, individual single-qubit gate operation can be applied on many qubits individually and simultaneously. A one-dimentional optical lattice is created by applying a pair of counterpropagating laser beams along the site of trapped atoms, so that the minima of the optical lattice is situated at the space coordinates of trapped atoms points. Then we introduce a two-qubit gate operation by making two neighboring atoms collide [1, 6, 7].

We decompose our proposed two-qubit gate operation in five steps. In the following as an example, we take two hyperfine states $|0\rangle = |F = 1, m_{\rm F} = 1\rangle$ and $|1\rangle = |F = 2, m_{\rm F} = 1\rangle$ of ^{87}Rb atoms and evaluate the gate operation process.

Each atom is made into a superposition state $(|0\rangle + |1\rangle)/\sqrt{2}$ in advance by a gate control laser beam propagating through the fiber attached to the aperture.

1. We choose two neighboring trapped atoms to be operated by the gate. The NFFD beams of the two atoms are gradually turned off so that the two atoms are left in the optical lattice.

2. The polarizations of the pair of the counterpropagating laser beams are rotated in opposite directions so that the qubit state $|0\rangle$ is transferred toward positive x-direction, while $|1\rangle$ is transferred toward negative x-direction. Therefore, it is possible to collide $|0\rangle$ of one atom and $|1\rangle$ of the other atom.

3. Now, component $|0\rangle$ of one atom and $|1\rangle$ of the other atom are trapped in the same potential well in the optical lattice. They interact with each other for a duration t_{hold} so that the particular state $|0\rangle|1\rangle$ acquires an extra phase $U_{int}t_{hold}$ compared to other components $|0\rangle|0\rangle$, $|1\rangle|0\rangle$, and $|1\rangle|1\rangle$. Here $U_{int} = (4\pi\hbar^2 a_s/m)\int|\psi|^4 d\mathbf{x}$ is the on-site interaction energy with the atomic mass m and the s-wave scattering length a_s. When t_{hold} satisfies the condition $U_{int}t_{hold} = \pi$, we obtain a nonlocal two-qubit gate $|00\rangle\langle 11| - |01\rangle\langle 01| + |10\rangle\langle 10| + |11\rangle\langle 11|$.

4. After acquiring the phase, two atoms are separated along the optical lattice by an inverse process of step 2.

5. The NFFD lasers are gradually turned on.

III. EXECUTION TIME AND FIDELITY

We have analyzed each step of the two-qubit gate operation and estimated the time required for each step to attain the fidelity 0.99, where fidelity is defined as the overlap between the ground state with the final potential and time-evolved wave function. Here we give an estimate of the execution time and the fidelity of the two-qubit gate operation that are found by numerical simulations, using the time-dependent Schrödinger equation with experimentally realistic parameters.

The overall execution time of a two qubit gate is given by

$$T_{\text{overall}} = 2(T_1 + T_2) + T_{\text{INT}} \simeq 8.45 \text{ ms}. \quad (1)$$

The overall fidelity is estimated as follows. Each of steps 1, 2, 4, 5 involves two independent processes. Since these steps involve two atoms, the fidelity associated with each step must be 0.99^2. Thus the overall fidelity is

$$0.99^8 \sim 0.923, \quad (2)$$

where we assumed that the interaction time is tunable so that step 3 gives a fidelity arbitrarily close to 1.

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