A three-dimensional steerable optical tweezer system for ultracold atoms

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We present a three-dimensional steerable optical tweezer system based on two pairs of acousto-optic deflectors. Radio frequencies used to steer the optical tweezers are generated by direct digital synthesis and multiple cross beam dipole traps can be produced through rapid frequency toggling and time averaging. We demonstrate production of arrays of ultracold atomic clouds in both horizontal and vertical planes and use this as an indicator for the three-dimensional nature of this optical tweezer system.

I. INTRODUCTION

Optical trapping has been a valuable tool in the field of ultracold atoms since the first demonstration by Chu et al.1. In particular, optical potentials are widely used due to being largely state insensitive which leaves quantum spin as a degree of freedom2 and allows the use of external magnetic fields for tuning atom-atom interactions via Feshbach resonances3,4. The introduction of the cross beam dipole trap, which provided tight confinement in three dimensions2, has enabled a number of advances such as the all optical production of Bose-Einstein condensates (BECs)5. In particular, BEC of cesium is not possible in a magnetic trap due to unfavorable scattering lengths6. Since then, generation of arbitrary and time dependent optical potentials has been demonstrated10. Such potentials are desirable for use in the fields of atomtronics11,12, atom interferometry13, and atom based quantum simulation14,15. A variety of techniques for engineering potentials are now commonly used. These techniques include the use of liquid-crystal spatial light modulators17–21, digital-micromirror devices22–24, and rapidly toggled10,25–27 and multi-toned acousto-optic deflectors (AODs)28–32.

In this article, we present a configuration of four AODs, arranged in two orthogonal pairs, with the fundamental diffraction orders of each pair forming a cross beam dipole trap. This configuration, paired with rapid toggling of the AOD driving frequencies10,25–26, allows the steering of multiple dipole traps in three-dimensional space. We show that such a configuration can be used to create a variety of non-trivial potentials in one-, two-, and three-dimensions. Specifically, we demonstrate $2 \times 2$ arrays of atomic clouds on both horizontal and vertical planes. Potential future avenues for our three-dimensional tweezer system include time averaged ring trapping26–27, vortex formation and superfluid flow by merging of independent BECs33,34, study of vortex lattice decay to quantum turbulence through collisions of multiple BECs in nonlinear geometries35, and quantum optics with Rydberg states of atoms36–39.

II. DESIGN

To construct our optical tweezer system, we used two pairs of orthogonal AODs (AAoptoelectronic, DTSXY-400). Each pair is aligned for +1 order Bragg diffraction on both AODs40 and operated with nominal center acoustic frequencies of 75 MHz. Light is sourced from a 1064 nm, 50 W fiber laser (IPG Photonics, YLR-50-1064-LP-SF) and delivered to the AODs using photonic crystal fibers (NKT Photonics, LMA-PM-15). Radio frequencies used to drive the AODs are generated by direct digital synthesis (DDS) using a commercially available device (Wieserlabs, FlexDDS-NG Rack).

The pairs of AODs are arranged such that, at the nominal center driving frequency, the doubly diffracted beam from one pair ($P_1$) propagates along the $y$-axis and can be steered in the $xz$-plane by dynamically altering the frequency in either one or both of AODs in the pair. Similarly, the doubly diffracted beam from the second pair ($P_2$) propagates along the $z$-axis and can be steered in the $xy$-plane. The nominal spot size radius at beam waist for the doubly diffracted beam from both pairs of AODs is $40 \mu m$. The vertical axis is aligned to the direction of acceleration due to gravity and is labeled as the $y$-axis. Multiple time averaged beams can be produced by repeatedly changing the AOD driving frequencies10,25–26. The toggled beams are made to be parallel to each other using lenses placed approximately one focal length in front of the AODs. A simplified arrangement of the optical tweezer system is shown in FIG. II where an example of four cross beam dipole traps in a tetrahedral arrangement is shown.

Up to 7.6±0.5 W of light can be delivered to the AODs via each of the photonic crystal fibers. The diffraction efficiency at the center frequencies of both pairs of AODs was measured to be $\sim 73\%$ with a full width at half maximum bandwidth greater than 25 MHz for all four AODs. The frequency change to displacement calibrations for $P_1$ and $P_2$ are $211\pm2 \mu \text{mHz}^{-1}$ and $-397\pm3 \mu \text{mHz}^{-1}$ respectively. The difference in scaling is attributed to the difference in focal lengths of the lenses used to correct propagation directions. The accessible volume for the optical tweezers exceeds $6 \text{ mm} \times 6 \text{ mm} \times 6 \text{ mm}$, which is comparable to the volume defined by the Rayleigh range of the tweezer beams.

Fixed frequency acousto-optic modulators (AOMs) connected to voltage controlled oscillators (VCOs) are...
used to rapidly switch and regulate the optical power incident on the AODs. The AOMs are aligned to the $+1$ order Bragg diffraction and the $-1$ order Bragg diffraction for $P_1$ and $P_2$, respectively, which prevents static interference between vertical and horizontal beams by ensuring frequency differences in excess of 40 MHz, which are much faster than any dynamics we consider. In addition, the polarizations for the vertical and horizontal beams are chosen to be orthogonal. Optical power is regulated by measuring the output power of the photonic crystal fibers and dynamically adjusting the RF amplitude in the AOMs. If we use only the AOMs as the primary fibers and dynamically adjusting the RF amplitude by measuring the output power of the photonic crystal fibers, then the AOMs spend most of the time in the off state with no RF applied and only a small fraction of time ($\sim 1\%$) in the on state. During the time that they are on, the AOM crystals heat up and cause the beam directions to drift, lowering the power available from the optical fibers. In addition, exposing the AOM crystals to high optical power for long periods of time can lead to thermal lensing and a consequent degradation of the beam mode, which results in lower fiber coupling efficiency. To mitigate these issues, we use a motorized flipper mirror to divert the laser beam into a beam dump and keep the AOMs in the on state during all preparatory stages of the experimental cycle.

The FlexDDS can store more than $10^6$ instructions in RAM distributed between 2 to 12 channels, depending on the configuration. A single instruction can set the phase, amplitude and frequency of a single channel. Typically one time step for optical tweezers consisting of two AODs requires four instructions, including wait-for-trigger commands. Each channel can be addressed individually and has a sample rate of 1 GS$ \cdot $s$^{-1}$ with a frequency range from 0.3 Hz to 400 MHz. The FlexDDS also enables control of the acoustic power inside the AODs using amplitude tuning words, which allows dynamic balancing of power between toggled beams. DDS instructions are loaded into RAM on the FlexDDS via TCP/IP and subsequently written to DDS chips via serial peripheral interface (SPI) by a digital command processor (DCP). The timing of the FlexDDS is controlled using external triggers from a field programmable gate array (FPGA). Instructions can be triggered from the FlexDDS at rates in excess of 250 kHz which are limited by the SPI write time of the FlexDDS and the access time of the AODs$^{26}$. Additionally, individual time delays of up to 134 ms with 8 ns resolution can be specified for each output channel (the master clock is locked to a GPS-disciplined 10 MHz reference). These time delays are used to account for finite propagation time of the acoustic waves when the frequencies are toggled, which result in “ghost” traps when toggling two or more acousto-optic devices in series$^{25}$. FIG. 4 shows a control schematic of the optical power delivery system and RF control.

In our experiment, ultracold $^{87}$Rb atoms in the $5^2S_{1/2}/F = 2, m_F = 2$ ground state are loaded into a cross beam dipole trap from a Ioffe-Pritchard (IP) trap. The dipole trap typically consists of one static horizontal beam (propagating along the $z$-axis of the IP trap) and two rapidly toggled vertical beams separated by 60 $\mu$m$^{14}$. Atomic clouds can be evaporatively cooled to quantum degeneracy by controlled decrease of the optical power in the horizontal beam(s)$^{13,24}$. To produce multiple clouds, we pull tweezer beams apart on minimum-jerk cost trajectories before evaporation. A minimum-jerk cost trajectory minimises the integral of the square of the third derivative (the jerk) of the trajectory$^{24}$

$$\int_0^\tau \left[ \frac{d^3}{dt^3} s(t) \right]^2 dt,$$

where we have assumed that the total transit time is $\tau$. By applying boundary conditions of $s(0) = x_0$, $s(\tau) = x_f$ and zero initial and final velocity and acceleration, we see that a minimum-jerk cost trajectory is defined by

$$s(t) = x_0 + D \left[ 10 \left( t/\tau \right)^3 - 15 \left( t/\tau \right)^4 + 6 \left( t/\tau \right)^5 \right],$$  \hspace{1cm} (1)
The gray shading behind the waveforms represents regions of constant frequency and black bars represent arrival times of triggers from the FPGA. Details of the optics between fiber outputs and the AODs have been omitted for clarity.

III. IMAGING

Our system was built with two orthogonal absorption imaging paths. Both paths image $^{87}$Rb on the $D_2$ line (780 nm). One path has the probe beam propagating along the $x$-axis towards a charge coupled device (CCD). The second imaging path has the probe beam propagating along the $y$-axis towards a CCD. The pixel size limited resolutions of the horizontal and vertical imaging paths are 11.1±0.01 µm and 4.10±0.01 µm, respectively.

The vertical imaging system also employs a current carrying coil located above the science cell which is used to levitate the atoms by applying a 15 G · cm$^{-1}$ field gradient. After adiabatic rapid passage to the strong field seeking state $|F = 2, m_F = -2\rangle$, the levitation field is applied during ballistic expansion of the atoms in order to keep the atoms from falling away from the focus of the objective lens. The objective lens for the vertical imaging path is a diffraction limited singlet (Thorlabs, AL2550H) with a numerical aperture of NA = 0.2 which, according to the Rayleigh criterion, gives a diffraction limited resolution of 4.8 µm.

To demonstrate the resolution of the vertical imaging system clearly, FIG. 4a shows matter wave interference fringes. BECs were prepared in two cross beam dipole traps, separated along the $z$-axis by 80 µm, consisting of a single horizontal beam and two rapidly toggled vertical beams (one for each trap). The optical power shared by the two vertical beams was ramped linearly to zero over a period of 100 ms and the two condensates were allowed to expand in the horizontal beam for 50 ms before 30 ms time-of-flight under the influence of magnetic levitation. A comparable fringe contrast and number of fringes was not found for the horizontal imag-
FIG. 4. (a) Matter wave interference fringes between two BECs of $^{87}$Rb with an initial separation of 80 $\mu$m, observed with the vertical imaging path at 30 ms time-of-flight. The experimental sequence is described in the main text. The color bars represent optical depth. (b) Matter wave interference fringes, produced using the same method as in (a), captured at 50 ms time-of-flight using the horizontal imaging path. These results clearly demonstrate a higher spatial resolution for the vertical path compared with the horizontal path since the visibility of interference fringes is strongly dependent on imaging resolution.

IV. RESULTS

In this section, we present some preliminary demonstrations of our ability to manipulate arrays of atomic clouds in three-dimensions. As previously mentioned, to arrange multiple ultracold atomic clouds into arrays, we start with a single cross beam dipole trap of thermal atoms loaded from an IP trap. The thermal atoms are split by dynamically altering the trapping potential such that beams are split as necessary. All tweezer beams followed minimum-jerk cost trajectories. When powers were balanced correctly (particularly important when splitting along the axis of gravity), splitting a single beam into $N$ beams would result in the trapped atomic cloud being split into $N$ atomic clouds with approximately equal atom number.

FIG. 4 illustrates how we produce four atomic clouds in a square array with nearest neighbor separation of 500 $\mu$m. The cross beam dipole trap used for loading atoms from the IP trap is formed from four overlapping beams, two horizontal and two vertical, which are pulled apart on minimum-jerk cost trajectories. Frames (a) - (c) show sequentially increasing time with equal increments. In a typical experimental sequence the total time for splitting is on the order of 100 ms.

FIG. 4 shows an absorption image captured using the vertical imaging system corresponding to four thermal clouds arranged in a horizontal plane. The arrangement was rectangular; the distance between neighboring clouds with respect to the $x$-axis was 400 $\mu$m and the separation with respect to the $z$-axis was 500 $\mu$m. The image was captured at 2 ms time-of-flight which resulted in a nearly uniformly absorbed probe beam at the atomic cloud positions due to the high in-trap atomic density.

Creating a square arrangement in a vertical plane required a modification of the experimental sequence due to the influence of gravity. Most importantly, the power balance was adjusted to be heavily in favor of the upper beam since gravity would keep all of the atoms in the lower beam if the powers were balanced. Second, the clouds were split in two steps. In the first step, clouds were split along the $y$-axis by 150 $\mu$m in 500 ms. In the second step the clouds were simultaneously split by a further 350 $\mu$m in the $y$-direction and 500 $\mu$m in the $z$-direction in 100 ms. FIG. 7 shows an arrangement of clouds produced using the above experimental sequence. In addition, the clouds were evaporatively cooled over a period of 2 s to produce one BEC at each of the four sites.

At the end of evaporation, each of the four clouds shown in FIG. 7 contained more than $6 \times 10^4$ atoms and the condensate fractions were between 0.1 and 0.4. The condensate fractions were extracted from two-dimensional bimodal (projected parabolic, corresponding to a Thomas-Fermi condensate and Gaussian corresponding to the thermal component) fits to the absorption image. The absorption image was taken at 12 ms time-of-flight.

V. SUMMARIZE

In this article, we have presented a three-dimensional optical tweezer system based on two pairs of orthogonal AODs. One pair of AODs was used to displace horizontally propagating laser beams in a vertical plane while the other pair was used to displace vertically propagating laser beams in a horizontal plane. Multiple cross beam dipole traps were produced through rapid toggling of the frequency of the sound waves in the AODs and time averaging. We have demonstrated production of arrays of ultracold atomic clouds in both horizontal and vertical planes. In particular, we have presented a square array of four BECs in a vertical plane and a $2 \times 2$ array of...
thermal clouds in a horizontal plane.

In future experiments, the three-dimensional optical tweezer system presented here could be used for creating time averaged optical ring traps and for studying vortex and superfluid flow effects resulting from the merging and collision of independent BECs. The dynamic reconfigurability of the optical tweezer system also makes it a prime candidate as a platform for quantum simulation with engineered Hamiltonians.

A recent experiment by Pu et al. has demonstrated the use of multiplexed AODs to demonstrate 22-partite entanglement in a $5 \times 5$ array of individually accessible atomic quantum interfaces. The experiment of Pu et al. used atoms in a single magneto-optical trap. Applying our apparatus to the experimental techniques of Pu et al. would allow entanglement to be demonstrated between truly isolated atomic ensembles.

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