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Diagnostics and loading of an atomic optical dipole trap

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We describe diagnostic techniques used for optimization of loading of an optical dipole trap with CO_2 laser and ^{87}Rb atoms. Atoms, precooled in a magneto-optical trap, were loaded into the trap formed by a weakly focused CO_2 laser beam with the waist of about 150 μm and power of 50 W. In addition to determining the atom number and temperature, the effect of the loading geometry on the time evolution of trapped atoms is discussed. It is shown that a direct study of this evolution can be used for determining the trap frequencies.

Keywords: cold atoms, atom trapping, optical dipole trap.

1. Introduction

Optical dipole traps are based on conservative optical dipole forces. Dipole traps work thanks to the interaction of properly configured magnetic field gradients with atomic magnetic dipole moments or non-uniform electric fields of non-resonant light beam with induced atomic electrical moments. Due to such interactions, forces are exerted on neutral atoms that allow their trapping, in magnetic (MTs) or optical dipole traps (ODTs) [1]. An important limitation of all dipole traps, MTs and ODTs, is that they do not cool trapped atoms (because of their conservative character) and require appropriate techniques for loading them with precooled atoms. Magnetic traps require the application of special coils or magnets and preparation of atomic samples in specific magnetic states, *i.e.*, they work only with atoms having non-zero angular momenta in their ground states. The optical dipole traps are not limited by this constraint, they have simpler constructions and address atoms and molecules in any ground states. Thanks to these features, ODTs have found numerous applications (see review [1] and references therein).

For any applications it is essential to characterize the trapped atomic sample. The most essential parameters that need to be determined are the number and temperature of the trapped atoms, trap lifetime and trap frequencies. In this paper, we describe a diagnostic procedure used for ODT with a CW CO_2 laser of 50 W power loaded with ^{87}Rb atoms. This diagnostics is applied for optimization of the trap performance and its loading from a standard magneto-optical trap. The optical imaging techniques allowed us also to study the time evolution of the trapped atom cloud and the excitation of various oscillation modes by suitable loading geometry. Such measurements allow direct determination of the trap frequencies which are essential characteristics of the trapped atom dynamics. The described method is a simple alternative to the standard method of measuring the trap frequencies by parametric resonance [1].

2. Basics of optical dipole trapping

Since, in general, the optical dipole forces depend on detuning between the light and atomic resonance frequency [1], in case of very far, red-detuned lasers ($\omega \ll \omega_0$, where ω and ω_0 denote the laser and atomic resonance frequency, respectively), this dependence is not important. For strongly detuned light beams, the light-induced dipole moments follow the light-beam electric fields with no phase shifts. A trap based on such interactions is called quasi electrostatic trap (QUEST) and, in the simplest case, can be formed by focusing the laser beam. For most atomic samples, a CO$_2$ laser with its wavelength of 10.6 μm and power of some tens of watts is a very good candidate for building such a trap.

Assuming a Gaussian intensity distribution within the beam

$$I(z, r) = I_0 \frac{w_0^2}{w^2(z)} e^{-2r^2/w^2(z)} \tag{1}$$

where the beam radius is given by

$$w(z) = w_0 \sqrt{1 + \left(\frac{z - z_0}{z_R}\right)^2}$$

the Rayleigh length

$$z_R = \frac{\pi w_0^2}{\lambda}$$

(w_0 being the beam waist, z_0 the waist position, and λ the laser light wavelength), one can calculate the trap's potential as $U_{\mathrm{dip}} = \alpha_{\mathrm{stat}} I$ where α_{stat} is the static polarizability

$$\alpha_{\mathrm{stat}} = \frac{3\pi c^2}{\omega_0^3}\frac{\Gamma}{\omega_0}$$

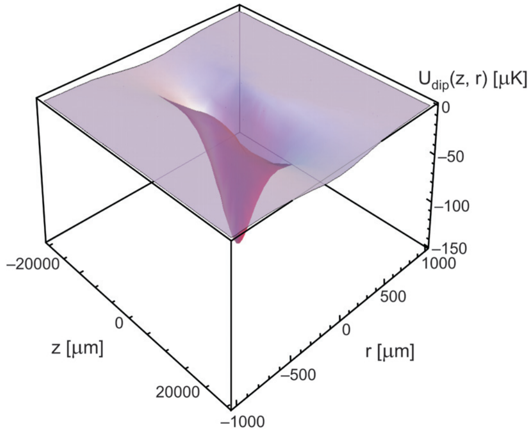

Fig. 1. ODT potential shape in a focused, CO_2 laser beam acting on ^{87}Rb atoms. The laser beam of 50 W power is focused to 150 μm waist (Rayleigh length 6700 μm), which results in the 148 μK trap depth.

while Γ – the natural linewidth of the resonant transition of trapped atoms, and c – the speed of light. The shape of such a potential is illustrated in Fig. 1.

3. Experiments with rubidium atoms in the ODT with CO_2 laser

3.1. Experimental setup

Since the optical dipole forces are conservative, the ODT must be loaded by precooled atoms. In the described experiment, cooling of ^{87}Rb atoms is accomplished by a magneto-optical trap (MOT) [2]. The experiments are performed using a single vacuum chamber design which houses the MOT and ODT. The MOT is loaded from rubidium vapor generated by a rubidium dispenser (SAES Getters). With cooling beams of 8.5 mm radius (e^{-2}) about 1×10^7 atoms are collected in the MOT. The MOT is spatially overlapped with a weakly focused CO_2 beam ($w_0 = 150$ μm and $z_R =$ $= 6700$ μm and of 50 W of total power). The setup is presented in Fig. 2.

3.2. Loading and diagnostics of an optical dipole trap

A typical loading sequence is presented in a diagram in Fig. 3. After MOT is loaded, the ODT loading phase starts. In this phase, the CO_2 beam is turned on and MOT cooling beams are detuned about 90 MHz from resonance to make polarization gradient cooling [3] more efficient. This stage results in atomic temperature decrease from 100 μK to 20 μK as established by atomic recapture measurement. Moreover, the repumping light intensity is lowered to 70 μW/cm^2 in order to store most of the trapped atoms in the $F = 1$ state which is almost dark, *i.e.*, not perturbed any further by light. This "dark MOT" phase substantially decreases light-induced losses from the trap during its loading. In the following step the MOT beams are switched

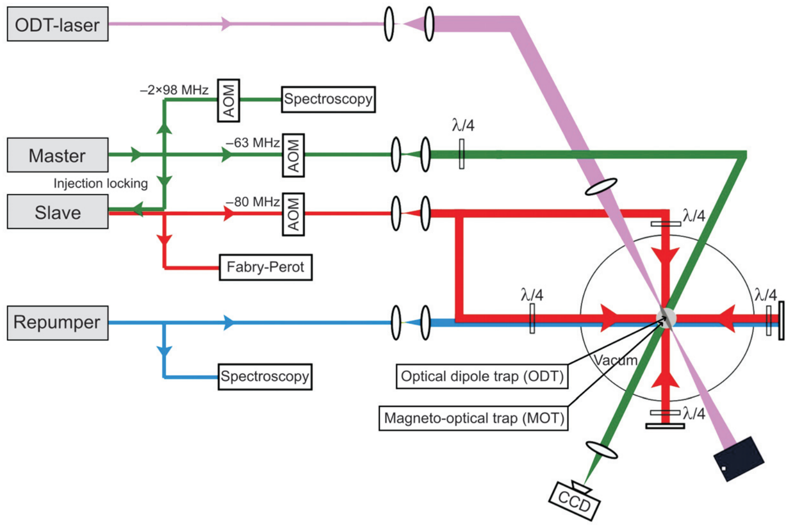

Fig. 2. Experimental setup. The Master, Slave and Repumper are single-mode diode lasers emitting at 780 nm. Their frequencies are controlled by acousto-optic modulators (AOMs), monitored by a spectrum analyzer (Fabry–Perot), and stabilized to atomic transitions using Doppler-free spectroscopy. Three orthogonal pairs of counter-propagating beams of these lasers are appropriately circularly polarized and, together with a quadrupole magnetic field (not shown), constitute the MOT. The MOT centre is overlapped with a focus of a CO_2 laser beam. An extra 780 nm laser beam and CCD camera are used for the trap diagnostics.

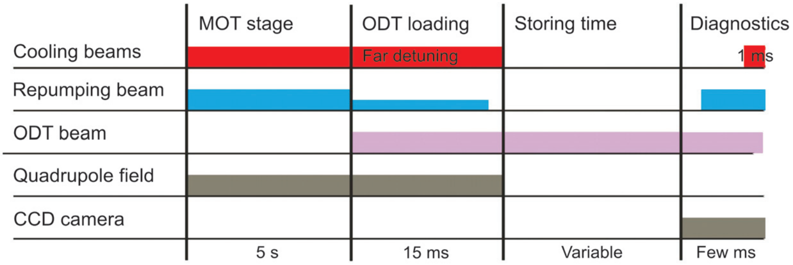

Fig. 3. Timing of the ODT loading and diagnostics.

off and the repumping light is extinguished completely a millisecond before the cooling beams to pump all the atoms to the $F = 1$ state to avoid trap loss due to spin-exchange collisions after the trap is loaded. After that procedure, the atoms are confined in the ODT potential. In the next phase, the diagnostics is performed using the fluorescence or absorptive imaging [4].

3.3. Diagnostics and optimization

After loading, a complex diagnostics of our ODT was performed, which allowed determination of its most important parameters (see the Table).

Table. ODTs for ^{87}Rb atoms with CO_2 laser parameters.

Calculated trap depth	148 μK
Calculated trap frequencies	4 Hz – longitudinal 253 Hz – transversal
Measured trap frequencies	3.0 (0.5) Hz – longitudinal 200 (5) Hz – transversal
Measured number of atoms	2×10^6
Measured temperature	40 μK
Measured lifetime	~350 ms

To determine the number of trapped atoms, both absorptive and fluorescence imaging methods were used. By changing the storing time period, the exponential decay of atom number could be observed and, consequently, the trap lifetime could be determined. The temperature of a trapped sample was measured using a series of time of flight images taken after releasing atoms from the trap. The trap frequencies were determined by observation of atom cloud evolution in the trap (Figs. 4 and 5).

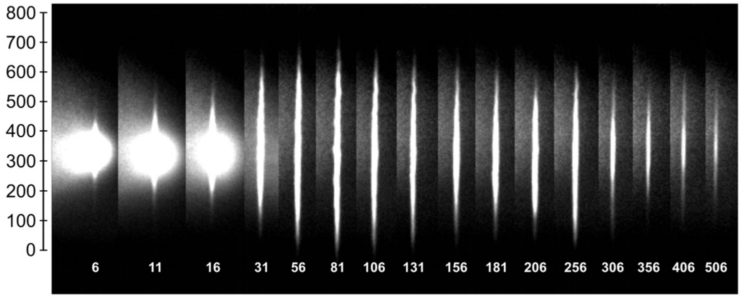

Fig. 4. Evolution of trapped atoms after their loading from the nearly spherical cloud in a “dark MOT”. Numbers on the horizontal scale show time (in ms) which elapsed between the end of loading phase and the picture taking. Vertical scale (in μm) shows the cloud extension.

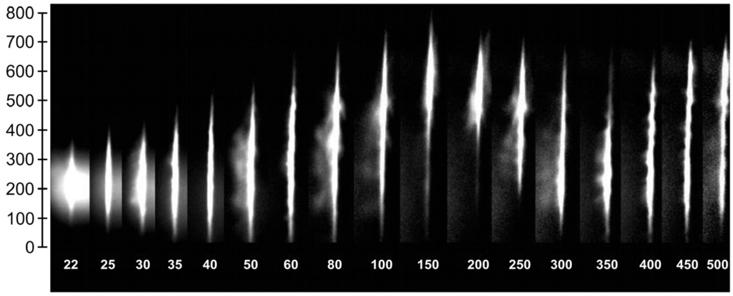

Fig. 5. Atoms loaded off-centre of ODT spreading out and oscillating with trap frequencies. As in Fig. 4, the numbers indicate time (in ms) elapsed between the end of loading phase and the picture taking and longitudinal extension (in μm) of the atomic cloud.

The Table presents the observed and expected values of the trap frequencies calculated along the lines presented in Refs. [1 and 5] with the Einstein coefficients as given in Ref. [6].

In Figure 4, a series of images present time evolution of atom cloud after its loading to ODT. In the case when the loading occurs to the centre of ODT, the atoms exhibit breathing oscillations, *i.e.*, they are spreading out and compressing again with the frequency which is twice the longitudinal trap frequency. Numbers at the bottom of Figs. 4 and 5 indicate time in ms between the end of the loading phase and taking the picture by CCD camera (fluorescence picture excited by a flash of resonant light). These images allow one to determine the trap frequencies. First three pictures in Fig. 4 show ODT on the "dark MOT" background. The reported breathing oscillations appear even when ODT beam is very well overlapped with the MOT centre.

The evolution appears distinctly different when the loading geometry is changed. In such case one can observe very strong oscillations excited by loading the atoms slightly radially off-centre of the dipole potential. As seen in Fig. 5, the oscillations have different character than in case of the central loading. They represent regular dipole oscillations with the measured longitudinal frequency 3.0 Hz, in our case of a weakly focused beam. These observations illustrate that oscillations of cold atom cloud can be efficiently exited by a suitably chosen way of the trap loading, and not only in a standard way by shaking the trap potential. Figure 5 illustrates also the transverse oscillations, the frequency of which was about 200 Hz. As limited by the observation time, the measurement accuracy of trap frequencies is about 10%, which could be further improved by extending the trap lifetime and observation duration. The discrepancy between the measured and calculated values is, however, bigger than this uncertainty. The exact reason for this discrepancy remains yet to be determined. Most likely, it is related to inaccurate determination of the trap beam waist, which needs to be improved for future work. Still, the direct recording of the spatial evolution of the trapped atomic cloud allows for determination of the trap frequencies in an alternative way to the standard parametric resonance [1].

4. Conclusions

The main result of the reported experiments is the demonstration of the ability to manipulate the evolution of a cold-atom sample in an ODT by a suitable loading procedure and use it for determination of the trap frequencies. This extends the methods of optimization described previously [7]. We have also described how the most essential parameters of the trapped atoms can be determined by optical diagnostics.

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