Geometric Manipulation of Ensembles of Atoms on Atom Chip for Quantum Computation

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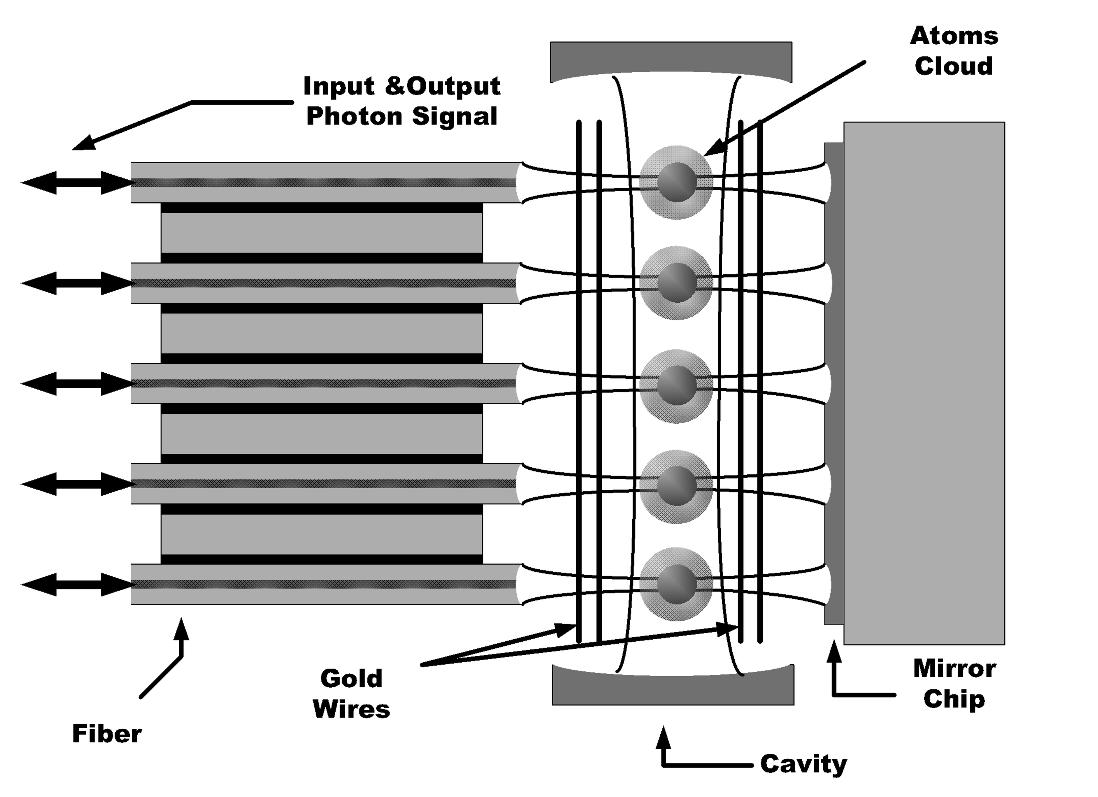
Motivation

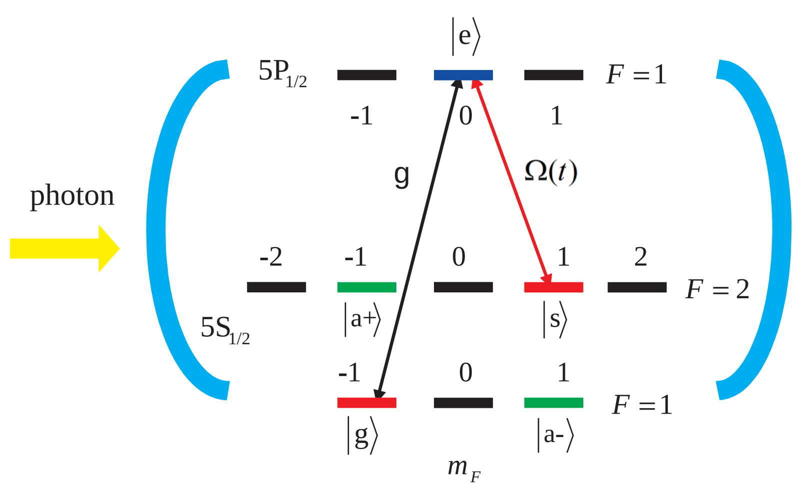
- Motivation: Neutral atoms are good candidate for quantum information processing, according to long coherence time. However, single atoms are difficult to address and not easy to achieve strong coupling with cavity photon. On the other hand, ensembles of atoms could effectively enhance the coupling rate by $\sqrt{N}$. They can also be used as quantum memory, quantum register for the application of quantum communication. So, using ensembles of atoms to build quantum computers on atom chips may be attractive and scalable.
- Goal: Propose a scheme of all-optical holonomic quantum computer based on cavity QED for ensembles of atoms. Decoherence according to thermal motion of atoms, inhomogeneous distribution of laser field and cavity loss could be effectively eliminated.

Schematic Setup



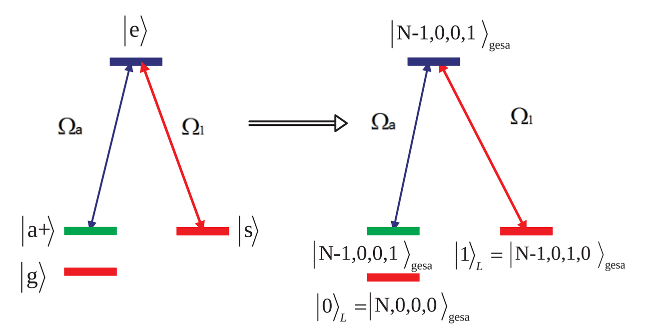
- Schematic setup of trapping ensembles of atoms in magnetic atom traps inside plano-concave optical microcavities (horizontal ones) is shown in the figure.
- Atoms are guided to a single magnetic trap by electrical current. Each atomic cloud has about 10^3 atoms.
- Each atomic cloud is trapped to be a qubit and form a processing cell. Single qubit gate can be realized by direct laser control the atomic cloud.
- Photon signals are input through the coupling of cavity and fibre via adiabatic control of the pumping laser.
- Different qubits could couple with each other mediated by photon of FP cavity(vertical one).
- When the information processing is completed, system outputs the result through single photon pulse to other quantum internet processers.

Basic Model



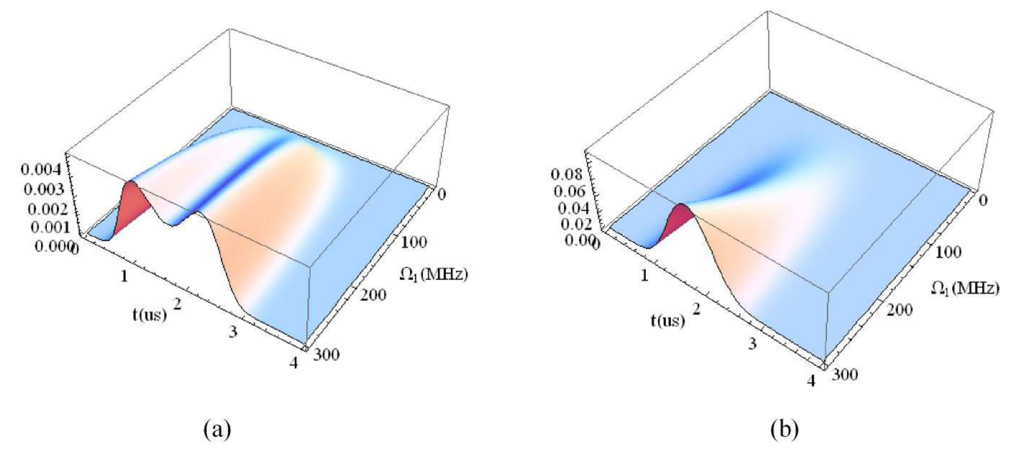
- The relevant states in ^{87}Rb are: clock states $|g\rangle = |F=1, m_F=-1\rangle$ and $|s\rangle = |F=2, m_F=1\rangle$; ancillary states $|a_-\rangle = |F=1, m_F=1\rangle$ and $|a_+\rangle = |F=2, m_F=-1\rangle$ in $5S_{1/2}$ manifold. And a state of manifold $5P_{1/2}$ serves an intermediate state $|e\rangle(|F=1, m_F=0\rangle)$.

One Qubit Phase Gate



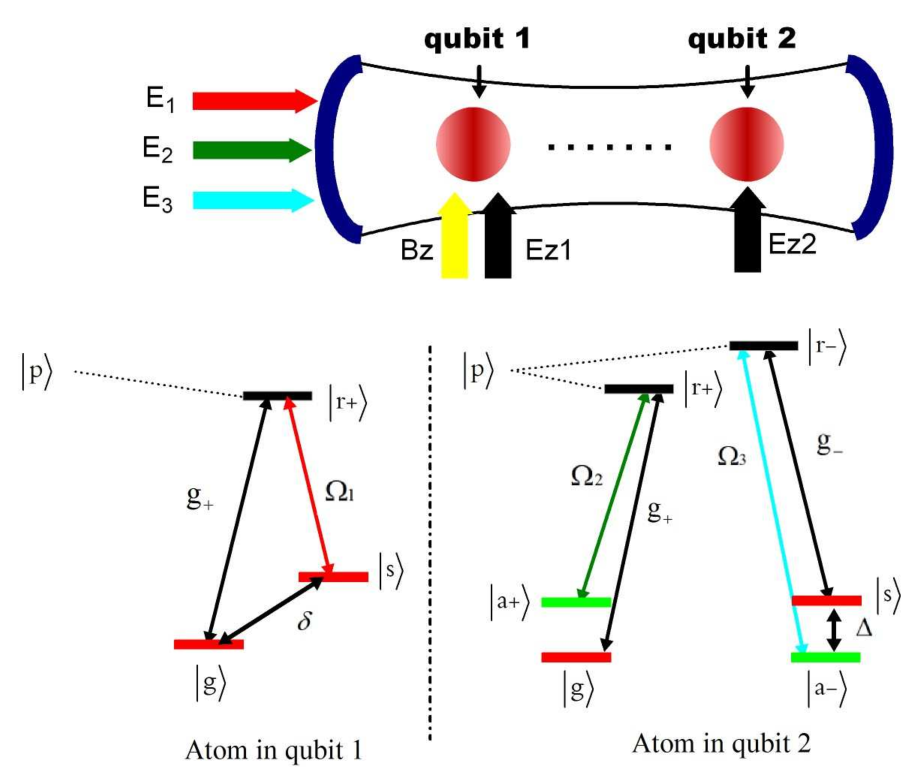
- The level diagram of coupling is shown in figure above to realize the gate $R_z^{(i)}(\phi_1) = \exp(i\phi_1|1\rangle_{Li,Li}\langle 1|)$.
- Single energy level can be directly mapped to a three level systems in second quantization representation.
- The Hamiltonian in second quantization representation could be written as: $H_1(t) = \Omega_1(t)\hat{\mathcal{E}}^\dagger\hat{\mathcal{S}} + \Omega_a(t)\hat{\mathcal{E}}^\dagger\hat{\mathcal{A}}_+ + \text{H.c.}$
- The geometric phase could be written as $\phi_1 = \oint \sin^2(\theta)\mathrm{d}\varphi$ $(\Omega_1(t) = \Omega\sin\theta t,$ $\Omega_a(t) = -\Omega\cos\theta t e^{-i\varphi})$

Average Number of Photons

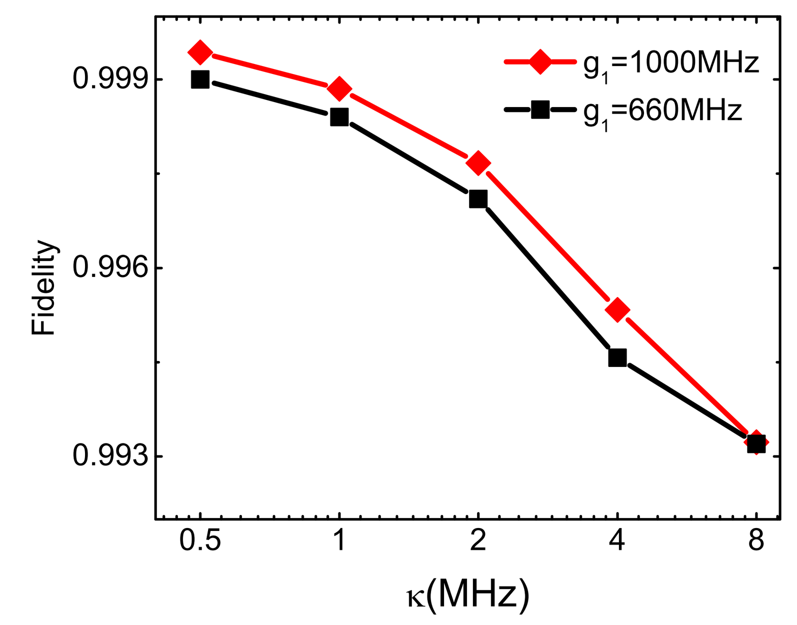


- The figure shows the number of cavity photons during the processing of controlled $\pi/32$ gate operation for the states prepared initially in $|10\rangle_L$(fig.(a)) and $|11\rangle_L$(fig.(b)). The parameters are chosen as $\Omega_2 = 50$MHz, $\Omega_3 = 300$MHz, $g_+ = 20$MHz, $g_- = 10$MHz. The number of photons has a peak value of about 10^{-3} during 4μs.

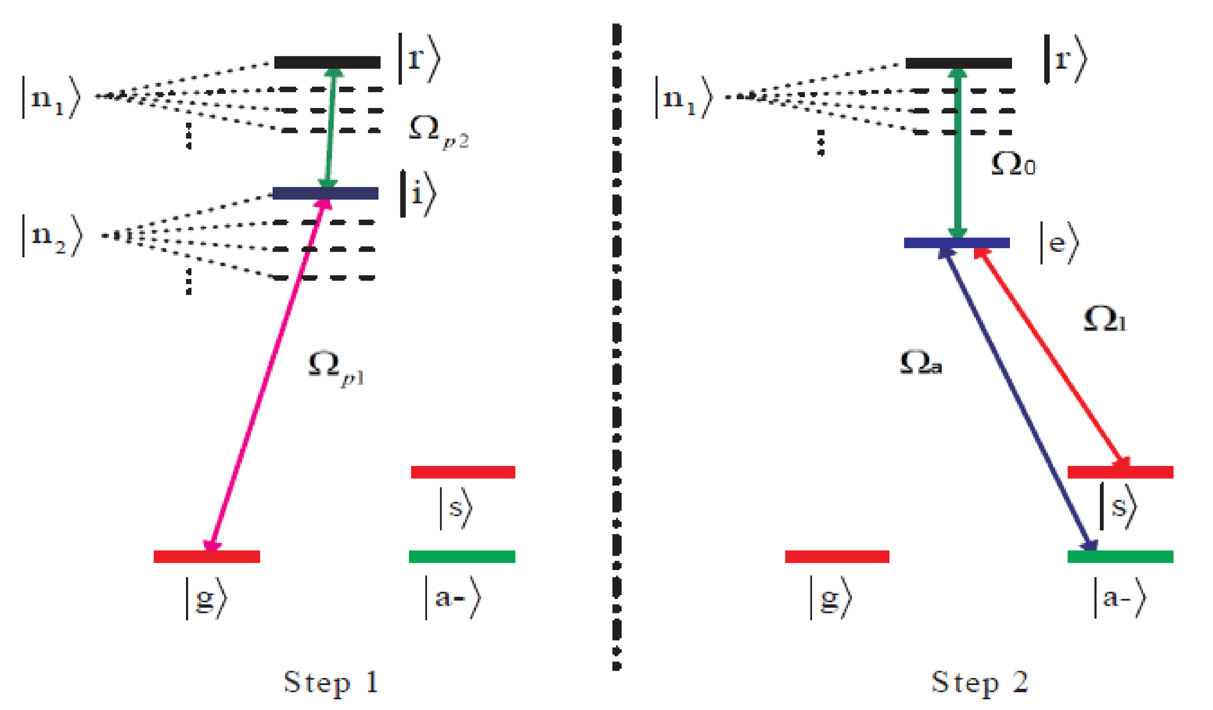
Two Qubit Controlled Phase Gate



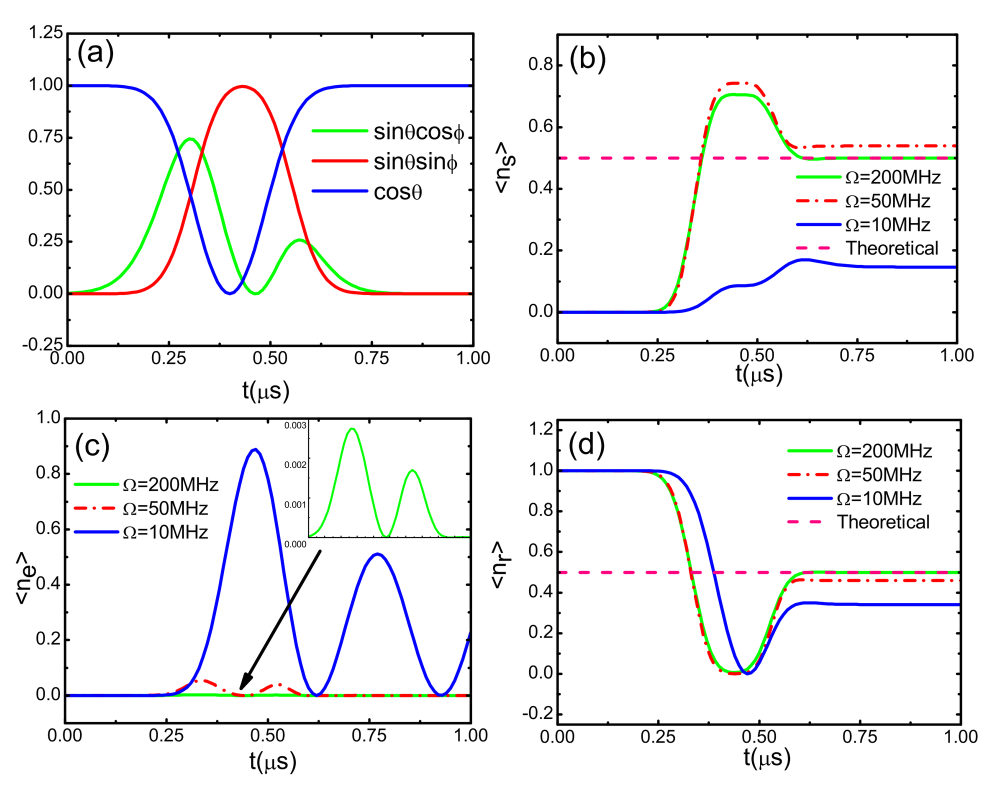
- Coupling diagram to realize a controlled phase gate $U^{(jk)}(\phi_3) = \exp(i\phi_3|10\rangle_{Lj,Lk}\langle 10|)$ is shown in the left when Stark effect and Zeeman effect are considered.
- We use external laser control to overcome the non-uniform coupling rate between cavity photon and atoms caused by uncertainty of atoms position and the inhomogeneous distribution of cavity mode.
- $\phi_3 = \oint d\varphi_2 \frac{\frac{g_2^2}{\Omega_2^2(t)}\sin^2\theta}{\frac{g_2^2}{\Omega_2^2(t)}\sin^2\theta + \frac{g_1^2}{\Omega_1^2(t)}\cos^2\theta + \cos^2\theta\sin^2\theta}, d\varphi_3 = 0.(\Omega_1(t) = \Omega_1\sin\theta t, \Omega_2(t) = \Omega_2\cos\theta t e^{-i\varphi_2}, \Omega_3(t) = \Omega_3\cos\theta t e^{-i\varphi_3})$
- Fidelity of a gate with $\phi_3 = \pi/16$ is shown in the figure on the right with different coupling constants.
- The average number of photons during the process of the gate $\phi_3 = \pi/16$ when initially prepared in $|10\rangle_L$ is shown in the box above as a function of time and coupling strength Ω_1.

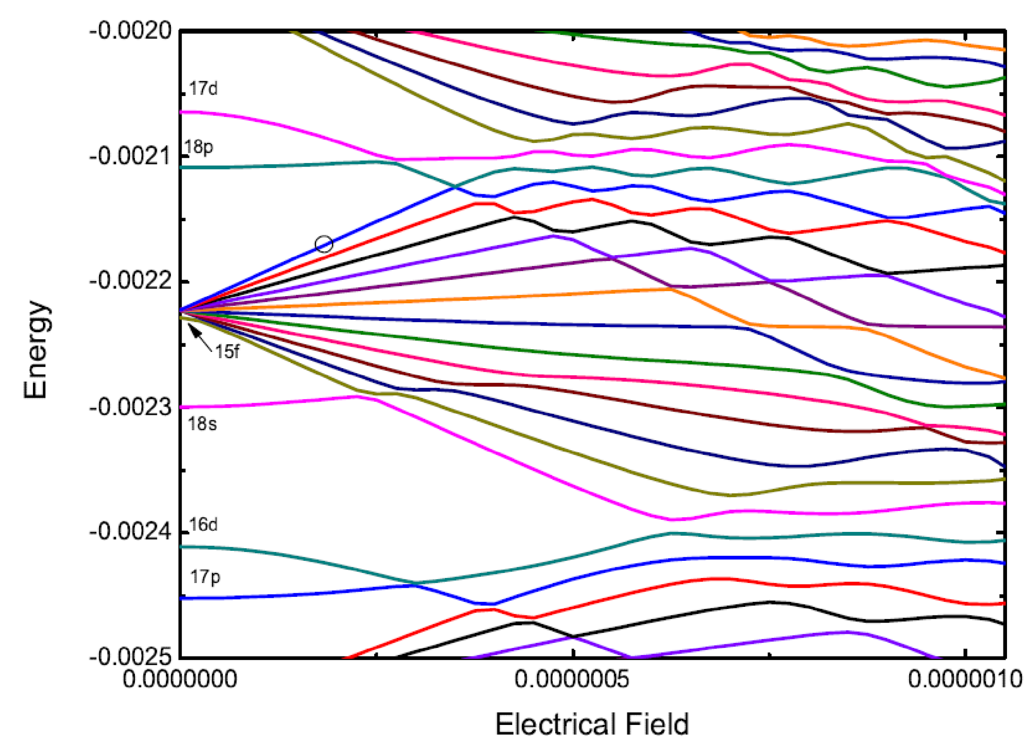


One Qubit Rotation Gate Around Y



- The coupling diagram to realize the gate $R_y^{(i)}(\phi_2) = \exp(i\phi_2\sigma_i^y)$.
- There are three steps to realize this gate. 1. Adiabatically pump the a single excitation from ground state to a register state. 2. Adiabatically control the coupling between single excitation states $|\mathbf{r}\rangle$, $|\mathbf{s}\rangle$, $|\mathbf{a}_-\rangle$. 3. Reverse Step. 1.
- $|n_1\rangle$ and $|n_2\rangle$ are two Rydberg states that served as register states in the process. Only single atom can be pumped to $|r\rangle$ due to dipole-dipole interaction when atoms are prepared in states $|r\rangle$ and $|i\rangle$. We choose them as the outmost Stark state when the cloud of atoms are illuminated in constant electrical field.
- $\phi_2 = \oint_C \cos\theta\mathrm{d}\varphi$ $(\Omega_0(t) = \Omega\sin\theta\cos\varphi, \Omega_1 = \Omega\sin\theta\sin\varphi, \Omega_a = \Omega\cos\theta)$.
- A simulation of the transition is shown in the figure below.





- We need to find Rydberg states which have large energy shift but small strength of transition to be our register state and intermediate state. This turns out to be the outmost Stark eigenstate. For the manifold $n = 15$ of ^{87}Rb, we circle the state we choose as our register state in the figure above. For our purpose, n_1 and n_2 are chosen to be 70 and 60 the have large enough dipole-dipole blockade effect.