Quantum Information and Computation, Vol. 12, No. 7&8 (2012) 0601–0608

FAST iSWAP GATE USING TWO Q SWITCHES

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Received November 14, 2010
Revised March 19, 2012

An effective approach to the construction of iSWAP gate has been proposed. Working with three atoms inside three coupled cavities, we analyze the transport and the confinement of a single photon along two different directions. It is shown that two Q switches can be built by tuning the transition energy of each atom. Applying a classical field, we can implement high-speed gate operation between photon and atom. In addition, the influence of decoherence on the gate fidelity is also discussed.

Keywords:

Communicated by: I Cirac & G Milburn

A quantum computer operates by manipulating the quantum state of given physical systems with a fixed sequence of quantum logic gates [1]. Therefore, implementing quantum logic gate is crucial to further progress towards for building a quantum computer. Recently, a lot of theoretical ideas have been floated to achieve quantum gate in different systems. We may mention cavity quantum electrodynamics (QED) [2, 3, 4, 5], quantum dots [6], and trapped ions [7] as examples. In experiment, motivated by the pioneering work [8], the realization of a controlled-NOT gate is reported by sequentially applying three Raman pulses to an ion [9]. In addition, three-qubit Toffoli gate has been realized in an ion trap quantum computer with a mean gate fidelity of 71% [10]. All the works mentioned above are very promising and highly inventive. However, scalability is the main obstacle for large-scale quantum information processing. For example, generating cluster state with a large number of qubit still remains elusive. With the aim of achieving scalable quantum computation, some attractive schemes [11, 12, 13] are investigated for the generation of one-dimensional or multi-dimensional cluster states by using the imaginary SWAP (iSWAP) gate.

Coupled cavity arrays are ideally suited to addressing individual spins as the optical wave-length of resonant mode is considerably smaller than the distance between two adjacent cavities. Up to now, the model has been realized in many experimental systems, such as photonic crystals [14], optical microcavities [15], and superconducting devices [16]. In addition, many theoretical works have been proposed to simulate Heisenberg spin chains [17], study the dynamics of two coupled cavities [18], and generate entangled states [19]. On the other hand, the development of Q switch opens a door for changing the cavity from high Q to low Q [20]. Some recent proposals based on Q switch exist including pulse shaping [21], quantum gate [22], quantum communication [23]. Different from the one-cavity case, by tuning an effective Q switch (a low-Q cavity), the problem that it is difficult to outcouple excitations from high-Q cavity might be solved through adiabatic transfer. Then one can use extremely-good cavity as an ideal environment for achieving high-fidelity quantum state manipulation between input pulse and atom.

In this paper, motivated by these works, we discuss how to deterministically implement an iSWAP gate by two Q switches in coupled cavities. Two cavity-atom systems q_1 and q_2 along two different directions act as the Q switches for a high-Q cavity (see Fig. 1). By actively tuning the transition frequencies of atoms q_1 and q_2, the photon in vertical and horizontal polarization (v and h) is stored in the cavity s via a reversible adiabatic process. Then, a two-photon Raman transition is induced by applying a classical field to atom s. After the photon is outcoupled from the cavity arrays, quantum gate operation between photon and atom is achieved. Our proposal has four advantages as follows: (1) The gate operation can be achieved using the full cavity bandwidth along two polarization directions due to the presence of two Q switches. That is, the cavity of low bandwidth is not necessary. (2) The interaction between stationary and flying qubits is very useful for quantum information processing. The process corresponds to adiabatic transfer completed for a long time. However, the adiabatic transfer is an effective way by which the input-output control of pulse can be performed. By applying a classical field, a relatively fast iSWAP gate is implemented. If the applied classical field is absent, in order to implement the gate operation, a swap gate followed by a control-Z gate together with two single-qubit rotations should be required. (3) Quantum information is encoded as qubits in h or v polarization state. Thus, single-qubit operations are easy to perform by linear optical elements. (4) The proposal is scalable, i.e., the multi-atom (photon) cluster state can be generated after sequentially interacting with one single-photon pulse (an atom).

First, we explain the basic idea of our scheme for implementing iSWAP gates. Consider three four-level atoms trapped in three cavities as shown in Fig. 1. All atoms have two ground states ($|g\rangle$ and $|f\rangle$) and two excited states ($|e\rangle$ and $|r\rangle$). The transitions $|f\rangle \to |e\rangle$ and $|g\rangle \to |r\rangle$ are coupled to cavity modes along x and y directions, respectively. Under rotating-wave approximation, the Hamiltonian of the whole system has the following form

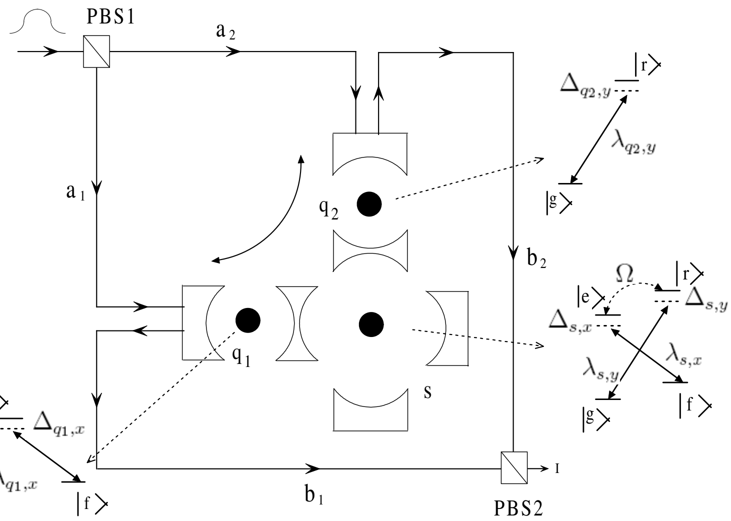

Fig. 1. Schematic setup to implement the iSWAP gate. Correspondingly, the energy level diagram of atoms is shown.

(setting $\hbar = 1$)

$$
\begin{aligned}
H &= H_s + H_b + H_{bs}, \\
H_s &= \Delta_{s,x}|e\rangle_s\langle e| + \Delta_{s,y}|r\rangle_s\langle r| + \Delta_{q_1,x}|e\rangle_{q_1}\langle e| + \Delta_{q_2,y}|r\rangle_{q_2}\langle r| \\
&\quad +\delta_{q_1,x}a^\dagger_{q_1,x}a_{q_1,x} + \delta_{q_2,y}a^\dagger_{q_2,y}a_{q_2,y} + (\Omega|e\rangle_s\langle r| + \lambda_{s,x}|e\rangle_s\langle f|a_{s,x} + \lambda_{s,y}|r\rangle_s\langle g|a_{s,y} \\
&\quad +\lambda_{q_1,x}|e\rangle_{q_1}\langle f|a_{q_1,x} + \lambda_{q_2,y}|r\rangle_{q_2}\langle g|a_{q_2,y} + \nu a^\dagger_{s,x}a_{q_1,x} + \nu a^\dagger_{s,y}a_{q_2,y} + \text{H.c.}), \\
H_b &= \int_{-\infty}^{\infty}\omega[b^\dagger_x(\omega)b_x(\omega) + b^\dagger_y(\omega)b_y(\omega)]d\omega, \\
H_{bs} &= \int_{-\infty}^{\infty}\sqrt{\frac{\kappa}{2\pi}}[b_x(\omega)a^\dagger_{q_1,x} + b_y(\omega)a^\dagger_{q_2,y} + \text{H.c.}]d\omega, \qquad (1)
\end{aligned}
$$

where the subscript $\{s, q_1,q_2\}$ corresponds to atom or cavity-$\{s, q_1,q_2\}$, while the subscript x/y denotes the x/y direction. $a_{\alpha,k}$ is the anihilation operator for the cavity α along k direction ($\alpha = \{s, q_1, q_2\}$ and $k = \{x, y\}$). $\lambda_{\alpha,k}$ is the coupling rate between the atomic transition and the corresponding cavity mode. A classical field drives the transition $|e\rangle \leftrightarrow |r\rangle$ with Rabi frequency Ω. Note that the classical field can be realized by a two-photon Raman transition via an auxiliary level [24]. $b_k(\omega)$ are the annihilation operators for these photons at frequency ω in free-space modes. κ is the cavity damping rate. ν describes the intercavity hoping rate of the photon. In one-quantum manifold, i.e., for the state $|g\rangle_s|f\rangle_{q_1}|g\rangle_{q_2}|0\rangle_s|0\rangle_{q_1,x}|1\rangle_{q_2,y}|vac\rangle$, the wave function of the system at arbitrary time is described by

$$
\begin{aligned}
|\psi\rangle \;=\; & C_1(t)|g\rangle_s|f\rangle_{q_1}|g\rangle_{q_2}|0\rangle_s|0\rangle_{q_1,x}|1\rangle_{q_2,y}|vac\rangle + C_2(t)|g\rangle_s|f\rangle_{q_1}|r\rangle_{q_2}|0\rangle_s|0\rangle_{q_1,x}|0\rangle_{q_2,y}|vac\rangle \\
& +C_3(t)|g\rangle_s|f\rangle_{q_1}|g\rangle_{q_2}|1\rangle_{s,y}|0\rangle_{q_1,x}|0\rangle_{q_2,y}|vac\rangle + C_4(t)|r\rangle_s|f\rangle_{q_1}|g\rangle_{q_2}|0\rangle_s|0\rangle_{q_1,x}|0\rangle_{q_2,y}|vac\rangle \\
& +C_5(t)|e\rangle_s|f\rangle_{q_1}|g\rangle_{q_2}|0\rangle_s|0\rangle_{q_1,x}|0\rangle_{q_2,y}|vac\rangle + C_6(t)|f\rangle_s|f\rangle_{q_1}|g\rangle_{q_2}|1\rangle_{s,x}|0\rangle_{q_1,x}|0\rangle_{q_2,y}|vac\rangle \\
& +C_7(t)|f\rangle_s|f\rangle_{q_1}|g\rangle_{q_2}|0\rangle_s|1\rangle_{q_1,x}|0\rangle_{q_2,y}|vac\rangle + C_8(t)|f\rangle_s|e\rangle_{q_1}|g\rangle_{q_2}|0\rangle_s|0\rangle_{q_1,x}|0\rangle_{q_2,y}|vac\rangle \\
& +f^y_{out}|f\rangle_s|f\rangle_{q_1}|g\rangle_{q_2}|0\rangle_s|0\rangle_{q_1,x}|0\rangle_{q_2,y}|\Phi\rangle, \qquad (2)
\end{aligned}
$$

where $|vac\rangle$ means that there is no photon in free-space modes. The amplitude of the output pulse f^x_{out} along x direction is related to the input by the standard input-output relation $f^x_{out} = \sqrt{\kappa}C_7(t) + f^x_{in}$. By the Schrödinger equation (under the action of the Hamiltonian (1)), we can obtain the following differential equations

$$
\begin{aligned}
\dot{C_1}(t) &= -i\nu C_3(t) - i\lambda_{q_2,y}C_2(t) - i\delta_{q_2,y}C_1(t) - (\kappa+\kappa_1)/2C_1(t) - \sqrt{\kappa}f^y_{in}, \\
\dot{C_2}(t) &= -i\lambda_{q_2,y}C_1(t) - i\Delta_{q_2,y}C_2(t) - \gamma_1/2C_2(t), \\
\dot{C_3}(t) &= -i\nu C_1(t) - i\lambda_{s,y}C_4(t) - \kappa_1/2C_3(t), \\
\dot{C_4}(t) &= -i\lambda_{s,y}C_3(t) - i\Omega C_5(t) - i\Delta_{s,y}C_4(t) - \gamma_1/2C_4(t), \\
\dot{C_5}(t) &= -i\lambda_{s,x}C_6(t) - i\Omega C_4(t) - i\Delta_{s,x}C_5(t) - \gamma_1/2C_5(t), \\
\dot{C_6}(t) &= -i\lambda_{s,x}C_5(t) - i\nu C_7(t) - \kappa_1/2C_6(t), \\
\dot{C_7}(t) &= -i\nu C_6(t) - i\lambda_{q_1,x}C_8(t) - i\delta_{q_1,x}C_7(t) - (\kappa+\kappa_1)/2C_7(t), \\
\dot{C_8}(t) &= -i\lambda_{q_1,x}C_7(t) - i\Delta_{q_1,x}C_8(t) - \gamma_1/2C_8(t), \qquad (3)
\end{aligned}
$$

where γ_1 is atomic spontaneous emission rate and κ_1 is the transverse decay rate of cavity. f^y_{in} represents the input pulse [21]. The dynamics of the system can be described numerically. Based on the system described above, we can perform the iSWAP gate between flying (photonic) and stationary (atomic) qubits by using two Q switches. Without loss of generality, let us assume that the state of the input photon is $1/\sqrt{2}(|h\rangle + |v\rangle)$ and the state of atom is $1/\sqrt{2}(|g\rangle_s + |f\rangle_s)$. After the polarization beam passes polarization beam splitter (PBS1), the photon in $|v\rangle$ or $|h\rangle$ propagates through the path a_1 or a_2. Once the photon passes through the whole setup shown in Fig. 1, the iSWAP gate will be completed. Under the basis $\{|g\rangle_s|v\rangle, |g\rangle_s|h\rangle, |f\rangle_s|v\rangle, |f\rangle_s|h\rangle\}$, the iSWAP gate is given by the following unitary transformation

$$
U_{iSWAP} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & i & 0 \\ 0 & i & 0 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}. \qquad (4)
$$

The implementation of the gate operation between atom s and photon consists of the following three steps:

(1) When we switch off the classical field, the evolution of the system is determined by the initial state of photon (for example, if the photon is in state $|v\rangle/|h\rangle$, it will enters the cavity q_1/q_2). In general, the whole system is a complicated problem to treat exactly. To make things clear, we ignore κ as our zeroth order approximation. Then, the approximate eigenstates of each cavity system can be expressed as (corresponding to the Hamiltonian H_s

omitting the hopping term)

$$\begin{aligned}|\phi^{\pm}_{s,k}\rangle &= N_k[(\Delta_{s,k} \pm \chi_{s,k})|h_k\rangle_s|0\rangle_{s,k} + 2\lambda_{s,k}|m_k\rangle_s|1\rangle_{s,k}],\\ |\psi^{\pm}_{\xi,k}\rangle &= N'_k[(\delta_{\xi,k} - \Delta_{\xi,k} \pm \Xi_{\xi,k})|h_k\rangle_\xi|0\rangle_{\xi,k} + 2\lambda_{\xi,k}|m_k\rangle_\xi|1\rangle_{\xi,k}],\end{aligned} \tag{5}$$

where $\chi_{s,k} = \sqrt{\Delta^2_{s,k} + 4\lambda^2_{s,k}}$ and $\Xi_{\xi,k} = \sqrt{\delta^2_{\xi,k} - 2\delta_{\xi,k}\Delta_{\xi,k} + \Delta^2_{\xi,k} + 4\lambda^2_{\xi,k}}$. h_x and m_x (h_y and m_y) are e and f (r and g), respectively. N_k and N'_k are the normalization factors. The subscripts $\{\xi, k\}$ are $\{q_1, x\}$ or $\{q_2, y\}$. The associated eigenenergies are

$$\begin{aligned}\varsigma^{\pm} &= \frac{1}{2}(\Delta_{s,k} \pm \chi_{s,k}),\\ \eta^{\pm} &= \frac{1}{2}(\delta_{\xi,k} + \Delta_{\xi,k} \pm \Xi_{\xi,k}).\end{aligned} \tag{6}$$

In the limit $\Delta_{s,k} \gg \lambda_{s,k}$ and $\Delta_{\xi,k} \gg \{\lambda_{\xi,k}, \delta_{\xi,k}\}$, we have $|\phi^-_{s,k}\rangle \approx |m_k\rangle_s|1\rangle_{s,k}$ and $|\psi^+_{\xi,k}\rangle \approx |m_k\rangle_\xi|1\rangle_{\xi,k}$. Because the eigenenergies change with atomic frequency in Eq. (6), we can adjust the detuning $\Delta_{\xi,k}$ to induce resonance between the cavities, i.e., by choosing $\eta^+ = \varsigma^-$, the state $|\psi^+_{\xi,k}\rangle$ is resonant with $|\phi^-_{s,k}\rangle$. The approximate hopping strength between $|\psi^+_{\xi,k}\rangle$ and $|\phi^-_{s,k}\rangle$ can be $\Gamma = \langle\phi^-_{s,k}|H'|\psi^+_{\xi,k}\rangle$ ($H' = \nu a^\dagger_{s,x}a_{q_1,x} + \nu a^\dagger_{s,y}a_{q_2,y} + \text{H.c.}$). When the frequencies of atoms q_1 and q_2 are slowly tuned over an increasing range as off- and on-resonance points, the input photon is adiabatically loaded into cavity s. Suppose that the whole system will be in the state $|\Psi(t)\rangle$ at arbitrary time. To adiabatically transfer the excitation from $|1\rangle_{\xi,k}$ to $|1\rangle_{s,k}$, the instantaneous energy gap between states $|\Psi\rangle$ and $|\Psi'\rangle$ satisfies the following adiabatic condition:

$$\frac{\langle\Psi'(t)|\frac{dH}{dt}|\Psi(t)\rangle}{|E_1(t) - E_2(t)|^2} \ll 1, \tag{7}$$

where $|\Psi'\rangle$ is the eigenstate closest to $|\Psi\rangle$ in energy. $E_1(t)$ and $E_2(t)$ are the corresponding instantaneous eigenvalues. For example, after the input pulse with h polarization enters the setup, we will transfer the photonic state from $|1\rangle_{q_2,y}$ to $|1\rangle_{s,y}$ via adjusting the switch q_2.

(2) The photon is confined inside cavity s by setting the detuning $\Delta_{\xi,k} = 0$. Note that the parameters is chosen to satisfy the condition of two-photon resonance between atom q_1/q_2 and cavity s. Then, $|1\rangle_{s,x}/|1\rangle_{s,y}$ is maximally decoupled from $|1\rangle_{q_1,x}/|1\rangle_{q_2,y}$. We apply a classical field (Ω) to the atom during the process, which is resonant with the transition $|e\rangle \leftrightarrow |r\rangle$. In the case of $\{\Omega, \Delta_{s,k}\} \gg \lambda_{s,k}$, we can adiabatically eliminate the excite states $|e\rangle$ and $|r\rangle$. Then the effective Hamiltonian in cavity s is given by

$$H_{eff} = \varphi[|f\rangle_s\langle f|a^\dagger_{s,x}a_{s,x} + |g\rangle_s\langle g|a^\dagger_{s,y}a_{s,y}] + \varphi'[|f\rangle_s\langle g|a^\dagger_{s,x}a_{s,y} + \text{H.c.}], \tag{8}$$

where $\varphi = \frac{\lambda^2_{s,k}}{2(\Delta_{s,k}+\Omega)} + \frac{\lambda^2_{s,k}}{2(\Delta_{s,k}-\Omega)}$ and $\varphi' = \frac{\lambda^2_{s,k}}{2(\Delta_{s,k}+\Omega)} - \frac{\lambda^2_{s,k}}{2(\Delta_{s,k}-\Omega)}$ (setting $\lambda_{s,k} = \lambda_{s,x} = \lambda_{s,y}$ and $\Delta_{s,k} = \Delta_{s,x} = \Delta_{s,y}$). We choose $\varphi = 2\varphi'$. The first two terms describe the Stark shifts, and the remaining terms give the interaction leading to a transition induced by two cavity modes. If the initial state for photon and atom s is $|g\rangle_s|1\rangle_{s,x}(|f\rangle_s|1\rangle_{s,y})$, for the interaction time $t = \frac{\pi}{2\varphi'}$, the state evolves to $i|f\rangle_s|1\rangle_{s,x}$ ($i|g\rangle_s|1\rangle_{s,y}$). On the other hand, the coefficient of the state $|g\rangle_s|1\rangle_{s,x}/|f\rangle_s|1\rangle_{s,y}$ keeps unchanged.

(3) Finally, the photon leaves the cavity q_1/q_2 as a time reversal process of step (1) (see Fig. 2). After traveling through the whole setup, the photon interferes at PBS2 and exits the system from the same port I. Concretely speaking, if the initial states of atom s and input pulse are $|g\rangle_s|h\rangle$, $|f\rangle_s|v\rangle$, $|g\rangle_s|v\rangle$, and $|f\rangle_s|h\rangle$, the final states will be $i|f\rangle_s|v\rangle$, $i|g\rangle_s|h\rangle$, $|g\rangle_s|v\rangle$, and $|f\rangle_s|h\rangle$, respectively. The system state evolution demonstrates the completed implementation of gate operation.

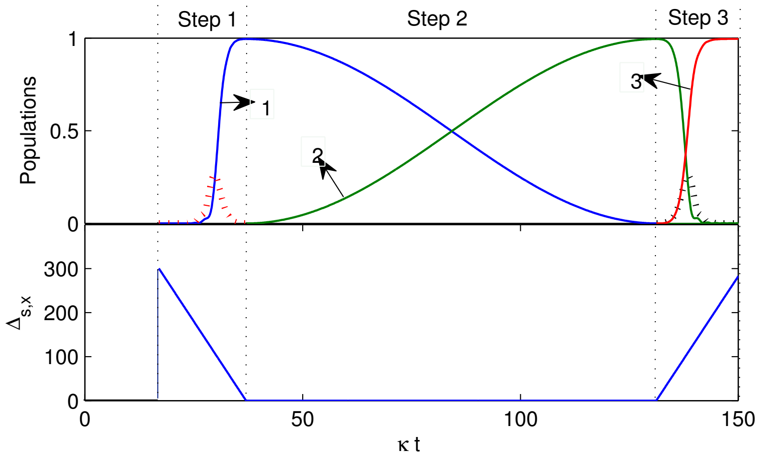

Fig. 2. Time evolution of probability amplitudes as a function of interaction time t when $\nu = \kappa$, $\Delta_{s,k} = 1000\kappa$, $\delta_{\xi,k} = 6\kappa$, $\Omega = 500\kappa$, $\lambda_{s,k} = 5\kappa$, and $\lambda = 25\kappa$, . Lines 1, 2, and 3 represent the probability amplitudes of the states $|g\rangle_s|f\rangle_{q_1}|g\rangle_{q_2}|1\rangle_{s,y}|0\rangle_{q_1,x}|0\rangle_{q_2,y}|vac\rangle$, $|f\rangle_s|f\rangle_{q_1}|g\rangle_{q_2}|1\rangle_{s,x}|0\rangle_{q_1,x}|0\rangle_{q_2,y}|vac\rangle$, $|f\rangle_s|f\rangle_{q_1}|g\rangle_{q_2}|0\rangle_s|0\rangle_{q_1,x}|0\rangle_{q_2,y}|\phi\rangle^{out}$, respectively. Here $|\phi\rangle^{out}$ is the output state of the fiber mode. Black (red) dot line represents the output (input) pulse shape.

In order to discuss the feasibility of the above theoretical analysis, the evolution of the whole system is calculated numerically. To shorten the representation, let us use the transfer process of the state $|g\rangle_s|f\rangle_{q_1}|g\rangle_{q_2}|0\rangle_s|0\rangle_{q_1,x}|1\rangle_{q_2,y}|vac\rangle$ as an example and choose that $\lambda_{\xi,k} = \lambda$ (see Eqs. (2) and (3)). As shown in the step (1) of Fig. 2, a Gaussian shape pulse (red dot line) is switched into the cavity s adiabatically by a linear change of $\Delta_{\xi,k}$. We see that the adiabatic process is shown clearly. Line 1 (2) describes the population of the state $|g\rangle_s|f\rangle_{q_1}|g\rangle_{q_2}|1\rangle_{s,y}|0\rangle_{q_1,x}|0\rangle_{q_2,y}|vac\rangle$ ($|f\rangle_s|f\rangle_{q_1}|g\rangle_{q_2}|1\rangle_{s,x}|0\rangle_{q_1,x}|0\rangle_{q_2,y}|vac\rangle$). It is obvious that the intended state transfer happens in step (2). In step 3, we observe the output pulse with Gaussian shape (black dot line). Therefore, the numerical simulation indicates a good agreement with our theoretical result. In the following, we investigate the influence of spontaneous emission and photon leakage on our protocol. Here the spontaneous emission of atom s is omitted because the excited states are almost unpopulated under the condition $\Delta_{s,k} \gg \lambda_{s,k}$. The decay rate of the cavity s is negligibly small compared to that of the cavity q_1/q_2 [22]. Then atomic spontaneous emission and the transverse decay rate (γ_1 and κ_1) in the cavities q_1 and q_2 play a dominant role during the whole dissipation process (set $\gamma_1 = \kappa_1 = \gamma$). In Fig. 3(a), the fidelity decreases with the increase of γ. In Fig. 3(b), one can notice that the larger λ is and the more insensitive the fidelity to γ is. Furthermore, in Fig. 3(c), the variation of the fidelity is shown when λ and γ change in a wide range. Appropriately increasing the coupling constant will improve the fidelity in the presence of dissipation.

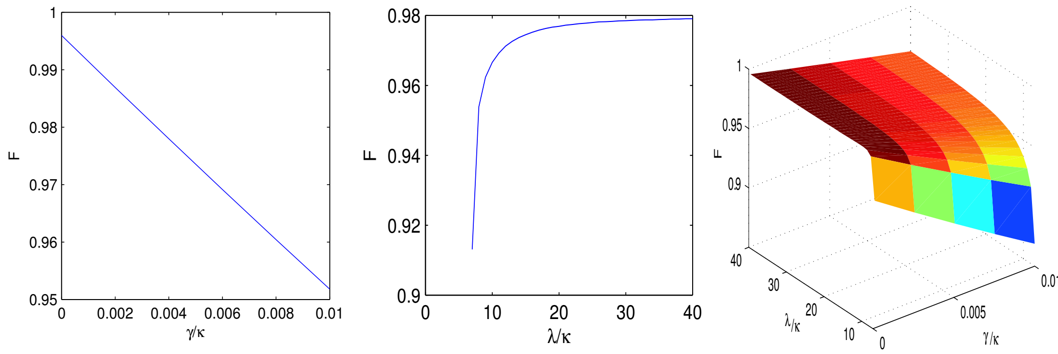

Fig. 3. (a) F versus γ for $\lambda = 25\kappa$. (b)F versus λ for $\gamma = 0.004\kappa$. (c) F as a function of γ and λ. Other parametric values are the same as those in Fig. 2.

Before concluding, we briefly discuss the experimental matter of the proposal. The atomic configuration could be realized by using the hyperfine levels of Ca [25] (Hg [26], and Rb [27]) atoms. In the microcavity regime, the coupling constant which equals to 100 MHz is predicted to be achievable [28]. Assuming that the cavity Q is dominated by the photon decay rate κ, we have $Q \sim 10^2$ ($\omega \approx 1$GHz). In the case, we can implement the gate operation with a fidelity larger than 99%. The total operation time is about 8μs. In addition, our scheme works robustly without the condition $\lambda_{q_1,x} = \lambda_{q_2,y}$. That is, the fluctuations of $\lambda_{q_1,x}$ and $\lambda_{q_2,y}$ have a weak influence on the fidelity. However, we also require that $\lambda_{q_1,x}$ and $\lambda_{q_2,y}$ are large enough. This is because the eigenstate $|\psi\rangle$ should be in the state $|1\rangle_{q_1,x}/|1\rangle_{q_2,y}$ at initial time in order to capture the pulse into the cavity s. In experiment, as single-photon multi-path interference has been used, a significant challenge for carrying out our protocol is maintaining the path length stability. If the length of a_1 is different from that of a_2, the variation of the atomic detuning will not ensure that the input pulse is switched into cavity s adiabatically. On the other hand, because of the unequal length between paths b_1 and b_2, single-photon interference will not occur at PBS2. With many impressive theoretical and experimental progress in recent years [14, 15, 16, 21, 22, 29, 30, 31], we expect that the proposal for implementing iSWAP gate might be achieved with a high fidelity in the near future.

In conclusion, we have shown how to implement two-qubit iSWAP gate between atom and photon in three coupled cavities. By tuning the atoms, two Q switches are gained along two polarization directions. When we apply a classical field to the atom s, a two-photon Raman transition happens. Based on the Raman transition, the gate operation using two active Q switches can be completed with a deterministic probability. Numerical analysis shows the influence of atomic spontaneous emission and cavity decay on the fidelity. Compared with previous approaches, the proposal is feasible in experiment because we use a cavity with full bandwidth along two polarization directions to perform a high-speed gate operation. Quantum information is stored in two different polarization states, so single-qubit transformation is easy to implement by passive linear optical elements. Moreover, the iSWAP gate can be directly applied in generating one-dimensional or two-dimensional cluster state.

Acknowledgments

This work was supported by National Natural Science Foundation of China under grant No. 10875020 and No. 10575017, the China Postdoctoral Science Foundation under grant No. 2011M500648, the Fundamental Research Funds for the Central Universities under grant No. HIT. NSRIF. 2010010, Heilongjiang Postdoctoral Fund under grant No. LBH-Z11126.

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