High efficient loading of two atoms into a microscopic optical trap by dynamically reshaping the trap with a spatial light modulator

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Abstract: We demonstrated trapping two neutral ^{87}Rb atoms in a two site optical ring lattice generated by reflecting a single laser beam from a computer controlled spatial light modulator directly. The ring lattice was transformed into a Gaussian trap by dynamically displaying the holograms animation movie on the modulator. The trapped atoms follow the evolution of traps and move into the same microscopic dipole trap at the end. The detected success rate of this manipulation is larger than 90%. Under imposing the near resonance light, we observed strong light-induce collision between two atoms.

OCIS codes: (020.3320)Laser cooling; (020.7010)Laser trapping; (270.5585)Quantum information and processing; (090.2890)Holographic optical elements.

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1. Introduction

Laser cooled neutral atoms in shallow far-off resonance traps have long coherence time [1]. The ability of trapping single atoms in microscopic far-off resonance traps (MFORT) and fully manipulating the external and internal degrees of freedom of quantum object opens a way to control the quantum state of neutral atoms [2–5], thus makes the neutral atoms be one of the most promising candidates for storing and processing quantum information. In atom-based scheme, a qubit is encoded in the internal or motional state of an atom. Quantum gates with neutral atoms have been theoretically proposed based on controlled collisions [6, 7] and Rydberg dipole-dipole interactions [8]. The latter has been experimentally demonstrated recently in two research groups [9, 10].

Controlled interaction between pairs of ultracold neutral atoms has been shown to yield state-dependent collisional phase shifts [11], to lead to coherent spin dynamics [12] and highly efficient production of ultracold molecules [13] in optical lattice. But because of the lack of addressability at single atom level in these experiments, their use is limited in quantum information processing that requires the measurement of individual quantum states. Motivated by this, the first presentation concerning the insertion and controlled interaction of two individual atoms inside the same optical MFORT has been developed recently [14], where atoms were initially stored in separate potential wells of a one-dimensional standing wave dipole trap, one of the two atoms was then extracted out of its potential well using optical tweezers and was

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inserted into the potential well of the second atom. But for some uncertainty of distance control between the atoms, the obtained success rate of preparing pairs of atoms separated by a predefined number of potential wells is about $30 \pm 2\%$ theoretically and $16^{+4}_{-3}\%$ experimentally.

Here we demonstrate a different approach to transport two individual atoms trapped in a two-site ring lattice into a single MFORT by utilizing a spatial light modulator (SLM). We employ our recently developed technique of dynamically rotating computer generated ring lattice just through displaying the hologram animation movie on the SLM [15], then we transform ring lattice with $l = 1$ into a single microscopic dipole trap. Two atoms initially trapped in the ring lattice are brought into single MFORT under the evolution of the computer generated holographic dipole traps. Our scheme is simple for experimental implementation, and we obtained a success rate larger than 95% of preparing pairs of atoms in a single MFORT experimentally. Meanwhile, with two atoms in the MFORT we observed a strong two-atom loss upon imposing the resonant light.

2. Dynamically reshaping the optical dipole trap with an SLM

Laguerre-Gaussian(LG_p^l) beams possess orbital angular momentum along the optical axis when l is not zero, where p and l are the radial and azimuthal indices of the LG modes [16]. The p=0 modes $LG_{p=0}^l$ have a spiral phase structure, hence the phase is undefined on the optical axis where light intensity must be zero [17]. The interference of opposite azimuthal indices l has the ring lattice shaped intensity distribution, which comprises $2l$ petals. Each petal has an intensity maximum which is a site (optical dipole trap) for an atom when the laser wavelength is red detuned. The ring lattice can be expressed cylindrically [15] by Eq. (1),

$$I_l = I\frac{2}{\pi|l|!}\,(\sqrt{2}r/w)^{2|l|}\exp(-2r^2/w^2)(2+2\cos(2l\phi)), \tag{1}$$

where $w = w_0\sqrt{1+(z/z_R)}$ is the beam waist in term of the Rayleigh range $z_R = \pi w_0^2/\lambda$.

The ring lattice can be generated by an SLM that imposes ring lattice holograms onto a single laser beam. To generate the ring lattice holograms we implemented an algorithm that has details in the Ref. [18] by using the MATLAB@ software. The function generating the output hologram displayed on the SLM is

$$mod\left[angle\left[LG\left(x,y,l,z,w_0,z_R\right)+LG\left(x,y,-l,z,w_0,z_R\right)\right]+x\cdot k_x,2\pi\right]\cdot\frac{256}{2\pi}, \tag{2}$$

where $LG\left(x,y,l,z,w_0,z_R\right)$ and $LG\left(x,y,-l,z,w_0,z_R\right)$ are the LG beams with opposite azimuthal indices l. The term $angle[LG(x,y,l,z,w_0,z_R)+LG(x,y,-l,z,w_0,z_R)]$ is the ring lattice phase pattern. And k_x is the x-component of k, and $x\cdot k_x$ is a blazed phase grating structure, acting as a tilted mirror to separate the ring lattice from the 0th-order non-modulated light.

The phase pattern has one phase jump of π for $l = 1$. The corresponding mode consists of 2 petals, which acts as double well when the detuning is red. For $l = 0$ there is not phase jump, the corresponding 1st-order blazing mode is just Gaussian mode, which is a single trap with the same optical axis as the double well ring lattice. Figure 1 shows CCD images of the traps of $l = [1,0]$, taken by an aberration-free objective group with a magnification factor of 160 and the corresponding holograms calculated by Eq. (2). However, Laguerre-Gaussian modes can not give a precise description of the diffraction patterns produced by holograms with spiral phase structure and their superposition shown as Fig. 1(b). A more precise description of diffraction patterns is provided by Kummer beams [19] instead of Laguerre-Gaussian beams. The amplitude of a monochromatic Gaussian beam after the Fraunhofer diffraction of holograms with l index spiral structure could be described fully by using the modified Bessel function of the first

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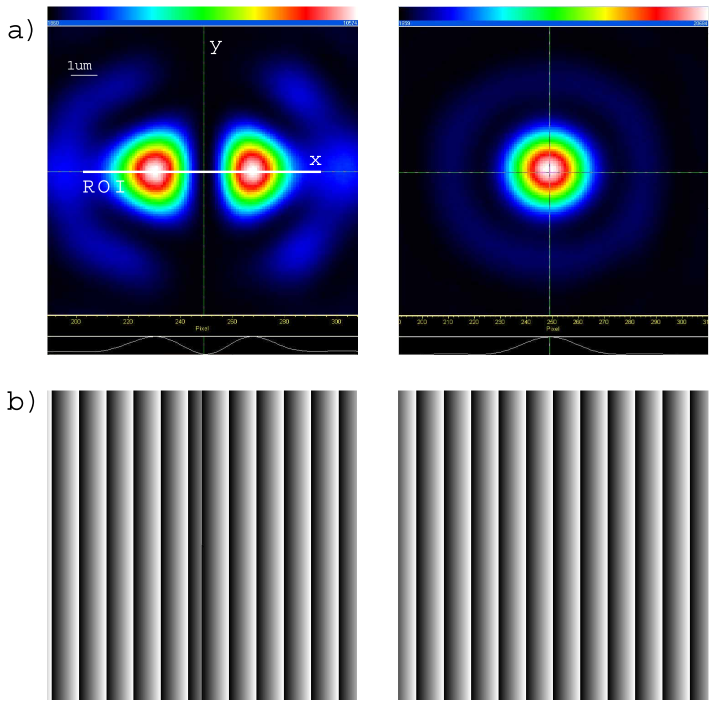

Fig. 1. (color online) The traps with $l = 1$ (left), $l = 0$ (right) and their holograms. (a) is observed optical intensity distribution of the traps, a pixel represents $1\mu m$. (b) is the corresponding gray-level holograms with 600×600 pixels. ROI stands for the region of interest.

kind $I_v(z)$ [20]:

$$u_l(r,\phi) = c_0 i^{-l} \frac{\pi^{3/2}}{2w_0^2} e^{il\phi} e^{-r^2/8w_0^2} \frac{r}{2w_0} [I_{(|l|-1)/2}(\frac{r^2}{8w_0^2}) - I_{(|l|+1)/2}(\frac{r^2}{8w_0^2})]. \tag{3}$$

The superposition of $u_{\pm 1}(r,\phi)$ from the Eq. (3) is the amplitude of the double well. If $l = 0$, amplitude distribution of the output beam is still Gaussian, describing the single trap. Switching between the double well and single trap phase pattern of modulated laser beam can be realized by changing the holograms displayed on the SLM. This transformation process is the coherent sum of the two electric field amplitudes of the diffracted Gaussian beam that can be described to be a linear mode given as follows:

$$I(\eta)_l = |(1-\eta)[u_1(r,\phi) + u_{-1}(r,\phi)] + \sqrt{2}\eta u_0(r,\phi)|^2, \tag{4}$$

where η is the percentage of Gaussian electric field amplitude component relative to the total electric field amplitude, which is time dependent linearly. The parameter η evolves from 0 to 1 corresponding to a transfer from double well to single Gaussian trap. The cross-section transformation envelope described by the Eq. (4) is shown in Fig. 2(a), 2(b). The calculation indicates that there is interference effect during the transformation process. The interference effect reduces the diffraction efficiency.

Experimentally,to transform the double trap to the single trap, we converted the output holograms shown as Fig. 1(b) to an audio video interleave (AVI) version's video with frames per

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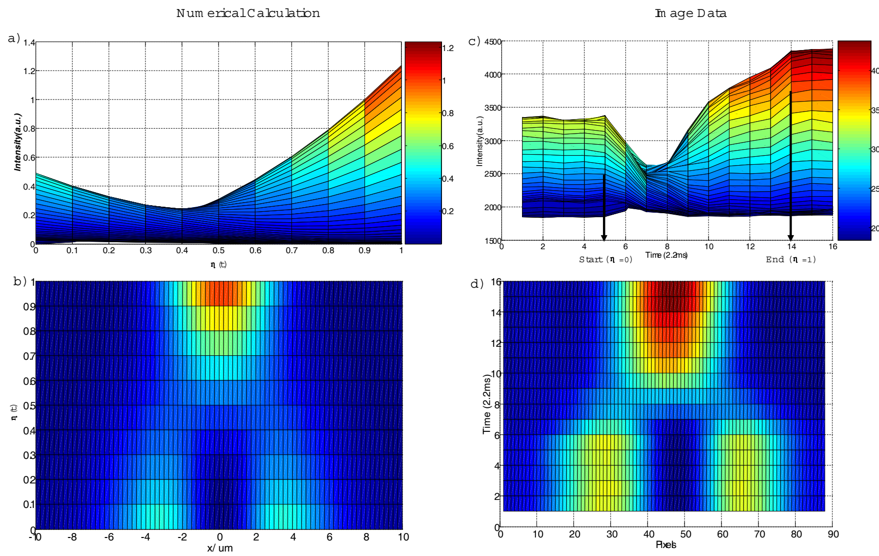

Fig. 2. (color online) Transformation between the double well and the single Gaussian trap. (a) and (b) are the numerical calculation of coherent transformation progress described by Eq. (4) and go to η-intensity view and η-position view respectively.(c) and (d) are image data reconstruction captured from the region of interest, (c) goes to time-intensity view, and (d) is a pixel-time view. The arrow indicates the starting and ending time of the transformation process.

second (fps) of 60 that is maximum refresh rate of the SLM (Holoeye, HEO 1080P). While playing the hologram movie on the desktop, the mode transforming holograms were simultaneously displayed on the SLM with video resolution and maximum refresh rates, and the double well ring lattices would evolve into single traps in succession. We used a CCD to monitor the time evolution of trap transformation. Because of the limited refresh rate of the CCD, we could not get the full region of the traps in good time resolution. To improve the time resolution, we set X axis cross-section as the region of interest(ROI),shown in Fig. 1(a). The image data from the ROI could be captured as frequently as every 2.2 millisecond. The final image data from ROI of the time evolution of cross-section is shown as Fig. 2(c) and 2(d). Figure 2(d) shows the transformation process being in phase. Meanwhile, the dip on the image data is well fit the theoretical mode that there is interference effect between two electric field amplitudes given by Eq. (4). When changing the holograms, first-order diffraction efficiency would decrease to 50% of the double well. This would lead to escape of certain amount of trapped atoms.

3. Loading atoms to the optical traps

We had succeeded in trapping single ^{87}Rb atoms in double well with optical potential of $1mK$ depth and identified the trapping by fluorescence observation [15]. The experimental setup was detailedly described [21, 22] before. Figures 3(a) and 3(b) show the fluorescence from atoms trapped in a double well and a single MFORT trap respectively. The blue line and red line are thresholds that we use to discriminate the states as follows: if the counting rate exceeds the blue line shown as in Fig. 3(a) it indicates that two single atoms are being trapped in the double well with one each, and if the counting rate exceeds the red line and below the blue line it means a single atom is in one well. Once the counting rate exceeds the blue line,we trigger the control system to start the following experimental sequence: (1) shut off the magneto-optical trap

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(MOT) laser for 150ms and play the holograms movie to make the trap shape transformation and to allow atom transfer between traps, (2) switch on the MOT light to induce collisions and detect the atoms in the single MFORT for 60ms. The time bin of the single photon counting module (SPCM, EGG AQRH-14-FC) is 20ms. We get the final results for 200 shots as shown in Fig. 3(c). From the signal we can learn that two atoms could not stay in the same MFORT under the MOT light. This is just the direct confirmation of the ”collision blockade” that would occur between trapped atoms in the ultra small trapping volume [2]. The one body loss rate is about 15.5% derived from Fig. 3(c).

But we cannot distinguish a two-atom loss and one-atom loss from two uncorrelated two-atom losses and one-atom loss during the transformation of the computer generated holograms, we quantify the latter by carrying out the entire experimental sequence with only one atom in double well. Figure 3(d) is the accumulated signal after 200 shots. It indicates that single atom would be transferred from lattice to single trap with high success rate. The probability is 96.5%. From this, we can omit the uncorrelated two-atom losses rate with 0.1% in our experiment. The uncorrelated one-atom loss probability from the double well is about 7.0%. So the success rate of inserting two atoms into a single microscopic dipole trap is larger than 90%.

The one-atom loss during switching of computer generated holograms is due to reduced first-order diffracting efficiency and shallower trap potential. The energy distribution of the single atom in the dipole trap is thermal and has the Boltzmann distribution. Adiabatic lowering of the trap depth would lead to atoms with a higher energy escaping. And the survival probability of the atom remaining in the dipole trap after the truncation of the Boltzmann distribution is given by [23]:

$$P_{surv}(\rho) = 1-(1+\rho+0.5\rho^2)e^{-\rho}, \tag{5}$$

where $\rho = E/k_B T$,E is trap potential,and $k_B T$ is the mean energy of trapped atoms. For our experimental parameters, the mean energy of trapped atoms loading from the MOT is about $70\mu K$ and the intermediate lowest trap potential is about $0.5mK$. So survival probability of single atoms is about 0.97 calculated from Eq. (5).

Collision leading to atom loss in the presence of near-resonant laser light is governed by the long-range resonant dipole-dipole interaction including radiative escape (RE), fine-structure-changing collisions (FCCs), which can be described by a simple semiclassical model called Gallagher-Pritchard model [24,25]. Asymptotically, the potential is of the form $V_{S+P} = -C_3/R^3$ for one atom in the ground and the partner atom in the excited state. For RE progress, spontaneous emission of a photon red-shifted from the atomic resonance can take place. The resulting kinetic energy gained by collisional atoms has a continuous distribution. If spontaneous emission does not occur, the atoms oscillate on the quasimolecular potential curve until they undergo a change of fine structure, and because of the large fine structure splitting(300K) in Rb, this process always causes an escape of both atoms from the shallow dipole trap. So we can learn that RE collision progress would response to the correlated one-atom loss event, in our experiment the probability is about 8%.

4. Conclusion

In conclusion, we have presented a simple implementation method of inserting two ^{87}Rb atoms into a single MFORT with high efficiency lager than 90%, and observed the strong interaction between these atoms leading to light-induced collisions. With this method, we could also trap two single ^{85}Rb atoms and bring them together to show the isotopic difference in trap loss collisions of laser cooled rubidium atoms [26] or we could combine one ^{87}Rb and one ^{85}Rb atom trapped in both sites of the double well to study the heteronuclear excited state-ground state collisions [27]. Determinate two atoms trapped in an MFORT can show how van der Waals

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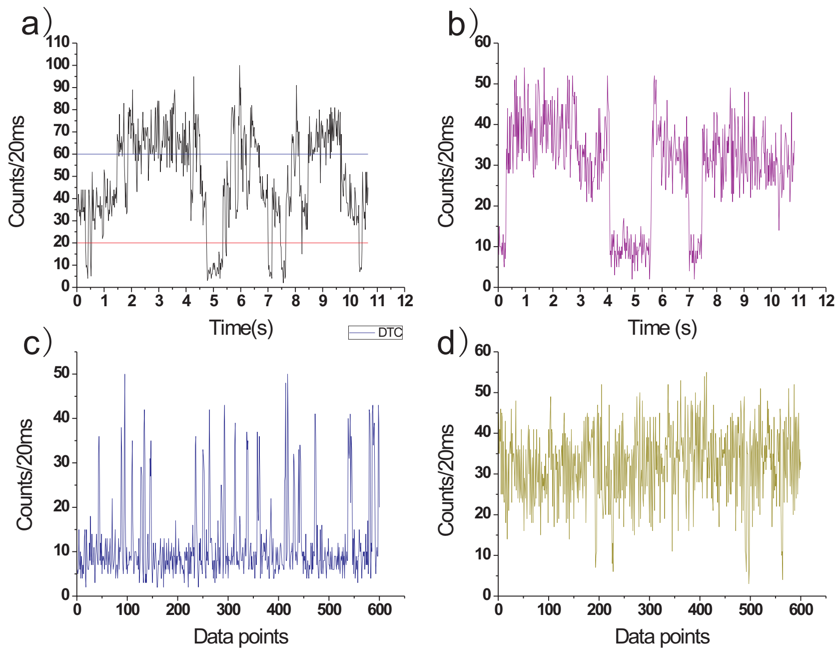

Fig. 3. (color online) Observed fluorescence of single atoms. Each point corresponds to a 20 ms time bin. Shown in (a) is the fluorescence signal from the whole two traps in the double well ring lattice. (b) is the fluorescence signal from atom in the single Gaussian trap. (c) is the accumulated fluorescence signal from single trap after two atoms trapped in the ring lattice being injected into single trap, total 200 shots in the signal, 3 points in each shot. (d) is the the accumulated fluorescence signal from single trap after single atoms trapped in either part of the ring lattice being inserted into the single trap, total 200 shots in the data, 3 points for each shot.

interactions lead to dephasing of the Rabi oscillations between ground and Rydberg States, and elucidate the role of Förster zero states in the dephasing [28]. Further, the technique can make possible many fascinating experiments, e.g. making single trapped diatomic molecules by using photoassociation, preparing an entangled Bell pair of atoms by exploiting coherent spin-changing collisions between two atoms trapped in a single trap, provided that motional state control of the atoms can be achieved. All of these works will finally lead to the quantum information processing with neutral atoms.

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