Controllable operation for distant qubits in a two-dimensional quantum network

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We propose a theoretical scheme to realize the coherent coupling of multiple atoms in a quantum network which is composed of a two-dimensional (2D) array of coupled cavities. In the scheme, the pairing off-resonant Raman transitions of different atoms, induced by the cavity modes and external fields, can lead to selective coupling between arbitrary atoms trapped in separated cavities. Based on this physical mechanism, quantum gates between any pair of qubits and parallel two-qubit operations can be performed in the 2D system. The scheme provides a new perspective for coherent manipulation of quantum systems in 2D quantum networks.

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Coherent manipulation of quantum systems at a distance is one of the crucial ingredients in the upcoming area of quantum technologies. The realization of quantum networks composed of many nodes and channels provides opportunities for such purpose, and thus is of great consequence to a series of frontiers, such as quantum computation, communication and metrology [1]. Fundamental to quantum networks are quantum interconnects, which achieve reversible quantum state transformation among separate systems across network nodes. Such quantum connectivity in quantum networks can be realized by matter-light interaction in cavity quantum electrodynamics setups at nodes [2], combined with channels of light tunneling across the nodes [3]. As kinds of matter particles (say, atoms, quantum dots, nitrogen-vacancy (NV) centres in diamond, etc), distributed in network nodes, can act as stationary qubits for information storage; while single photons are suitable to act as flying qubits, that are convenient for conveying from and to the nodes the information exchanged through the matter-light interaction.

In recent years, much attention has been paid to using the atom-light interaction in coupled cavity arrays for investigating novel physical phenomena and its possible applications [4]. Coupled cavity arrays possess advantages over some other systems such as Josephson junction arrays and optical lattices, in respect that in coupled cavity systems the neighboring sites are usually separated by dozens of micrometres thus it is convenient for allowing access to individual site.

Many theoretical studies concerning the use of coupled cavity arrays have been done, as to realize controllable operation for quantum simulation of many-body phenomena [5–11] and for distributed quantum information processing [12–30]. All such researches focus on the cases of either two-site [4, 12, 14, 24, 27, 28] or one-dimensional (1D) [5–8, 11, 13, 26, 29, 30] coupled cavity arrays. Extending such studies to two- (2D) or three-dimensional (3D) coupled cavity arrays is in some sense of more significance, as it is shown that some kinds of 2D and 3D quantum states (say, cluster states) are universal resource for quantum computation [31]. There have been studies considering the 2D coupled cavity arrays, the correlative examples can be found in Ref. [32] and [33], which respectively consider the realization of the fractional quantum Hall system and 2D one-way quantum computation. In these schemes [32, 33], the nearest-neighbor coupling is essential for the nonlocal quantum coherence across the 2D network nodes.

In this paper, we first propose a scheme to control coherently the coupling between two arbitrary atomic qubits at distant (not necessarily the nearest-neighbor) nodes in a 2D array of coupled cavities. The scheme follows a previous study by Zheng et al. [30], which deals with a 1D case considering the neighboring cavities that are linked by other resonators such as ‘short optical fibers’. In the scheme, the off-resonant Raman transitions between two ground states of the atoms, induced by the cavity modes and the external fields, can lead to selective coupling between arbitrary two distant atoms across the 2D network nodes, while with all the atoms as well as with all the cavity modes only virtually excited. Quantum logic operations between any pair of distant atomic qubits and parallel two-qubit operations on selective qubit pairs can be implemented by appropriately selecting the parameters of the external fields.

We consider a coupled $N \times N$ cavity array, as shown in FIG. 1. In each site (denoted here by $jk$) there are two cavity modes, which respectively couple to their neighboring ones through the $x$ and $y$ directions with inter-
cavity photon hopping. The interaction Hamiltonian for the coupling between the cavities can be modeled by

\[ H_1 = \sum_{j,k} \{ v_x a_j^x a_{j+1}^x + v_y a_j^y a_{j+1}^y + \text{h.c.} \}, \]

where \( a_{jk}^u \) (\( u = x, y \)) denotes the annihilation operator for the mode of the \( jk \)th cavity, and \( v^u \) is the coupling rate between cavities in the \( u \) channel. Each site contains a \( \Lambda \)-type atom, with two ground states \( |g\rangle_{jk} \) and \( |f\rangle_{jk} \), and one excited state \( |e\rangle_{jk} \), as shown in Fig. 2. The atom interacts with these cavity modes through the transition \( |g\rangle_{jk} \leftrightarrow |e\rangle_{jk} \), with coupling rates \( g_{jk}^u \) and \( g_{jk}^y \), and detunings \( \Delta_{jk,1}^u \) and \( \Delta_{jk,1}^y \). Two classical fields with Rabi frequencies \( \Omega_{jk}^x \) and \( \Omega_{jk}^y \) are applied to drive the atomic transition \( |f\rangle_{jk} \leftrightarrow |g\rangle_{jk} \), with detunings \( \Delta_{jk,2}^u \) and \( \Delta_{jk,2}^y \).

The interaction Hamiltonian describing the interaction of the atoms with the cavity modes and classical fields can be written as

\[ H_2 = \sum_{j,k=1}^N \sum_{u=x,y} \left[ g_{jk}^u a_k^u a_{jk+1}^u + \text{h.c.} \right] + \Omega_{jk}^u a_j^u \langle e | \hat{a}_j^u | f \rangle \langle f | \hat{a}_j^u | g \rangle + \text{h.c.}. \]

We adopt periodic boundary conditions \( a_{jk}^u = a_{jN} \) and \( a_{jk}^u = a_{jN} \), by introducing the nonlocal bosonic modes \( e_{mn}^u \) \( u = x \), \( y \), and making the transformation \( a_{jk}^u = \frac{1}{N} \sum_{m=1}^N \sum_{n=1}^{\tilde{N}} \exp[-i(\tilde{N}m + \tilde{N}n)]e_{mn}^u \). Thus we can rewrite the Hamiltonian \( H_1 \) and \( H_2 \) as

\[ H_1 = \sum_{u=x,y} \sum_{m,n} \left[ \sum_{j,k=1}^N \omega_{mn}^u e_{mn}^u e_{mn}^u + \text{h.c.} \right], \]

and

\[ H_2 = \sum_{u=x,y} \sum_{m,n} \left[ \sum_{j,k=1}^N \Omega_{jk}^u e^{i\Delta_{jk,1}^u t} e_{mn}^u e_{mn}^u + \text{h.c.} \right] \]

where \( \omega_{mn}^x = 2v_x \cos(\frac{\pi}{N}) \), \( \omega_{mn}^y = 2v_y \cos(\frac{\pi}{N}) \). We now go into a new frame by defining \( H_2 \) as a free Hamiltonian, and obtain the interaction Hamiltonian for the whole system as

\[ H_2' = \sum_{j,k=1}^N \sum_{u=x,y} \{ \Omega_{jk}^u e^{i\Delta_{jk,1}^u t} e_{mn}^u e_{mn}^u + \text{h.c.} \} \]

Considering the large detuning case with \( \Delta_{jk,2}^u \gg \Omega_{jk}^u \), and \( \Delta_{jk,1}^u = \omega_{mn}^u - \omega_{mn}^u \), we can adiabatically eliminate the excited state \( |e\rangle_{jk} \), and turn \( H_2' \) to

\[ H_2'' = -\sum_{j,k=1}^N \sum_{u=x,y} \left\{ \sum_{m,n} \left[ \sum_{j,k=1}^N \Omega_{jk}^u e^{i\Delta_{jk,1}^u t} e_{mn}^u e_{mn}^u + \text{h.c.} \right] \right\} \]

where \( \xi_{jk}^u = \frac{(\Omega_{jk}^u)^2}{\lambda_{jk}^u} \), and \( \lambda_{jk}^u = g_{jk}^u (\frac{1}{\Delta_{jk,1}^u - \omega_{mn}^u} + \frac{1}{\Delta_{jk,2}^u}) \). The first and second terms of Eq. (6) describe Stark shifts respectively induced by the classical fields and bosonic modes, while the last two terms describe the multiple off-resonant Raman transitions for each atom induced by
the classical fields and the bosonic modes. Under the condition $|\Delta_{\nu,1} - \omega_{\nu,1} - \Delta_{\nu,2}| \gg \lambda_{\nu,1}$, the bosonic modes are only virtually excited. This thus leads to the quadrupled Stark shifts and effective coupling between the atoms, and gives the effective Hamiltonian

$$H_e = \sum_{j,k} \sum_{u=x,y} \{ -\varepsilon_{j,k}^u [f]_{jk} \langle f \rangle + \sum_{m,n} [-\zeta_{j,k}^u g]_{jk} \langle g | c_{mn} c_{mn}^\dagger \rangle + \chi_{j,k}^u S_{pq}^+ S_{pq}^- \} \times e^{-i[(\Delta_{pq,1} - \Delta_{pq,1}) - (\Delta_{pq,2} - \Delta_{pq,2})]t} + h.c. \},$$

(7)

with

$$\varepsilon_{j,k}^u = \frac{(\lambda_{j,k}^u)^2}{\Delta_{j,k,1} - \omega_{mn} - \Delta_{j,k,2}},$$

(8)

and

$$\chi_{j,k}^u = \sum_{m,n} \frac{1}{2} \frac{1}{\Delta_{j,k,1} - \omega_{mn} - \Delta_{j,k,2}} \times \frac{1}{\Delta_{pq,1} - \omega_{mn} - \Delta_{pq,2}} \times \frac{1}{e^{-i[2(j-p) + 2(k-q)]}} \{ \equiv \chi_{j,k}^u \} \times e^{-i[(\Delta_{pq,1} - \Delta_{pq,1}) - (\Delta_{pq,2} - \Delta_{pq,2})]t} + h.c. \},$$

(9)

As the quantum number of the bosonic modes is conserved during the interaction, they will remain in the vacuum state if they are initially in the vacuum state. Then $H_e$ reduces to

$$H_e = \sum_{j,k} \sum_{u=x,y} \{ \varepsilon_{j,k}^u [f]_{jk} \langle f \rangle + \sum_{p,q} \chi_{j,k}^u S_{pq}^+ S_{pq}^- \} \times e^{-i[(\Delta_{pq,1} - \Delta_{pq,1}) - (\Delta_{pq,2} - \Delta_{pq,2})]t} + h.c. \},$$

(10)

where $\varepsilon_{j,k}^u = \sum_{m,n} \varepsilon_{j,k}^u - \varepsilon_{j,k}^u$.

The Hamiltonian in Eq. (10) allows for the coherent operation of two arbitrary distant qubits across the 2D quantum network. In order to do so, we apply classical fields to the $j$-th and $p$-th qubits, and select the frequencies for the cavity and classical fields in such a way that the conditions $g_{j,k}^u = g_{pq}^u$, $\Omega_{j,k}^u = \Omega_{pq}^u$, and $\Delta_{pq,1} - \Delta_{pq,2} = \Delta_{pq,2} - \Delta_{pq,1}$ are also fulfilled. Thus the effective Hamiltonian $H_e$ reduces to

$$H_{e,j,k} = \varepsilon_{j,k}^u [f]_{jk} \langle f \rangle + \chi_{j,k}^u S_{pq}^+ S_{pq}^- \} \times e^{-i[(\Delta_{pq,1} - \Delta_{pq,1}) - (\Delta_{pq,2} - \Delta_{pq,2})]t} + h.c. \},$$

(11)

with $\varepsilon_{j,k}^u = \sum_{u=x,y} \varepsilon_{j,k}^u$, $\chi_{j,k}^u = \sum_{u=x,y} \chi_{j,k}^u$, and $j \neq p$.

We assume the $j$-th and $p$-th qubits are first in state $|\psi(0)\rangle = |f \rangle_{jk} |g \rangle_{pq}$, the time evolution can be expressed as $|\psi(t)\rangle = e^{-iH_{e,j,k}t} |\psi(0)\rangle = e^{-i\Delta_{pq,1}t} \cos(\chi_{j,k}^u t) |f \rangle_{jk} |g \rangle_{pq} - i \sin(\chi_{j,k}^u t) |j \rangle_{jk} |p \rangle_{pq}$. After an interaction time $\frac{\pi}{\chi_{j,k}^u}$, the two qubits evolve to a maximal entangled state $|\psi\rangle_{e,n} = e^{-i\Delta_{pq,1}t} \cos(\chi_{j,k}^u t) |f \rangle_{jk} |g \rangle_{pq} - i \sin(\chi_{j,k}^u t) |j \rangle_{jk} |p \rangle_{pq}$. Or, if the two qubits are in state $|\psi(0)\rangle = (c_0 |f \rangle_{jk} + c_1 |g \rangle_{jk}) |g \rangle_{pq}$, with $|c_0|^2 + |c_1|^2 = 1$. After an interaction time $t = \frac{\pi}{\chi_{j,k}^u}$, the state of the $j$-th qubit is now transferred to that of the $pq$-th qubit, i.e., the two qubits are finally in $|\psi\rangle_{e} = |g \rangle_{jk} (-i e^{-i\Delta_{pq,1}t} c_0 |f \rangle_{pq} + c_1 |g \rangle_{pq})$.

We notice that the selective parallel two-qubit operation on different qubit pairs can also be implemented in such a 2D model. Suppose that one wants to perform gates on qubit pairs $(j,k,pq)$ and $(j'k',p'q')$. Then we drive each of these qubits with two classical fields. The parameters of the system are suitably adjusted so that all such conditions $g_{jk}^u = g_{pq}^u$, $\Omega_{jk}^u = \Omega_{pq}^u$, $\Delta_{jk,1} = \Delta_{pq,1}$, $\Delta_{jk,2} = \Delta_{pq,2}$, $g_{jk}^{k'} = g_{pq}^{k'}$, $\Omega_{jk}^{k'} = \Omega_{pq}^{k'}$, $\Delta_{jk,k'} = \Delta_{pq,k'}$, $\Delta_{jk,k'} = \Delta_{pq,k'}$, and $|\Delta_{jk,1} - \Delta_{pq,1} - \Delta_{jk,2} + \Delta_{pq,2}| \gg \lambda_{jk}^u$ for $(jk,pq; k'p',q')$ are also satisfied. In such a case, qubit $j,k$ ($j',k'$) only couples to qubit $pq$ ($p',q'$), while it decouples to qubits $j'k'$ ($jk$) and $p'q'$ ($pq$). Therefore the effective Hamiltonian is given by

$$H_{e,par} = \varepsilon_{j,k}^u [f]_{jk} \langle f \rangle + \chi_{j,k}^u S_{pq}^+ S_{pq}^- \} \times e^{-i[(\Delta_{pq,1} - \Delta_{pq,1}) - (\Delta_{pq,2} - \Delta_{pq,2})]t} + h.c. \},$$

(11)

where $\varepsilon_{j,k}^u = \sum_{m,n} \varepsilon_{j,k}^u - \varepsilon_{j,k}^u$, $\chi_{j,k}^u = \sum_{u=x,y} \chi_{j,k}^u$, and $j \neq k'$. This thus allows us to effectively perform two-qubit operations on qubit pairs $(jk,pq)$ and $(j,k')$ ($p,q')$ simultaneously.

To confirm the validity of all our above arguments, we numerically simulate the dynamics governed by the derived effective model in Eq. (11), and compare it to the dynamics governed by the full Hamiltonian

$$H_f = \sum_{j,k} \sum_{u=x,y} \{ \omega_{j,k}^u |f \rangle_{jk} \langle f | + \omega_{g,e}^u |e \rangle_{jk} \langle e | + \sum_{u=x,y} \sum_{j,k} \langle g^u \rangle_{j,k} a_{jk}^u a_{jk}^u \} \times e^{-i[(\Delta_{pq,1} - \Delta_{pq,1}) - (\Delta_{pq,2} - \Delta_{pq,2})]t} + h.c. \},$$

(13)

where $\omega_{j,k}^u$ and $\omega_{g,e}^u$ are the frequency for the state $|g \rangle_{jk}$ and $|e \rangle_{jk}$ ($\langle g \rangle_{jk}$ is assumed to be null energy level), and $\omega_{c,j,k}$ and $\omega_{c,j,k}$ are frequencies for the cavity and classical fields. We consider the number with $N = 2$, and set the parameters in the following way (in $u = x, y$): $v_u = g$, $\Omega_{j,k}^u = \Omega_{pq}^u = 1.5g$, $\Delta_{j,k}^u = \Delta_{pq}^u = 10g$, $\Delta_{j,k}^u = \Delta_{pq}^u = 13.9g$, $\Delta_{j,k}^u = \Delta_{pq}^u = 20g$, $\Delta_{j,k}^u = \Delta_{pq}^u = 23.9g$, and $\Omega_{j,k}^u = 0$ ($j,k = 12, 21$). The validity of the effective model is numerically simulated by taking the evolution of the occupation probability $P = |\langle \psi | \psi(t) \rangle|^2$ of the state $|\psi \rangle = |f \rangle_{12} |g \rangle_{12} |g \rangle_{21} |g \rangle_{22}$ as an example, while assuming initially the atoms are in state $|\psi \rangle$ and all the cavity modes are in vacuum state. FIG. 3 illustrates the numerical results obtained from both the effective (red-solid line) and full (blue-dashed line) Hamiltonians. Discrepancies between the two curves are due to higher terms for the parameters $\varepsilon_{j,k}^u$ and $\chi_{j,k}^u$. Even now, it is obvious that the effective model is valid, its deviation can be made to be smaller as soon as the relative parameters are appropriately fixed.
In Fig. (3), we get 
$$\sum_{i=1}^{\chi} \chi_i$$
For |(blue-dashed line) models, the atoms are initially in state
$$|\psi(t)\rangle = |11\rangle|21\rangle|g\rangle_{22},$$
while all the cavity modes are in vacuum state. The relative parameters are set to be
$$(u = x, y): v^x = g, \Omega^x_{11} = \Omega^x_{22}, g_1^{x} = 2.9 g, \Delta_{11,1} = \Delta_{22,1} = 9 g, \Delta_{11,2} = \Delta_{22,2} = 13.9 g, \Delta_{12,1} = \Delta_{21,1} = 20 g, \Delta_{21,2} = \Delta_{22,2} = 23.9 g, $$
and $\Omega^x_{jk} = 0$ $(jk = 12, 21)$.

It is necessary to give a brief discussion of the experimental feasibility of the proposed scheme. For $N = 2$ and for the parameters introduced in Fig. (3), we get
$$\chi_1 = \sum_{u=x,y} \chi_{jkpq} = \sum_{u=x,y} \sum_{m,n} \frac{1}{2} \chi_{11} \chi_{22} e^{-i(2 \frac{\Delta_{11,1}}{2} + \frac{\Delta_{22,1}}{2})} = 7.67 \times 10^{-3} g, $$
and the time needed to complete the entangling operation between qubit 11 and qubit 22 is $t = 0.52 \times 10^5 g$.

The probability that the atoms undergo a transition to the excited state due to the off-resonant interaction with the classical fields is $p_1 = \frac{2 \times 10^{-11}}{\Delta_{21,1}^2} = 2.25 \times 10^{-2}$.

Meanwhile, the probability that the field modes are excited due to off-resonant Raman couplings is
$$p_2 = \sum_{u} \sum_{jk} \frac{(\chi^x_{jk})^2}{\Delta_{11,1} + \Delta_{22,1}} = 4.96 \times 10^{-4}. $$

The effective decoherence rates due to the atomic spontaneous emission and the field decay are $\gamma_e = p_1 \gamma$ and $\kappa_e = p_2 \kappa$, where $\gamma$ and $\kappa$ are the decay rates for the atomic excited state and the field modes, respectively. The parameter in a strongly coupled single quantum dot-cavity system reported in Ref. [3] is $\gamma \sim 5 \times 10^{-4} g (\kappa = \frac{\gamma}{1000})$.

This corresponds to a cooperativity factor $g^2/2\gamma \kappa \sim 10^5$, which is assumed to be available [38]. Then the effective decoherence rates are
$$\gamma_e \sim 6.75 \times 10^{-5} g$$
and $\kappa_e \sim 2 \times 10^{-7} g$. This leads a gate fidelity with $F \simeq 1 - \gamma_e + \kappa_e/\gamma \simeq 99\%$.

In conclusion, we propose a theoretical scheme to realize the coherent coupling between two arbitrary qubits in a 2D quantum network. We consider the scheme in a 2D coupled cavity system. In such a case, the pairing off-resonant Raman transitions of distant atoms, induced by the cavity modes and external fields, can lead to selective coupling between two arbitrary atoms trapped in separated cavities; quantum gates between any pair of qubits and parallel two-qubit operations in the network can be performed. The scheme can also be applied to N-V ensemble-based quantum network [39, 40].

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