Experimental apparatus and methods for synthesizing 1D single-atom array

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Abstract. We present apparatus and methods for laser cooling and trapping of single rubidium-85 atoms. The setup consists of a magneto-optical trap and identical optical microtraps lined up by using a programmable acousto-optic deflector. The apparatus designs and systematic arrangement are described in conjunction with the limitations of the techniques and the scope for future improvement. Individual control over the position and power of each trap attained in our work is the key to addressable and scalable quantum system.

1. Introduction
Neutral atoms offer well isolation from the environment [1], tunable interaction and scalable quantum system [2]. Within the past decade of neutral atom approach to quantum computing, the state-of-the-art on the qubit preparation with coherent controls through laser spectroscopy and other additional fields has been advanced rapidly. At the same time, individual manipulation and local addressability in many-body quantum system became an exciting frontier in atomic experimental physics. Following this, the research direction dramatically moved from the effectiveness of preparing single atoms [3–6] limited by the probabilistic energy shared between the colliding partners in the light-assisted process to the vacancy determination and atom rearrangements. The later is generally considered more accessible for realizing a defect-free array of single atoms [7–11]. Recent atom-by-atom assembly experiments have not yet confronted practical boundary pertaining to the maximum number of trapped single atoms and the size of the array continues to rise [2, 7, 12, 13]. Added to that, we present the detail of apparatus and methods for synthesizing a scalable one-dimensional single-atom array. Our experimental design is based on conventional techniques and their limitations. For instance, a six-beam magneto-optical trap (MOT) [14–16] was used to cool rubidium-85 atoms before loading into an array of optical dipole traps created by an acousto-optic deflector (AOD) [2, 5, 17]. The systematic arrangement described in this work has been constructed and will be further used to artificially reproduce the quantum dynamics under precisely controlled conditions to pragmatically simulate interacting quantum systems.
2. Experimental apparatus

2.1. Vacuum system and magnetic coils
An ultra-high vacuum system serves to prolong single atom lifetime by minimizing scattering with the room temperature background gases. The system shown in figure 1(c) and 3(a) is an assembly of a borosilicate glass cell of dimensions 30 mm x 30 mm x 100 mm, a 10 l/s ion pump (Agilent: 9195005), a 150 l/s ion pump (Agilent: 9191542) and rubidium getters. An angle valve separated the vacuum system from a turbo-molecular pump and a scroll pump. The system was baked for 2 days at 180 degree Celsius while the turbo pump and the scroll pump were running. After that, the angle valve was turned off and both ion pumps were energized. The pressure slowly decreased and finally settled around 9×10^{-11} mbar as read from the 10 l/s ion pump controller. Proceeding separately, two sets of coils were placed around the glass cell. A circular Anti-Helmholtz one consisting 150 turns per coil was for the MOT. The other was 3-axis cube Helmholtz coil of which the central uniform field was employed to relocate the position of zero magnetic field.

2.2. MOT setup
The optical alignment for a retroreflective six-beam MOT consist of cooling and repumping beams as shown in figure 1(a). The MOGLabs cateye diod laser (ECDL, MOGLabs: CEL002) provided 70.0 mW of cooling power. An output of 0.5 mW was divided for Doppler-free saturated absorption spectroscopy (DSAS) and the other path (69.5 mW) was frequency shifted by a double-passed +110 MHz acousto-optic modulator (AOM, ISOMET: 1206C). The remaining 11.0 mW of the outbound beam was coupled to a tapper chip (eagleyard: EYP-TPA-0780-01000-3006-CMT03-0000) for power amplification, followed by series of optics for beam shaping. The amplified beam of up to 600 mW was frequency shifted by a double-passed -80 MHz AOM (ISOMET: 1205C-2) before coupled into an optical fiber. The cooling laser was frequency locked on $5S_{1/2}, F = 3 \rightarrow 5P_{3/2}, F = 3co4$ transition giving that the total frequency detuning range is between -52 MHz to -4 MHz from $5S_{1/2}, F = 3 \rightarrow 5P_{3/2}, F = 4$ transition. For a repumping beam, a self-made laser controller and external cavity diode laser in cateye configuration were used to produce 90.0 mW of output power. A small proportion of 0.5 mW split for DSAS. The rest was frequency shifted by a single-passed +40 MHz AOM (ISOMET: 1201E-2) before feeding into an optical fiber. The repumping beam was frequency locked on $5S_{1/2}, F = 2 \rightarrow 5P_{3/2}, F = 2co3$ transition, thus the detuned frequency was +8.6 MHz from $5S_{1/2}, F = 2 \rightarrow 5P_{3/2}, F = 3$ transition.

At the edges of optical fibers, the maximum power of 35.0 mW and 3.0 mW of outgoing cooling and repumping beam were combined by polarization beam splitter (PBS, Thorlabs: PBS122) as shown in figure 1(b). The merged beam was subsequently expanded to 8 mm of diameter and parted into three beams. Before entering the glass cell, a quarter-wave plate altered the polarization state of each beam to $\sigma^+$. Then, a set of quarter-wave plate and mirrors was used to align 3-axis $\sigma^+ - \sigma^-$ counter-propagating cross beams overlapping at centre of the cell. Because of geometric restriction, the MOT beams on an xy-plane made a small angle of 60 degree as illustrated in figure 1(c). A cooling power is equally divided into three beams for each axis. On the other hand, a repumping power on a vertical axis was higher than the other axes because polarization of both beams were perpendicular before split at first PBS. The figure 1(c) demonstrates the crossed MOT beams the glass cell and orientation of an objective lens for an optical dipole trap.

2.3. Optical dipole trap array and imaging setup
A self-made 840 nm diode laser system with an output power of 650 mW provided a parallel laser beam which was coupled into an optical fiber. At the output side, a half-wave plate was used to adjust the proportional powers at the two outward-bound ports of the PBS. The power...
Figure 1. Schematic diagrams of the optical alignment for cooling and repumping processes (a), the combined beams near glass cell (b) and six crossed beams at the glass cell (c).

of desired beam was passively stabilized using polarization maintaining optical fiber (Thorlabs: P3-780PM-FC-2). Driven by a multi-tone RF frequency, the acousto-optical deflector (AOD, AA opto-electronic: DTSX-400) radially spread the beam into five identical rays that went through a 4f system which consists of two similar focal length of 300mm lenses. Subsequently, additional HWPs and PBSs helped to maximize transmitted power and clean up the polarization of all beams. The trap beams continued along the path towards a dichroic mirror (Semrock: FF801-Di02-25x36) and an objective lens (Mitutoyo: G Plan Apo 50X) after which five tight optical traps form a one-dimensional array with a total maximum power of 50 mW (figure 2). Fast production of identical, stable, and independent optical dipole traps is the keys to pragmatic atomic manipulation. In this work, the multi-tone RF frequency was generated from software-defined radio (Ettus: USRP X310) combined with a daughterboard (Ettus: UBX 160) and a GNU Radio software. Then, the multi-tone RF frequency was amplified by power amplifier (AA opto-electronic: AMPB-B-34-10.500) before being sent to the AOD. Following this, the
Figure 2. The alignment of the optical dipole trap beam and the imaging system.

frequency, amplitude, and phase of each RF frequency, which corresponds to individual trap
depth and position, have been independently adjusted for trap optimization.

Certain part of 780 nm light scattered with atoms in the dipole traps has been collected by
the objective lens and then back propagated to the dichroic mirror. Weak reflected beam was
focused by the widefield tube lens (Thorlabs: TTL200) into the EMCCD. The stray light was
filtered out by two 780 nm narrow bandpass clean-up filters (Semrock: LL01-780-12.5) right
before the camera.

3. Methods and results

3.1. Density and temperature of the MOT

While most applications give precedence on atom number, the density and temperature of the
MOT are rather crucial to trapping single atoms. In order to measure these values, the MOT
was imaged onto a CCD camera (Thorlabs: DCU223C) by placing a 50 mm convex lens 100
mm away from the MOT. Fluorescence signals of the MOT formation have been accumulated
for a duration of 1 ms, all data points collected over 8 s were fit with the loading rate equation
\[ y = a(1 - e^{-t/b}) \]
where \( a \) is a saturated signal and \( b \) is the MOT loading time. After that, the saturated signal was converted to atom number (figure 3(b)) where the loading time was
deduced. The MOT density can be obtained by averaging 40 MOT pictures in the saturation
state as shown in figure 3(b). The averaged MOT picture has been fit with a Gaussian function

The MOT radius was used to calculate the volume and MOT density afterward.

Separate experiments based on the release and recapture method have been conducted to
measure the MOT temperature. By shutting down magnetic field and the cooling beam, the
cloud of atoms expanded for a short period of time. At the end, the magnetic field and cooling
beam were turned on again to image the remaining MOT. The cloud size was fit to thermal
expansion relation

\[ R^2(t) = R_0^2 + (2k_BT/m)t^2 \]
to find the kinetic temperature.

During the experiment, cooling and repumping power were 3.0 mW and 0.3 mW. The detuned
frequency of cooling and repumping beam were -5.7 MHz and +8.6 MHz, respectively. The getter
was steadily supplied with direct current of 4.3 A to maintain the pressure inside the glass cell
at 3×10^{-9} mbar. While rectified with 3 A of current, the magnetic field gradient measured in
the axial axis of the MOT coils was 24.3 G/cm and 13.8 G/cm in a radial axis. According to
this parameter setting, the system regularly generated a 94 µK gaseous cloud with 1.10×10^8 of
atom number at density 1.79×10^{11} cm^{-3} with negligible physical property drifts.

Our results show that the atom number and the MOT density are approximately of the same
order of magnitudes comparing to a standard MOT [18]. On the contrary, the MOT temperature
observed was almost two order lower than the Doppler cooling limit which is 140 µK for rubidium-85. This effect is typically a polarization gradient cooling induced by the remaining repumping beams, which were never turned off even at the state of release and recapture.
Figure 3. MOT at the center of the glass cell (a) enclosed within a circular Anti-Helmholtz coil is placed on vertical rounded by the 3-axis cube compensation coil. Curve fitting of the MOT loading is displayed in (b) where the inset shows MOT picture from the CCD.

3.2. Optical dipole trap array
Realization of the optical dipole trap array is shown in figure 4. We created five optical dipole traps from RF frequencies of 96, 98, 100, 102 and 104 MHz. The array was imaged by using an objective lens (Olympus Plan N Apo 40x) followed by 200 mm tube lens and CCD camera. Each trap has beam waist of 1 µm with separation length of 4 µm. Due to an imperfection of the RF and AOD system which acts as frequency mixer, the interference of RF frequency significantly distorts trap amplitude. Thus, this effect leads to non-homogeneous of the trap power (figure 4(a)). By optimizing the phases and amplitude of each RF frequency, the homogeneous trap amplitude could be created (figure 4(b)).

Figure 4. An array of unoptimized (a) and optimized (b) optical dipole traps.

3.3. Atom loading to the optical dipole trap
After the MOT was loaded, atoms would be transferred to the optical dipole trap. A couple of lenses was placed to increase beam waist to 4 µm which facilitating atom loading to the optical dipole trap. With power of 50 mW and beam waist of 4 µm for a single optical dipole trap, these result trap depth of $U_0 = h \times (-23) \text{ MHz} = k_B \times 1.1 \text{ mK}$. Figure 5(a) shows histogram of fluorescent signal in the optical dipole trap from 500 repetitions where all used parameters are shown in table 1. An experimental sequence started from turning on MOT coils, the cooling beam and the repumping beam for 1 second to load the MOT while the optical dipole trap was remained. After that, a 50 ms fluorescent imaging, which was imaged 10 ms after MOT coils was turned off, yielded an average 35 atoms in the trap.
Table 1. Table of used parameters on atom loading to the optical dipole trap.

| Parameters                   | Values                        |
|------------------------------|-------------------------------|
| Cooling power                | 5.0 mW                        |
| Cooling detuning             | -5.7 MHz                      |
| Repumping power              | 0.3 mW                        |
| Repumping detuning           | +8.6 MHz                      |
| Dipole trap beam             | 50 mW                         |
| Magnetic field gradient      | 16.2 G/cm (axial), 9.2 G/cm (radial) |
| pressure                     | $3 \times 10^{-10}$ mbar      |

From the histogram, it is clearly that single atom resolution is unresolvable. This may have an effect from stray light of all laser beam and environment. Moreover, number of atom in the optical dipole trap is broadly because uncontrolled of laser beam power, which causes fluctuation of the MOT density during MOT loading process.

Figure 5. Histogram of atom loading to the optical dipole trap from 500 repetitions (a) where the inset shows optical dipole trap from EMCCD. Time sequences of atom loading to the optical dipole trap (b).

4. Limitations and further improvements
A current apparatus has few limitations that can be improved. First, the number of the optical dipole trap was up to 10 traps due to 840nm power limitation. By changing to higher laser power, the maximum trap number can be increased up to 100 traps which is limited by bandwidth of AOD. Second, since we use MOT beam for imaging atom in the optical dipole trap, stray light from MOT beam results high background imaging. To reduce this effect, the imaging beam should be a small diameter retro-reflected beam separated from MOT beam. Next, the loading parameters should be optimized to collisional blockade regime which will increase probability of single atom loading. Then, laser power fluctuation should be stabilized by a power stabilizer. Finally, the 1D array provides less variety for applications. Spatial Light Modulator (SLM) can be used to improve to 2D trap array which provides much more variety for the experiment.
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References
[1] Wang Y, Kumar A, Wu T Y and Weiss D S 2016 Science 352 1562–5
[2] Endres M, Bernien H, Keesling A, Levine H, Anschuetz E R, Krajenbrink A, Senko C, Vuletic V, Greiner M and Lukin M D 2016 Science 354 1024–7
[3] Schlosser N, Reymond G, Protsenko I and Grangier P 2001 Nature 411 1024–7
[4] Grünzweig T, Hilliard A, McGovern M and Andersen M F 2010 Nat. Phys. 6 951–4
[5] Lester B J, Luick N, Kaufman A M, Reynolds C M and Regal C A 2015 Phys. Rev. Lett. 115 073003
[6] Carpentier A V, Fung Y H, Sompet P, Hilliard A J, Walker T G and Andersen M F 2013 Laser Phys. Lett. 10 125501
[7] Nogrette F, Labuhn H, Ravets S, Barredo D, Béguin L, Vernier A, Lahaye T and Browaeys A 2014 Phys. Rev. X 4 021034
[8] Vala J, Thapliyal A V, Myrgren S, Vazirani U, Weiss D S and Whaley K B 2005 Phys. Rev. A 71 032324
[9] Kim H, Lee W, Lee H G, Jo H, Song Y and Ahn J 2016 Nat. Commun. 7 13317
[10] Barredo D, De Léséleuc S, Lienhard V, Lahaye T and Browaeys A 2016 Science 354 1021–3
[11] Lee W, Kim H and Ahn J 2016 Opt. Express 24 9816–25
[12] Lee W, Kim H and Ahn J 2017 Phys. Rev. A 95 053424
[13] Barredo D, Lienhard V, de Léséleuc S, Lahaye T and Browaeys A 2018 Nature 561 79–82
[14] Kowalski K, Cao Long V, Dinh Xuan K, Głódź M, Nguyen Huy B and Szonert J 2010 Computational Methods in Science and Technology 2 115–29
[15] Camara A, Kaiser R and Labeyrie G 2014 Phys. Rev. A 90 063404
[16] Dalibard J and Cohen-Tannoudji C 2008 J. Opt. Soc. Am. B 6 2023–45
[17] Grimm R, Weidemüller M and Ovchinnikov Y B 2000 Adv. Atom. Mol. Opt. Phy. 42 95–170
[18] Townsend C G, Edwards N H, Cooper C J, Zetie K P, Foot C J, Steane A M, Szriftgiser P, Perrin H and Dalibard J 1995 Phys. Rev. A 52 1423–40