Fast Ground State Manipulation of Neutral Atoms in Microscopic Optical Traps

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(Received 23 September 2005; published 14 February 2006)

We demonstrate Rabi flopping at MHz rates between ground hyperfine states of neutral ^{87}Rb atoms that are trapped in two micron sized optical traps. Using tightly focused laser beams we demonstrate high fidelity, site specific Rabi rotations with cross talk on neighboring sites separated by 8 μm at the level of 10^{-3}. Ramsey spectroscopy is used to measure a dephasing time of 870 μs, which is ≈ 5000 times longer than the time for a $\pi/2$ pulse.

DOI: 10.1103/PhysRevLett.96.063001 PACS numbers: 32.80.Pj, 03.67.Lx, 39.25.+k

Over the last decade quantum computing has attracted much attention due to the possibility of solving certain problems much faster than a classical computer [1]. A number of different approaches [2] are currently being pursued to build a scalable quantum computer and significant progress has been made with trapped ions, nuclear magnetic resonance, single photons, and solid state Josephson junctions. Neutral atoms trapped by optical fields are also being studied intensively as a viable approach to demonstrating quantum logic. Neutral atom approaches are attractive for a number of reasons starting with the availability of well-developed techniques for laser cooling and trapping [3,4] and the potential for scalability [5]. The qubit basis states can be represented by ground state hyperfine levels which have long decoherence times and are therefore suitable for storing quantum information. The qubits can be rapidly initialized and manipulated with near resonant optical fields through optical pumping and stimulated Raman processes. A number of protocols for two-qubit gates have been proposed [6] including ground state collisions, optically induced short range dipole-dipole interactions, and dipole-dipole interactions between highly excited Rydberg levels [7–9]. The Rydberg atom approach appears particularly attractive since it has the potential for achieving fast, MHz rate gates whose fidelity is only weakly dependent on the motional state of the atoms [10].

We report here on progress towards demonstrating quantum logic operations using neutral atom qubits in optical traps. Recent achievements in neutral atom quantum computing include the implementation of a five qubit quantum register by Meschede and colleagues [11,12] and sub-Poissonian loading of single atoms to nearby dipole traps by the Grangier group [13,14]. In this Letter we demonstrate loading and ground state manipulation of neutral ^{87}Rb atoms in two closely spaced microscopic optical traps. By optically addressing each of these traps, we demonstrate two-photon Rabi flopping between ground hyperfine states $|0\rangle \equiv |F = 1, m_F = 0\rangle$ and $|1\rangle \equiv |F = 2, m_F = 0\rangle$ at a rate of 1.36 MHz. This rate corresponds to a time period of 183 ns to perform a $\pi/2$ Rabi rotation. The Rabi rotations are performed with negligible cross talk between the two traps: a π rotation on one site causes less than $1.4 \times 10^{-3}\pi$ rotation on the other site. Using Ramsey spectroscopy, we measure a decoherence time of $T_2 = 870$ μs. To our knowledge, our results demonstrate the best figure of merit, (dephasing time)/(Rabi rotation time), achieved to date for neutral atom quantum computing. Furthermore, our optical addressing scheme which uses acousto-optic modulators to spatially scan tightly focused beams can be readily extended to address multiple qubit sites in a one- or two-dimensional array, which could form the basis for a scalable quantum logic device.

We proceed with a detailed description of our experiment. As shown in Fig. 1, we start with a standard $\sigma^+ - \sigma^-$ 6-beam magneto-optical trap (MOT) that is loaded from a background vapor [15] in an ultrahigh vacuum, 16 cm diameter stainless steel chamber. The MOT beams have a total intensity of ≈ 12 mW/cm^2 and are 12 MHz red detuned from the $F = 2 \rightarrow F' = 3$ cycling transition. A repumping beam tuned to the $F = 1 \rightarrow F' = 2$ transition is superimposed with the MOT beams. The MOT produces an atom cloud with a density of about 10^9/cm^3.

Two tightly focused beams that spatially overlap with the MOT cloud form two far-off-resonant traps (FORTs). The FORT beams are obtained from a diode laser at a wavelength of 1010 nm. The output of this laser is split into two beams with the use of a birefringent calcite crystal. The two spatially separated beams are then imaged into the center of the chamber with a custom designed lens system (NA 0.35). The resulting 80 mW FORT beams are focused to a near-diffraction limited waist of $w_f = 2.7$ μm. The separation between the two FORT sites at the focus is $d = 8$ μm. The linearly polarized FORT beams form ≈ 1 mK deep potential wells at the focus. By varying the MOT parameters we can load from 1 to about 10 atoms from the MOT into each of the FORT sites. The data presented in Figs. 2–4 were taken with about 10 atoms in each site. The temperature of the atoms that are trapped in the FORTs is measured to be 70 μK. The $1/e$ lifetime of the atoms in the FORT sites is 780 ms, limited by collisions with the background vapor.

In Fig. 1(a), we show a false-color fluorescence image of the atoms that are trapped in the two FORT sites A and B

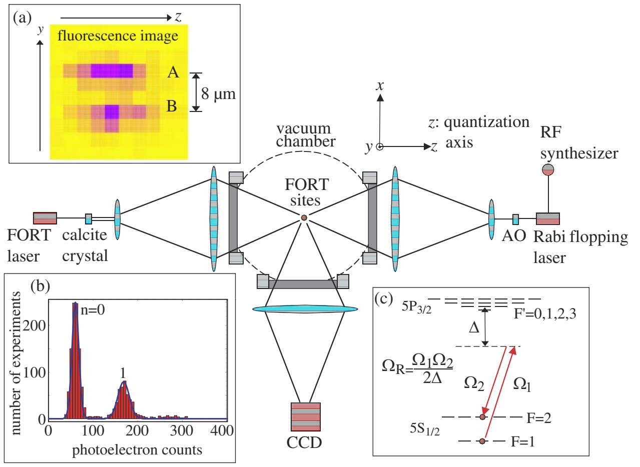

FIG. 1 (color online). The experimental setup. Two tightly focused beams that spatially overlap with a MOT form closely spaced optical traps. The MOT beams are not shown for simplicity. Inset (a) shows a fluorescence image of the atoms that are trapped in the 2 μm sized FORTs (termed sites A and B, respectively). Inset (b) shows a photoelectron count histogram from 1500 loading experiments into a single trapping site, demonstrating the ability to load and measure single atoms. Inset (c) shows the relevant energy level structure of ^{87}Rb. Two laser beams whose frequency difference equals the hyperfine transition frequency implement Rabi rotations on the qubit states. The Rabi rotation beams are steered to either site A or site B with the use of an acousto-optic (AO) modulator.

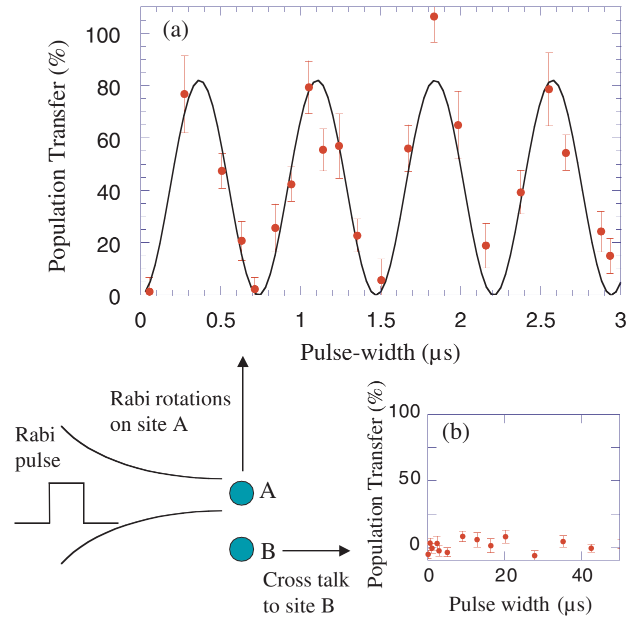

FIG. 2 (color online). Fast rabi rotations on one site with negligible cross talk to the other site. In plot (a), we start with all the atoms in state $|0\rangle$ and measure the fraction of atoms in state $|1\rangle$ as a function of the duration of the two-photon pulse. We observe Rabi flopping between two-qubit states at a rate of $\Omega_R = 2\pi \times 1.36$ MHz. This rate corresponds to a $\pi/2$ rotation time of 183 ns (see text for details). Plot (b) shows that the cross talk to the other site is negligible and demonstrates our ability to individually address the two sites.

with ≈ 10 atoms per site. The image is taken with an electron-multiplying CCD camera and the fluorescence from the atoms is collected with a custom lens system (NA 0.40) that is verified to have a resolution of 3 μm at the position of the FORT sites. The image of Fig. 1(a) and the data in the following figures is taken using the following loading and measurement cycle. After loading the MOT for several seconds, we reduce the intensity of the MOT beams by a factor of 2 and increase the detuning to 18 MHz for a period of 100 ms, thereby cooling the atoms to a temperature of 30 μK and loading the two FORT sites. We turn off the MOT and repumping beams for 100 ms and let the atoms that are trapped in the MOT diffuse out of the viewing region. We then apply Rabi or Ramsey pulses as desired and probe the $F = 2$ atoms that are trapped in the FORTs for 10 ms with the MOT beams attenuated to an intensity of 100 μW/cm^2. The $F = 1$ atoms are completely dark to the probing light. The FORT laser ac Stark shifts the cycling transition. The mean shift for different Zeeman m-level transitions is measured to be 40 MHz to the blue. The frequency of the probing beam is tuned to compensate for this mean shift. After 10 ms of continuous probing, the atoms boil out of the trap and are lost. Figure 1(a) is an average of nine images (each with a 10 ms exposure time).

Future studies of two-qubit gates will require loading and measurement of single atoms in the FORTs. Figure 1(b) shows a photoelectron count histogram from repeated loading of a single site that demonstrates the ability to load and measure single atoms with high fidelity. The blue curve is a fit to the $n = 0$ and $n = 1$ atom peaks that accounts for the double Poissonian process of atom loading and photon counting. The fit shows that the average number of atoms loaded was about 0.5. Additional data for increased loading rates show slightly sub-Poissonian atom number statistics [13,14]. The data of Fig. 1(b) are taken with an integration time of 20 ms using a different readout protocol whose details will be reported elsewhere. The data that follow on Rabi rotations of the qubit states were obtained by loading approximately 10 atoms into each of the FORT sites and using the readout protocol described in the preceding paragraph. Taking measurements on 10 atoms at a time is advantageous here in that it allows us to rapidly obtain good measurement statistics. Although we do not expect collisions to be an issue for our measurement parameters, any atomic collisions that do occur in the FORT could lead to decoherence and loss of fidelity. Thus the results given below are a conservative measurement of the performance to be expected from single atom experiments.

As shown in Fig. 1(c), two-photon Rabi rotations between states $|0\rangle$ and $|1\rangle$ are performed with two laser beams whose frequency difference equals the hyperfine transition frequency of 6 834 683 kHz. The two beams are obtained by modulating the current of a single diode laser at half the transition frequency. This modulation produces two sidebands with the desired frequency separation. The carrier is then removed with the use of a filtering cavity with a finesse of 50. The two sidebands pass through an acousto-optic (AO) modulator and are focused to a near-diffraction limited waist of $w = 4.1\ \mu$m in the chamber where they overlap with FORT sites A or B. We individually address the two FORT sites by changing the acoustic wave frequency (and thereby the diffraction angle) of the AO modulator. The frequency shift of the individual beams caused by the AO modulator is not of importance due to the two-photon nature of the stimulated Raman process. The total power in the two sidebands is 45 μW and the detuning from the $5P_{3/2}$ excited state is $\Delta = -2\pi \times 41$ GHz. The polarization of the sidebands is identical and is circular with respect to the quantization axis z.

We proceed with a detailed discussion of Rabi rotations on ground hyperfine states. With the Rabi frequencies of the individual beams denoted as Ω_1 and Ω_2, the two-photon driving Rabi frequency between the logical qubit states $|0\rangle$ and $|1\rangle$ is [1] $\Omega_R = \Omega_1\Omega_2/2\Delta$. Here, Δ is much larger than the decay rate of the excited state. In Fig. 2, we demonstrate fast Rabi rotations on one of the FORT sites with negligible cross talk to the other site. The initial state is selected by turning off the hyperfine repumping beam for a duration of 8 ms at the end of the FORT loading cycle, and thereby optically pumping all the atoms into the $F = 1$ Zeeman states. After this optical pumping we apply a bias magnetic field of 10.7 G along the quantization axis to separate out different Zeeman m-level transition frequencies, thereby isolating $m = 0$ atoms. We then apply a two-photon Rabi pulse of variable duration and probe the percentage of atoms that make a transition from $|0\rangle$ to $|1\rangle$. Plot (a) shows the Rabi flopping of atoms in FORT site A. Each data point is an average of 12 experimental runs. The normalization of the vertical axis is obtained by optically pumping all the atoms into $F = 2$ and observing the total fluorescence. The uncertainty of this normalization is $\pm 10\%$. We observe a sinusoidal variation with high contrast [16]. The solid line is a sinusoidal fit and yields a two-photon Rabi frequency of $\Omega_R = 2\pi \times 1.36$ MHz [17]. Considering that a single-qubit Hadamard gate requires a $\pi/2$ rotation, this rate corresponds to a single-qubit manipulation time of $\pi/2\Omega_R = 183$ ns. This is a factor of 44 faster than what has previously been achieved in neutral atom quantum computing [11].

The performance of single qubit addressing is a key benchmark for quantum computing. In ion trap quantum computing, addressing errors of $\approx 10^{-2}$ have been demonstrated using focused beams [18] and precise control of the micromotion of the ions [19]. Figure 2(b) shows the population transfer at FORT site B, while the Rabi flopping beam is aligned to site A. We do not see appreciable excitation for pulse widths as large as 43 μs. With our detection sensitivity of $\pi/6$ rotation, this implies that the cross talk [ratio of Rabi frequencies: $\Omega_R(\text{site B})/\Omega_R(\text{site A})$] is less than 1.4×10^{-3}. This upper bound on the cross talk is only a few times higher than the theoretical value of e^{-2d^2/w^2} which evaluates to 4.9×10^{-4} for our experimental parameters. With the help of the AO modulator, we can switch the Rabi flopping beam to address FORT site B instead of FORT site A. For this case, we have verified that we repeat the results of Fig. 2, with site A and site B interchanged. The cross-talk measurement relies on the ability to address either FORT site with a tightly focused Rabi flopping beam. To remove any cross talk added in the measurement process due to finite spatial resolution of the fluorescence collection optics we performed the cross-talk measurements by loading atoms into only one site at a time. This was done by turning off the FORT beam at the other site.

An important advantage of the optical addressing scheme is that the amount of cross talk is independent of the speed of the single-qubit operations. This is in contrast to the magnetic addressing scheme where higher speeds would require larger field gradients [11]. For example, a 1 MHz Rabi flopping rate with pulse area cross talk for 8 μm separated sites at the 10^{-3} level would require a B-field gradient of greater than 10 T/cm using $m = \pm 1$ Zeeman states.

We next proceed with our measurements of the decoherence time of the qubit states. For this purpose, we use Ramsey's method of separated oscillatory fields [20,21]. With all atoms starting in state $|0\rangle$, we apply two $\pi/2$ pulses that are separated by a time T. We then measure the fraction of atoms that make a transition to state $|1\rangle$ as a function of the two-photon detuning δ. The contrast of the fringe patterns is expected to decay exponentially with a time constant T_2 which is the decoherence time of the hyperfine qubit. Several physical mechanisms including background magnetic fields and atomic motion in the FORTs lead to dephasing of the $|0\rangle$ and $|1\rangle$ states [10,22]. Figures 3(a)–3(d) show the result of this measurement for $T = 100\ \mu$s, 300 μs, 1 ms, and 3 ms, respectively. Each data point is again an average of 12 experimental runs. The solid line in each plot is a sinusoi-

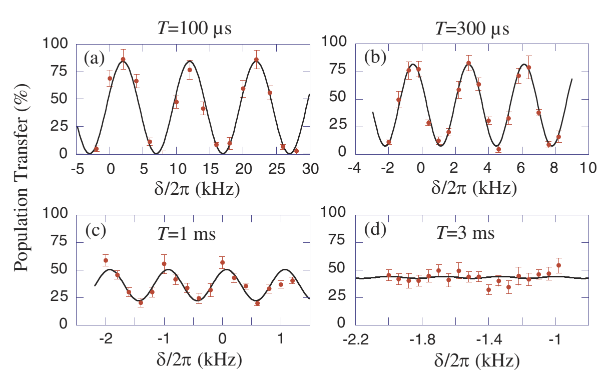

FIG. 3 (color online). Ramsey spectroscopy on the $|0\rangle \rightarrow |1\rangle$ hyperfine transition. We apply two $\pi/2$ pulses with a delay T and measure the fraction of atoms in state $|1\rangle$ as a function of the two-photon detuning δ.

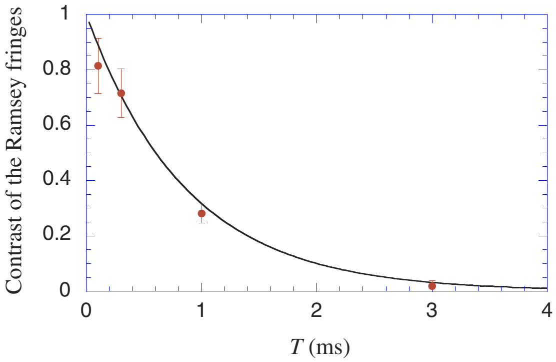

FIG. 4 (color online). The contrast of the Ramsey fringes of Fig. 3 as a function of the time delay between two pulses, T. The solid line is an exponential fit to the data.

dal fit with an offset. As expected, we observe a fringe pattern with a reduced contrast as T becomes larger. In Fig. 4, we plot the contrast of the fringes in Fig. 3, as a function of T. The best exponential fit to the data points yields a dephasing time of $T_2 = 870\ \mu$s. This gives a figure of merit of (dephasing time)/ ($\pi/2$ Rabi rotation time) $= (870\ \mu\text{s})/(183\ \text{ns}) = 4750$.

In conclusion, we have demonstrated site specific ground state manipulation at MHz rates and long decoherence times of hyperfine transitions of neutral atoms in two nearby dipole traps. In the future, it will be relatively straightforward to increase the power of the Rabi flopping beams by several orders of magnitude and thereby obtain manipulation rates in the 100 MHz range. Combining such fast one-qubit gates with two-qubit Rydberg gates [7] may provide a powerful building block for a scalable quantum computer.

We would like to thank Antoine Browaeys and Philippe Grangier for helpful discussions. This work was supported by the U.S. Army Research Office under Contract No. DAAD19-02-1-0083 and NSF Grants No. PHY-0205236 and No. CCF-0523666.

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