Atomic dipole trap formed by blue detuned strong Gaussian standing wave

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Abstract

We have investigated the properties of a standing-wave configuration of Gaussian laser beams which gives a linear array of three-dimensional atomic dipole traps. This is achieved by two counter-propagating waves with different beam waists so that at the nodes the field intensity of the standing wave is not completely cancelled at all radial positions across the beam. This creates an intensity dip in both the axial and radial directions that can be used as an atomic trap for blue detuning of the light. We simulated the behaviour of two level atoms in this trap using dressed state Monte-Carlo method and in this paper we show that it gives good trapping when the residual intensity at the bottom of the traps is small. © 1998 Elsevier Science B.V.

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1. Introduction

There has been a steady progress in neutral-atom trapping during the past decade resulting in improved production of dense, ultracold atomic vapour. Such samples are useful for high resolution spectroscopy, investigations of ultracold atom collisions and after further increase in phase-space density they allow the study of quantum-statistical effects of weakly interacting particles, such as Bose–Einstein condensation and anomalous light scattering. Several atom traps have been suggested and tested experimentally: the magneto-optical trap [1,2], magnetic traps [3–5], the light-gravitational trap [6] and optical dipole traps. An important feature of traps which use the dipole force is that they confine all magnetic substates. This extra degree of freedom enables the study of new phenomena such as excitation of one state and the influence of the others. The optical dipole traps formed by one focused laser beam or two crossed beams have been demonstrated by the Stanford group [7,8]. Reduction of the photon scattering rate to a very low level was achieved by using a far off resonant red detuned beam [9,10]. A Russian group suggested ways of making traps with much smaller dimensions using near field diffraction of laser light [11,12].

However all of these traps are based on red-detuned light, the atoms are attracted towards regions of high intensity where the perturbation of the atomic levels is the largest. By using blue-detuned light to create a box with a repulsive potential forming the walls the perturbation on the atoms is much reduced. In an experiment in which sodium atoms were confined by sheets of blue detuned light [13] the coherence time was 300 times longer than in a trap with red detuning, because atoms only interacted with the light for a short period of time.

We suggest a different configuration of this type of dipole trap using a strong blue detuned standing wave with

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Gaussian radial profile. The behaviour of atoms in the standing wave has been studied by several authors [14,15]. For red detuned lasers atoms are radially confined but not cooled to zero velocity – they become bunched at nonzero axial velocities. Thus red detuning is not useful for trapping in this configuration but it is effective for slowing down atoms in very short distances [16] whilst keeping them radially focused.

2. A standing wave dipole-force trap

To exploit the advantage of the blue detuned dipole trap and overcome the tendencies to radial atomic escape in the standing wave we suggest the use of two counter-propagating beams with different beam waists, but waists being at the same position. In this configuration with two counter-propagating beams of the same intensity, $I_0$, at $z = 0$, the total intensity is given by:

$$I(z,r) = I_0 \left( \frac{w_{0+}}{w_+} \exp \left( -\frac{r^2}{2w_+^2} \right) - \frac{w_{0-}}{w_-} \exp \left( -\frac{r^2}{2w_-^2} \right) \right)^2 + 4 \frac{w_{0+}}{w_+} \frac{w_{0-}}{w_-} \exp \left( -\frac{r^2}{2w_+^2} \right) \exp \left( -\frac{r^2}{2w_-^2} \right) \sin^2 \left( \frac{\varphi_+/2 - \varphi_-/2}{2} \right).$$

(1)

The subscript $s = +$ is used for beam going in the positive direction of the $z$-axis and $s = -$ for the counter-propagating beam. The rest of the symbols are parameters of the Gaussian wave which are defined in Table 1. When $w_{0+} = w_{0-}$, Eq. (1) reduces to the usual equation for a standing wave intensity.

A plot of the intensity in such a standing-wave with two counter-propagating beams of waists $w_{0+} = 10\lambda$, $w_{0-} = 2\lambda$ is given in Fig. 1.

<table>
<thead>
<tr>
<th>Table 1</th>
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<tbody>
<tr>
<td>Definition of parameters of the light field formed by a Gaussian beam along the positive $z$-axis ($s = +$) and a counterpropagating beam ($s = -$)</td>
</tr>
<tr>
<td>Radius of beam waist</td>
</tr>
<tr>
<td>Rayleigh range</td>
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<tr>
<td>Beam radius</td>
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<tr>
<td>Radius of curvature</td>
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<tr>
<td>Phase</td>
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<td>Guoy phase</td>
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Fig. 1. Profile of the intensity of the standing wave near nodes for $w_{0+} = 10\lambda$, $w_{0-} = 2\lambda$.

2.1. Basic properties of the configuration

The intensity dips in the standing-wave are clearly visible in Fig. 1 and these correspond to potential wells in which atoms can be confined. So an array of small traps can be created. In this section we will concentrate on the basic geometrical properties of the trap – conditions for its existence and its radial width. Therefore we are mainly interested in the dependence of intensity minima on beam waists and on the space coordinates. Minima occur when

$$\varphi_+ - \varphi_- = 2M\pi, \quad M = 0, \pm 1, \pm 2, \ldots$$

They are shifted from $z = MA/2$, except for the case when $M = 0$ because the Guoy phases are not the same for the beams of different waists. The intensity at these minima is

$$I(z,r) = I_0 \left( \frac{w_{0+}}{w_+} \exp \left( -\frac{r^2}{2w_+^2} \right) - \frac{w_{0-}}{w_-} \exp \left( -\frac{r^2}{2w_-^2} \right) \right)^2.$$  

(3)

To find the edge of the trap in radial direction we look for the maximum of Eq. (3) with respect to the radial coordinate:

$$r_{\max}^2 = \frac{2w_{0+}^2 w_{0-}^2}{w_+^2 - w_-^2} \ln \left( \frac{w_{0+} w_{0-}^2}{w_{0+}^2 w_{0-}} \right).$$

(4)

Using Eq. (4) we can establish the interval along the $z$ axis where the dips exist by putting $r_{\max} = 0$; acceptable solutions for the depth are only found in the region: $-\zeta_{\max} < z < \zeta_{\max}$ where

$$\zeta_{\max}^2 = \frac{w_{0+}^2 w_{0-}^2}{\frac{8}{3} w_{0+}^2 + \frac{8}{3} w_{0-}^2}.$$  

(5)

So an array of traps along the $z$ axis is created in this region.
Careful inspection of Eqs. (4) and (5) shows that the relative width \( r_{\text{max}} / r_{\text{max0}} \) (where \( r_{\text{max0}} \) is the trap width at \( z = 0 \)) is just function of the beam waist ratio \( w_{s0} / w_{0a} \) and relative axial position \( z / z_{\text{max}} \). Similarly we can find \( r_{\text{max0}} / w_{0a} = f(w_{s0} / w_{0a}) \). These are plotted in Fig. 2. Subplot (a) proves the fact that the bigger the difference in beam waists, the bigger the trap width in proportion to the width of the smallest beam, and the radial width changes more rapidly with axial position. Subplot (b) shows the actual width of the trap. Beams of similar size which are tightly focused give very narrow traps — widths down to a few wavelengths can be obtained.

Now we pay attention to the estimation of the trap depth which is taken as the difference of potential energy of the atom at the bottom of the well and at the lowest intensity edge of the trap, as described by Eqs. (2), (4) and (5). The value of the atomic potential energy is proportional to the value of Rabi frequency at that place. The Rabi frequency for this configuration is given by

\[
\Omega_d(z,r) = d\sqrt{I(r,z)} / \hbar ,
\]

where \( d \) is a component of the atomic electric-dipole moment in the direction of the polarisation of the beams. We will use the designation \( \Omega_0(z) \) as the amplitude of the Rabi frequency at \( z = 0 \). In Fig. 3 we used the Rabi frequency for the estimation of the trap depth because we want to pick up the main dependences of the trap depth on its geometry in the most general way using the same parameters as in Fig. 2. Subplot (a) shows how the difference of the Rabi frequencies at the bottom of the trap and the edge decreases with the position of the trap within the interval of its existence for the same beam waist ratio as in the previous figure. The largest difference between beam waists gives the deepest traps but the depth of these traps decreases with the relative axial distance. In subplot (b) we can follow the value of residual Rabi frequency \( R_{\Omega} = \Omega_d(z,0) / \Omega_0(z) \) at the bottom of the trap. This value is exactly zero only at \( z = 0 \) because only at this point the two beams have the same intensities. Again we can observe a steeper rise of the Rabi frequency at the bottom of the trap for the configurations with quite different beam waists. This value is not important if we intend to trap atoms nearby \( z = 0 \) but it is the main limiting factor if we want to use some of the position dependent properties of this configuration, e.g. radial compression or slowing using chirping technique [16,18]. For blue detuning the atoms moving along the axis of the beams congregate near the intensity minima where they weakly interact with the light. The bigger the difference between beam waists the wider and deeper the trap will be see Fig. 2. Hence, we have to make a compromise regarding our demands on the trap depth if we want to obtain trap a few wavelengths wide in radial direction. To model this situation we calculated the evolution of a group of atoms for traps with different values of residual Rabi frequency at the bottom of the wells.

### 3. Results of the dressed states Monte-Carlo simulations

In this section we want to show that the described method can be used for making a deep trap by means of low power lasers and by keeping the atoms in the trap for a long time. Despite the fact that “long time” in trapping experiments means a time interval of several seconds and despite the fact we used the fast SGI Power Challenge at
the Technical University in Brno for our calculations we had to reduce this time interval to hundreds of microseconds (10000/$\Gamma$) to decrease the length of our simulation to a couple of days (for 100 atoms). We found without any optimization that the Rabi frequency of about 155 GHz to a couple of days for 100 atoms. We found without any rounds 10000

poses.

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parameters; trap widths and beam waists were established
to compare the trapping efficiency in traps with the same
depths and therefore we fixed the adiabatic escape veloc-
ty. We used detuning and residual Rabi frequency as free
parameters. Trap widths and beam waists were established using the relations mentioned in the previous chapter. That is why the presented values of the parameters are not necessarily the best combination for experimental pur-
poses.

We chose the dressed state Monte-Carlo simulation [19,16] because it is easy to apply to our two-dimensional problem. The inclusion of the radial dimension is simply a matter of putting in gradients of the Rabi frequency along the radial axis. The following plots show some of the results we obtained using the dressed state Monte-Carlo method applied to two level atoms of the same mass as that of Cs ($A = 133$).

The result of a simulation showing the velocity and position distribution of 100 atoms in the trap up to $t = 100000/\Gamma$ is presented in Fig. 4. We chose a deep trap with the adiabatic escape velocity $v_{z,0} = b|z|/\sqrt{\Omega^2(z,r_{max}) + \Delta^2 - (\bar{\Delta})}m$ which equals 0.05 $\Gamma/k$. We wanted to show the influence of the residual Rabi frequency at the bottom of the trap, and the value $R_{\beta} = 0.001$ in the axial position $z = 100\lambda$ was sufficient. Beam waists of $w_{0x} = 6.7\lambda$ and $w_{0z} = 7.8\lambda$ were necessary to obtain the mentioned trap with the radial width $r_{max} = 8\lambda$.

We started the simulation with all the atoms at $r = 0$ and $z = 10\lambda$ (see subplot (e) and (f) in Fig. 4). The initial velocity distributions were Gaussian with width 0.01 $\Gamma/k$ centred on the zero velocity. The peaks in the $v_z$ distribution (see subplot (a)) near $\pm 0.01 \Gamma/k$ are due to the fact that the Rabi frequency is not exactly zero at the bottom of the trap, and more spontaneous transitions to ‘‘antitrapping’’ dressed atom levels shift the atom with respect to the initial Gaussian distribution. This effect did not occur for lower values of $R_{\beta}$, and the simulation showed that $R_{\beta} = 0.0001$ is small enough to eliminate this effect. From the oscillations regarding the widths of radial position and velocity distribution (see subplot (b) and (c)) we can deduce that the period of radial motion was about $6000/\Gamma$.

Two atoms were heated up to a higher radial velocity than that chosen, $v_{z,0} = 0.05$, and finally they escaped from the trap in radial and consequently in axial direction. From the

Fig. 4. The results of Monte-Carlo simulations for $v_z$, (a), $v_r$, (b), $r$ (c) and $z$ (d), (e), (f) initial position distribution. The time axis starts at the bottom and follows multiples of 10000/$\Gamma$ from $t_0 = 0$ for velocities and $t_1 = 100/\gamma$ for positions up to $t_0 = 100000/\Gamma$. The remaining parameters were $\Omega R = 155\Gamma$, $\Delta = 25\Gamma$, $R_D = 0.001$, $z = 10\lambda$, $w_{0x} = 6.7\lambda$, $w_{0z} = 7.8\lambda$.

\footnote{We did not take into account any interactions between atoms.}
Atoms are placed in nodes nearer to \( z \) than 0.01 and this number gradually rises up to 70% for \( G = 2 \) but it is shifted by the Guoy phase factor.

Fig. 5. The results of Monte-Carlo simulations showing the number of atoms in one trap for 7000/\( \Gamma \) seconds with the following parameters of the trap: \( R_{0u} = 155 \Gamma, R_{0d} = 0.0001, z = 5 \lambda \), adiabatic escape velocity was chosen \( v_r = 0.1 \Gamma / k \). To satisfy these conditions for different detuning we obtain: (a) \( \Delta = 10 \Gamma: w_{0+} = 9 \lambda, w_{0-} = 10 \lambda, r_{\text{max}} = 11 \lambda. \) (b) \( \Delta = 25 \Gamma: w_{0+} = 6.2 \lambda, w_{0-} = 11 \lambda, r_{\text{max}} = 11.5 \lambda. \) (c) \( \Delta = 50 \Gamma: w_{0+} = 6.25 \lambda, w_{0-} = 14 \lambda, r_{\text{max}} = 12.5 \lambda. \)

We simulated the process using the dressed state Monte Carlo method and it shows that for the chosen parameters and residual Rabi frequency which equals 0.001 \( \Gamma \) we got excellent trapping results with Gaussian distribution of axial velocities. Even 98% of atoms remained trapped with the residual Rabi frequency ten times higher for the time up to 10000/\( \Gamma \) but the axial velocity distribution was not Gaussian. One could find symmetrical peaks due to a higher degree of spontaneous emission jumps. The simulation has proved that longer lifetimes can be expected for bigger detunings and shallower traps.

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