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Pulsed polarization gradient cooling in an optical dipole trap with a Laguerre-Gaussian laser beam

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Abstract. We utilized a blue-detuned Laguerre-Gaussian (doughnut) laser beam to trap cold rubidium atoms by optical dipole force. "Pulsed" polarization gradient cooling was applied to the trapped atoms to suppress the trap loss due to heating caused by random photon scattering of the trapping light. In this trap about 10^8 atoms were initially captured and the trap lifetime was 1.5 s, which was consistent with losses due to background gas collisions. This trap can readily be applied to atom guiding, compression, and evaporative cooling.

PACS. 32.80.Pj Optical cooling of atoms; trapping – 39.90.+d Other instrumentation and techniques for atomic and molecular physics

Optical dipole force has been extensively used for manipulation of atomic motion. An evanescent wave formed by internal reflection of a blue-detuned laser beam at a glass surface acts as a mirror for atoms [1,2]: up to 10 bounces of cesium atoms dropped onto the mirror have been observed [2]. The blue-detuned evanescent wave has also been used for guiding of atoms in a hollow-core optical fiber [3]. Various geometrical configurations of optical dipole trap for atoms have been demonstrated [4–6] and used for precision measurements [5] and increasing atomic phase-space density [4,6].

Recently we demonstrated a new optical dipole trap using a blue-detuned Laguerre-Gaussian (LG) laser beam which has a "doughnut" transverse intensity distribution [7]. Since the LG modes form a complete set of solutions to the paraxial Helmholtz equation, the LG beam can be focused without changing the transverse intensity profiles. This is a great advantage in designing trap potentials, in particular when one would perform compression or evaporative cooling of atoms [8]. In the previous work, however, the trap lifetime was limited to ~ 150 ms mainly by heating due to random photon scattering (spontaneous emission) of the trapping light [7,9]. In this paper, we report on the application of polarization gradient cooling (PGC) [10] to suppress the trap loss by the heating. PGC works even in the trap because the atoms are confined in the dark core of the doughnut beam where the trapping light induces smaller light shift of the atomic ground state sublevels than the PGC laser light. At a low trap density ($< 10^{10}$ cm^{-3}), where the intratrap collisional losses could be negligible, we could prolong the trap lifetime to 1.5 s, which was consistent with losses due to background gas collisions.

The experimental details were similar to those described in the previous work [7]. To provide an LG beam for the dipole trap we utilized an astigmatic mode converter [11] consisting of two cylindrical lenses and one spherical lens as illustrated in Figure 1a. This converter transforms an HG_{nm} beam (or equivalently TEM_{nm} beam), where n and m correspond to the number of node lines, to an LG_{nm} beam, where n and m denote radial and azimuthal indices, respectively. The HG beam was generated by a Ti:sapphire (TS) laser pumped by a 9W all-line argon ion laser. A tungsten wire of 20 μm diameter was positioned inside the cavity to force the TS laser into a desired HG-mode operation (Fig. 1a). We could obtain any mode of HG_{00} up to HG_{04} in this way. In the experiment described below, the TS laser was operated in the HG_{03} mode with an output power of 700 mW, which was a half of that in the HG_{00} mode. The TS laser was easily tuned to a desired frequency by adjusting a thin etalon and a birefringent filter inside the cavity. Figure 1b and c show the beam intensity distributions monitored by a charge coupled device array before (HG_{03}) and after (LG_{03}) the mode converter, respectively.

A geometrical configuration of the dipole trap is illustrated in Figure 2. Precooled rubidium atoms were confined in the dark core of the blue-detuned doughnut (LG_{03}) beam. At the trap center, a diameter of the doughnut beam was 1.5 mm, and that of the dark core was about 0.5 mm. After passing through the trap region, the doughnut beam was divided into two, focused, and redirected to intersect the dark core at an interval of 2 mm

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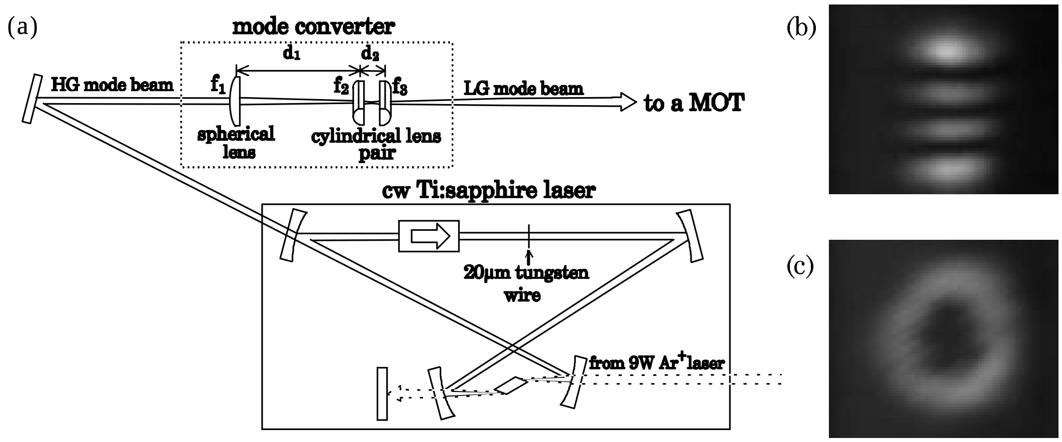

Fig. 1. (a) Experimental setup for generation of Laguerre-Gaussian (LG) beams. Ti:sapphire laser is forced to operate in higher-order Hermite-Gaussian (HG) mode by a 20 μm tungsten wire inside the cavity. The mode converter consists of one spherical lens (focal length: f_1) and two mutually-parallel cylindrical lenses (f_2 and f_3). The axes of the cylindrical lenses make an angle of 45 degrees with the node line of the HG mode beam. Dimensions are: $d_1 = 250$ mm, $d_2 = 35$ mm, $f_1 = 250$ mm, $f_2 = f_3 = 25$ mm. (b) and (c) are the beam intensity profiles monitored before (HG_{03}) and after (LG_{03}) the mode converter, respectively.

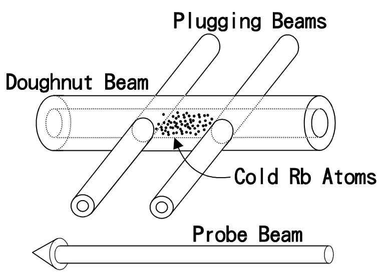

Fig. 2. A geometrical configuration of the dipole trap with an LG (doughnut) beam.

for confinement of the atoms along the doughnut beam. These two "plugging" beams had a diameter of 0.7 mm. The trapping beams were tuned ~ 50 GHz above the D_2 ($5S_{1/2} \rightarrow 5P_{3/2}$) transition.

Loading of the dipole trap was accomplished as follows. We first captured 6×10^8 ^{85}Rb atoms in a standard vapor-cell magneto-optical trap (MOT) [12] under a background pressure of $\sim 10^{-9}$ Torr. The diameter and temperature of the MOT were 1.5 mm and 150 μK, respectively. The atoms in the MOT were then further cooled to 10 μK by PGC. Just after the MOT beams (both the trapping and repumping beams) were tuned off by acousto- optic modulators, the doughnut and plugging beams were introduced into the atomic cloud by opening a mechanical shutter within 1 ms; then the dipole trap was constructed.

The number and temperature of the atoms in the dipole trap were measured with time-of-flight (TOF) technique: after a certain trapping time, all the trapping beams were shut off, and then the atoms falling by gravity were detected as a time-dependent absorption signal of a weak probe laser beam propagating 7 mm below the doughnut beam (Fig. 2). The probe laser having a diameter of 0.3 mm was tuned to the $5S_{1/2}$, $F = 3 \rightarrow 5P_{3/2}$, $F' = 4$ transition. During probing, a repumping laser resonant with the $5S_{1/2}$, $F = 2 \rightarrow 5P_{3/2}$, $F' = 3$ transition illuminated the probe region so that all the atoms passing through the probe region were in the $5S_{1/2}$, $F = 3$ state and contributed to the TOF signal. We could deduce the number and temperature of the trapped atoms from the peak height and width of each TOF signal.

To suppress the trap loss due to heating caused by random photon scattering of the trapping light, we periodically applied the pulses of the PGC beams to the trapped atoms. As the PGC beams we used the trapping beams for the MOT. The PGC beams were tuned 80 MHz below the $5S_{1/2}$, $F = 3 \rightarrow 5P_{3/2}$, $F' = 4$ transition, and their intensities were ~ 1 mW/cm^2 each. The atoms in the trap spent about a half of their time in the $5S_{1/2}$, $F = 3$ ground state because the detuning of the trapping beams was much larger than the hyperfine frequency difference between the two ground states (3.04 GHz) and the spontaneous emission (optical pumping) rate of $\sim 10^3$ s^{-1} was much faster than the trap loss rate. PGC works on the atoms when they are in the $5S_{1/2}$, $F = 3$ ground state, therefore we expected that the trapped atoms were cooled by the PGC beams. There are two reasons why we applied the PGC beams to the trap not continuously but intermittently. First, the trap loss due to light-assisted collisions is proportional to the excitation rate of the PGC beams [17]. Second, light shifts induced by the PGC beams was comparable to the trap potential height (~ 40 μK); therefore, if we applied the PGC beams continuously, the atoms would diffuse away from the trap.

The longest trap lifetime was obtained when the pulse duration and interval were 0.2 ms and 5 ms (duty cycle was 4%), and the detuning of the trapping beam was +42 GHz. The full circles in Figure 3 shows the number of atoms in the trap as a function of trapping time under these conditions. The decay did not fit to a single

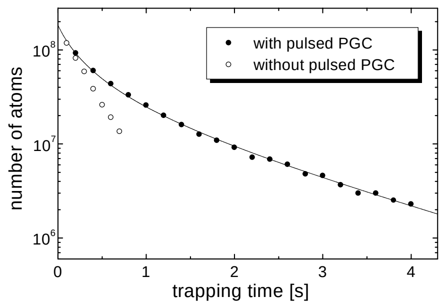

Fig. 3. The decay of trapped atoms when pulsed PGC was applied (the full circles) and not applied (the open circles). The solid curve is a fit based on a solution to the equation $\mathrm{d}N/\mathrm{d}t = -N/\tau - bN^2$, yielding $\tau = 1.5$ s and $b = 2.2 \times 10^{-8}$ s^{-1}.

exponential but to a curve based on a solution of the equation $\mathrm{d}N/\mathrm{d}t = -N/\tau - bN^2$ (the solid curve in Fig. 3). By extraporating the decay line to zero trapping time [13], we estimated the number of atoms initially loaded in the dipole trap to be 2×10^8 (loading efficiency from the MOT to the dipole trap was 30%) [14]. The slow exponential decay (the first term in the right hand of the equation) had a time constant of $\tau = 1.5$ s, which was consistent with losses due to collisions with background gases [15]. This indicates that the trap loss due to heating was efficiently suppressed by pulsed PGC. Indeed the temperature of the trapped atoms was kept 13 μK, which was close to a temperature of 10 μK achieved by PGC just before the dipole trap was turned on. On the other hand, when pulsed PGC was not applied to the trap, the lifetime decreased to ~ 0.3 s (the open circles in Fig. 3) [9] and the temperature increased to 25 μK which was close to the estimated trap potential height [16]. The initial fast decay (the second term) resulted from losses due to intratrap collisions, which were mainly ground-state hyperfine-changing collisions (GHC) in the present case [17,18]. As mentioned above, about a half of atoms in the trap were in the $5\mathrm{S}_{1/2}$, $F = 3$ (upper) ground state. The kinetic energy released in the GHC is about 150 mK, which is large enough to eject the colliding atoms out of the trap. From the trap loss coefficient for GHC measured in reference [18] ($\beta \sim 2 \times 10^{-11}$ cm^{3}s^{-1}) and the extrapolated initial decay rate of ~ 3 s^{-1}, we estimated the initial trap density to be $\sim 2 \times 10^{11}$ cm^{-3}. This value is close to our MOT's density of 1.6×10^{11} cm^{-3} and supports the above considerations.

If we could suppress the trap loss due to GHC by optically pumping the atoms to the dark (lower) hyperfine ground state using an additional laser, the atoms in the trap could be easily compressed by gradually reducing the diameter of the doughnut beam. Although adiabatic compression accompanies heating [8], the dark version of pulsed PGC would keep the atomic temperature low enough to store the atoms in the dipole trap. Among the optical cooling methods, Raman cooling [5] and velocity selective coherent population trapping [19] can reduce the atomic temperature below the one-photon recoil energy (subricoil cooling), whereas pulsed PGC cannot in principle since it relies on spontaneous emission of photons for its cooling mechanism [10]. We believe, however, the phase space density could be easily increased by compression with the help of pulsed PGC as discussed above. Moreover, we expect that evaporative cooling would work in our dipole trap just by lowering the trap potential height. The experimental study is now in progress.

In conclusion, we have captured a large number of atoms ($\sim 10^8$) in the dipole trap using a Laguerre-Gaussian (doughnut) beam. Application of pulsed PGC to the trap has suppressed the trap loss due to heating and drastically prolonged the trap lifetime. We believe this trap has a great potential for guiding of atoms or increasing the phase space density of atoms.

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References

1. V.I. Balykin, V.S. Letokhov, Yu.B. Ovchinnikov, A.I. Sidorov, Phys. Rev. Lett. **60**, 2137 (1988); M. Kasevich, D. Weiss, S. Chu, Opt. Lett. **15**, 607 (1990).
2. C.G. Aminpoff, A.M. Steane, P. Bouyer, P. Desbiolles, J. Dalibard, C. Cohen-Tannoudji, Phys. Rev. Lett. **71**, 3083 (1993).
3. H. Ito, T. Nakata, K. Sakaki, M. Ohtsu, K.I. Lee, W. Jhe, Phys. Rev. Lett. **76**, 4500 (1996).
4. C.S. Adams, H.J. Lee, N. Davidson, M. Kasevich, S. Chu, Phys. Rev. Lett. **74**, 3577 (1995).
5. N. Davidson, H.J. Lee, C.S. Adams, M. Kasevich, S. Chu, Phys. Rev. Lett. **74**, 1311 (1995).
6. H.J. Lee, C.S. Adams, M. Kasevich, S. Chu, Phys. Rev. Lett. **76**, 2658 (1996).
7. T. Kuga, Y. Torii, N. Shiokawa, T. Hirano, Y. Shimizu, H. Sasada, Phys. Rev. Lett. **78**, 4713 (1997).
8. K.B. Davis, M.-O. Mewes, M.A. Joffe, M.R. Andrews, W. Ketterle, Phys. Rev. Lett. **74**, 5202 (1995).
9. In the previous work, we kept the repumping beam "on" while the atoms were stored in the dipole trap; this assured the atoms in the trap to be populated in the $5\mathrm{S}_{1/2}$, $F = 3$ (upper) hyperfine ground state, and the resultant trap lifetime was 150 ms [7]. From the later experiment, we learned that the trap lifetime without pulsed PGC could be extended from 150 to 300 ms by shutting "off" the repumping beam before the dipole trap was tuned on. Simple calculation gives that without the repumping beam the atoms in the trap are, as mentioned in the text, evenly populated in $5\mathrm{S}_{1/2}$, $F = 3$ and $5\mathrm{S}_{1/2}$, $F = 2$ ground states, and the rate of spontaneous emission decreases to about two-third of that with the repumping beam. Also, a factor of 2 reduction of the population in the upper hyperfine ground state correspondingly reduces the rate of ground-state hyperfine-changing collisions [17,18] to half. We assume these were the main reason for the extension of the trap lifetime.

10. See *Special issue on Laser Cooling and Trapping*, edited by S. Chu and C. Wieman, J. Opt. Soc. Am. B **61** (1989).
11. M.W. Beijersbergen, L. Allen, H.E.L.O. van der Veen, J.P. Woerdman, Opt. Commun. **96**, 123 (1993).
12. C. Monroe, W. Swann, H. Robinson, C. Wieman, Phys. Rev. Lett. **65**, 1571 (1990).
13. For a short trapping time (< 10 ms) the number of remaining atoms in the dipole trap could not be deduced directly from the TOF signals because we could not distinguish between the atoms from the dipole trap and those from the MOT.
14. In the present work the number of atoms captured in the MOT was twice as many as that in the previous work [7], because we had slightly increased the background pressure of rubidium vapor and improved quality of the MOT beams. This caused the increase of the number of atoms loaded in the dipole trap (from 1×10^8 to 2×10^8). However the present loading efficiency was almost the same as the previous one ($\sim 30\%$).
15. The time constant of the trap loss due to background gas collisions was 1.4 s, which was determined from a collection profile of the MOT.
16. As mentioned in the previous work [7], the temperature of the dipole trap without any cooling was determined by the potential height of the doughnut beam. The potential height was almost inversely proportional to the detuning of the doughnut beam. The present detuning of +42 GHz was smaller than that in our previous work of +57 GHz, resulting in increase of the trap temperature from 18 μK to 25 μK.
17. D. Sesko, T. Walker, C. Monroe, A. Gallagher, C. Wieman, Phys. Rev. Lett. **63**, 961 (1989).
18. C. Wallace, T. Dinneen, K.-Y. Tan, T. Grove, P. Gould, Phys. Rev. Lett. **69**, 897 (1992).
19. A. Aspect, E. Arimond, R. Kaiser, N. Vansteenkiste, C. Cohen-Tannoudji, Phys. Rev. Lett. **61**, 826 (1988); J. Lawall, S. Kulin, B. Saubamea, N. Bigelow, M. Leduc, C. Cohen-Tannoudji, Phys. Rev. Lett. **75** 4194 (1995)