Spatially selective loading of an optical lattice by light-shift engineering using an auxiliary laser field

P F Griffin, K J Weatherill, S G MacLeod, R M Potvliege and C S Adams

Department of Physics, University of Durham, Rochester Building, South Road, Durham DH1 3LE, UK
E-mail: c.s.adams@dur.ac.uk

New Journal of Physics 8 (2006) 11
Received 16 October 2005
Published 30 January 2006
Online at http://www.njp.org/
doi:10.1088/1367-2630/8/1/011

Abstract. We report on a method of light-shift engineering where an auxiliary laser is used to tune the atomic transition frequency. We show that the technique provides enhanced loading of laser cooled $^{85}\text{Rb}$ and $^{87}\text{Rb}$ atoms into deep optical traps. Furthermore, by using a blue-detuned optical molasses, light-shift engineering offers remarkable spatial selectivity in the loading of an optical lattice.

Contents

1. Introduction 2
2. The ac–Stark shift for multiple laser fields 2
3. Experiment 5
4. Discussion of results 6
5. Conclusion 9
Acknowledgments 9
References 9

1 Author to whom any correspondence should be addressed.
1. Introduction

Optical dipole traps and optical lattices are finding an ever increasing range of applications in experiments on Bose–Einstein condensation (BEC) [1]–[6] and degenerate Fermi gases [7]–[10], optical clocks [11], single-atom manipulation [12, 13], and quantum information processing (QIP) [14]–[16]. In some applications such as the optical lattice clock [11] or laser cooling within the trap, one is interested not only in the light-shift of the ground state, which determines the trap depth, but also the relative shift of a particular excited state. One has some control over this differential shift as the ground and excited states have different resonances, and the laser can be tuned to a ‘magic’ wavelength where the ground and excited state polarizabilities are the same [11, 13, 17]. However, using a ‘magic’ wavelength is not always appropriate either because one is no longer free to select the laser wavelength to minimize spontaneous emission, or because of the unavailability of suitable light sources. An alternative is to use an independent laser to alter the differential light-shift between particular states. This idea has been used to reduce the broadening of the ground-state hyperfine splitting of trapped atoms [18]. The use of an auxiliary laser to tune the resonance frequency has also been used to image the position of atoms in an atomic beam [19]. An interesting question is whether light-shift engineering could be used to improve the loading into ‘deep’ optical dipole traps, which is made ineffective by the large differential light-shift between the ground and excited states [20]–[22]. A significant advantage of using an independent laser beam to tune the differential light-shift is that it can be applied to specific regions of a trap, enabling efficient loading of selected lattice sites only.

In this paper, we propose a method of light-shift engineering where an auxiliary laser beam is used to tune the resonance frequency of the laser cooling transition. We demonstrate that this technique can be used to enhance the loading of a ‘deep’ optical lattice and selectively load a specific region of an optical lattice. The paper is arranged as follows: in section 2, we present the theory of light-shifts in the presence of multiple laser fields and highlight the general applicability of our method of light-shift engineering. We then move on to consider a specific example, namely rubidium atoms in a combination of CO2 and Nd:YAG laser fields. In section 3, we describe an experiment to demonstrate that our technique can be used to enhance the loading of a deep optical trap or load a selected region of an optical lattice. The experimental results are discussed in section 4 and finally we conclude in section 5.

2. The ac–Stark shift for multiple laser fields

In order to alter the laser cooling resonance without a large change in the depth of the optical dipole trap, the wavelength of the light-shift engineering beam should be chosen such that the light-shift of the excited state is significantly larger than, or opposite in sign to, that of the ground state. To select an appropriate wavelength, one needs to know the wavelength dependence of the polarizability for atoms in the excited state. As the dynamic polarizabilities of excited states are not well documented, below we calculate the specific case of the $5p$ state in Rb using a model potential. However, first we give a general expression for the light-shift of a particular magnetic sublevel in an atom: The light-shift of a magnetic hyperfine state with total angular momentum $F$ and projection $m_F$ in a field produced by multiple linearly polarized laser beams ($i = 1$ to $N$)
The intensity of laser term (i.e. an effective magnetic field). The scalar polarizability, \( \alpha \), and state, i.e. \( H \alpha_i \) where \( | \alpha_i \rangle \) is an arbitrary electric field. These equations are solved in position space by expanding the wavefunctions on a discrete basis of radial Sturmian functions. In the zero-frequency limit, the resulting values of position space by expanding the wavefunctions on a discrete basis of radial Sturmian functions.

where \( \alpha'_0 \) and \( \alpha'_j \) are the scalar and tensor polarizabilities at the wavelength of laser \( i \), \( E_{\text{hfs}} \) is a diagonal matrix with components corresponding to the hyperfine splitting of the required level, \( Q' \) is a matrix with components \( \langle F, m_F | Q_\mu | F', m_F' \rangle \) with \( Q_\mu = (3J_\mu^2 - J(J + 1))/J(2J - 1) \) and \( J_\mu \) is the electronic angular momentum operator in the direction of laser field \( i \), and \( I_i \) is the intensity of laser \( i \). Note that for circular polarization the light-shift also contains a vector term (i.e. an effective magnetic field). The scalar polarizability, \( \alpha_0 \) is the average of the dipole polarizabilities \( \alpha_{xx}, \alpha_{yy} \) and \( \alpha_{zz} \) for an atom exposed to a laser field polarized, respectively, in the \( x-, y- \) and \( z- \)directions: \( \alpha_0 = (\alpha_{xx} + \alpha_{yy} + \alpha_{zz})/3 \). The scalar polarizability is the same for all \( m \)-components. In general, the tensor polarizability lifts the degeneracy between different \( m \)-sublevels. For the ground state in alkali atoms (\( J = \frac{1}{2} \)), the tensor polarizability \( \alpha'_1 = 0 \), but for \( p \)-states, where \( \alpha_2 = (\alpha_{xx} - \alpha_{zz})/3 \), its effect can be significant.

In order to obtain the scalar and tensor polarizabilities as function of wavelength for Rb atoms, we represent the interaction of the valence electron with the core by the model potential proposed by Klapisch [25]. The polarizabilities are calculated by the implicit summation method [26]. Thus \( \alpha_{xx} \) (and similarly for \( \alpha_{yy} \) and \( \alpha_{zz} \)) is obtained as \( \alpha_{xx} = -e(\langle |0| x|1 \rangle + \langle |0| x| -1 \rangle)/\mathcal{F} \), where \( |0 \rangle \) represents the state vector of the unperturbed 5s, or 5\( p \)-state, and \( |\pm 1 \rangle \) are such that

\[
(E_0 \pm \hbar \omega - H_0)|\pm 1 \rangle = e\mathcal{F}x|0 \rangle.
\]

Here \( H_0 \) is the Hamiltonian of the field-free model atom, \( E_0 \) is the eigenenergy of the unperturbed state, i.e. \( H_0|0 \rangle = E_0|0 \rangle \), and \( \mathcal{F} \) is an arbitrary electric field. These equations are solved in position space by expanding the wavefunctions on a discrete basis of radial Sturmian functions and spherical harmonics [27]. In the zero-frequency limit, the resulting values of \( \alpha_0 \) [5s], \( \alpha_0 \) [5\( p \)] and \( \alpha_2 \) [5\( p \)] converge towards 333 \( a_0^3 \), 854 \( a_0^2 \) and \(-151 a_0^1 \), respectively, in satisfactory agreement with previous experimental and theoretical work [28]. Our result for \( \alpha_0 \) [5s] at 1.064 \( \mu \)m, 722 \( a_0^3 \), agrees well with experiment and other work (see [29] and references therein). The polarizabilities as a function of wavelength are shown in figure 1.

As noted above, in order to tune the differential light-shift between two states it is desirable to choose a wavelength of the auxiliary laser field such that the polarizability of one state is large and opposite in sign. For rubidium, the 5\( s \) polarization is large and negative between about 800 and 1300 nm, i.e. blue-detuned relative the 5\( p \) to 6s and 5\( p \) to 4d resonances, see figure 1. Due to the availability of laser sources, we choose to use the combination of a CO\(_2\) laser for the optical dipole trap and a Nd:YAG laser to tune the differential light-shift. From figure 1, one sees that the scalar polarizability of the 5\( s \) and 5\( p \) states have the same sign at the wavelength of the trapping laser, \( \lambda = 10.6 \mu \)m, whereas they have opposite signs at the wavelength of the light-shift engineering beam, \( \lambda = 1.064 \mu \)m. It follows that one can use a combination of CO\(_2\) and Nd:YAG lasers to tune the differential light-shift between the 5\( s \) and 5\( p \) states to a desired value given sufficient laser power.

In figure 2, we show the spatial dependence of the differential light-shifts between the ground state and the \( ^{85}\text{Rb} \) 5\( p^2 \)P\(_{3/2} \)(\( F = 4 \)) excited state for an atom in the vicinity of (a) a CO\(_2\)
Figure 1. Calculated polarizabilities of the $5s$ and $5p$ states of Rb. For the $p$ state, we show the scalar and tensor polarizabilities, $\alpha_0 = (\alpha_{xx} + \alpha_{yy} + \alpha_{zz})/3$ and $\alpha_2 = (\alpha_{xx} - \alpha_{zz})/3$, respectively. For the $s$ state, $\alpha_0 = \alpha_{xx} = \alpha_{yy} = \alpha_{zz}$.

Figure 2. Differential light-shifts as a function of position along an axis perpendicular to both the CO$_2$ and Nd : YAG laser propagation directions. The differential light-shift corresponds to the additional detuning of the cooling laser seen by ground-state atoms. It is equal to the light-shifts of the $m_F = -4, \ldots, +4$ magnetic sublevels of the $5p^2P_{3/2}(F = 4)$ minus that of the ground state in $^{85}$Rb for atoms in (a) the CO$_2$ laser lattice only, (b) the overlapped CO$_2$ and Nd : YAG region, with parallel polarizations, and (c) with orthogonal polarizations. The peak intensities and spot sizes of the CO$_2$ (Nd : YAG) laser are $I_0 = 2.3 \times 10^6$ W cm$^{-2}$ ($I_0 = 5.5 \times 10^5$ W cm$^{-2}$) and $70 \mu$m ($30 \mu$m), respectively.
region unless the cooling light is detuned far to the red by an amount larger than the differential light-shift (∼−80 MHz). Adding the additional laser beam reduces the differential shift by an amount that depends on their relative polarizations, figures 2(b) and (c). If the dipole trapping light and light-shift engineering beam have the same polarization then for this choice of laser intensities the differential shift is not reduced by enough to reach the unperturbed resonance frequency (zero-differential shift). However, if the lasers are orthogonally polarized then one pair of states is pulled down into the region of negative-differential shift, which could allow laser cooling to be effective in the centre of the overlap region, even when the cooling light is slightly blue-detuned relative to the unperturbed resonance frequency. Note that for these parameters, the shift to negative-differential light-shift only occurs due to the contribution of the tensor polarizability, $\alpha_2$. Similar plots and the same conclusions are obtained for $^{87}$Rb.

3. Experiment

To investigate the influence of the light-shift engineering effect depicted in figure 2 on the loading of an optical dipole trap, we used the experimental setup shown in figure 3(a). A vacuum chamber, fitted with home-made zinc selenide (ZnSe) UHV viewports [30] to accommodate the CO$_2$ laser beams, provides a background pressure of $1.2 \times 10^{-10}$ torr. An AC O$_2$ laser beam, (propagating along the z-axis in figure 1) with power 45 W, is focused to a waist ($1/e^2$ radius) of 70 $\mu$m at the centre of the chamber. The beam is collimated and retro-reflected to form a one-dimensional optical lattice. The power of the CO$_2$ laser beam is controlled using an acousto-optic modulator (AOM). The peak intensity at the centre of the lattice, $I_0 = 2.3 \times 10^5$ W cm$^{-2}$, gives a ground state light-shift $U_0 = -\frac{1}{2} \alpha_0 I_0 / (\varepsilon_0 c) = \hbar (-36$ MHz$)$, using $\alpha_0 = 333 \ a_0^3$ for the ground-state polarizability at 10.6 $\mu$m. A Nd : YAG laser beam (propagating at +45° to the y-axis in the x–y-plane) with power 7.8 W is focused by a $f = 150$ mm lens to overlap with the CO$_2$ lattice in the trapping region. The Nd : YAG laser has a circular focus with a beam waist of 30 $\mu$m in the overlap region. This gives an intensity of $I_0 = 5.5 \times 10^3$ W cm$^{-2}$ leading to a ground state light-shift $U_0 = h (-18.6$ MHz$)$ using our calculated value of $\alpha_0 = 722 \ a_0^3$ at 1.064 $\mu$m. The CO$_2$ and Nd : YAG laser beams are linearly polarized along the x- and z-axes, respectively, corresponding to case (c) in figure 2. Ideally, one would also like to study other polarizations but we were restricted to the perpendicular case by our experimental setup.

A focused Nd : YAG laser beam, with variable power, locally heats an alkali metal dispenser providing a controllable source of thermal Rb atoms [31] that are loaded into a magneto-optical trap (MOT), centred on the dipole trap. The cooling and repumping light for the MOT are provided by home-built extended cavity diode lasers frequency stabilized using polarization spectroscopy [32]. The CO$_2$ and Nd : YAG laser beams are left on throughout the MOT loading phase. After typically 3 s, the magnetic field is switched off, the cooling laser beam intensities are reduced from 55 to 10 mW cm$^{-2}$ and the detuning is increased to $\Delta = -8\Gamma$, where $\Gamma = 2\pi(6$ MHz$)$ is the natural linewidth of the transition, to create an optical molasses. After 10 ms of molasses, the atom cloud has a typical temperature of 40 $\mu$K, measured by time-of-flight. During the molasses phase, the hyperfine repumping laser intensity is lowered from 6 to 200 $\mu$W cm$^{-2}$ and then switched off completely with a shutter for the final 5 ms such that atoms are pumped in the lower hyperfine state [33]. After the molasses phase, the cooling light and the Nd : YAG laser are extinguished for a few hundred milliseconds, then the CO$_2$ laser is turned off and the MOT beams (tuned to resonance) are turned back on to image the cloud. A CCD camera collects the
Figure 3. (a) Experimental arrangement showing the intersection of the CO$_2$ and Nd : YAG laser beams. (b) Images and line profiles of the $^{85}$Rb column density without (left) and with (right) the Nd : YAG laser. The molasses detuning ($-50$ MHz) is chosen to optimize the total number of atoms rather than the number in the overlap region. The viewing direction is approximately perpendicular to both the CO$_2$ and Nd : YAG laser propagation directions.

fluorescence to give a spatial profile of the trapped atoms. Experiments have been performed on both $^{85}$Rb and $^{87}$Rb.

4. Discussion of results

A typical atom distribution viewed approximately perpendicular to the CO$_2$ and Nd : YAG beam axes is shown in figure 3(b). One sees that the CO$_2$ lattice loads efficiently out in the wings where the trap depth is smaller. This effect has been widely observed in experiments on far-off resonance optical dipole traps [20]–[22] and arises due to the smaller differential light-shift between the ground and excited states away from the focus. For a one-dimensional optical lattice, atoms loaded in the wings are prevented from migrating towards the centre by the lattice potential. More significantly, in figure 3(b)(right frame), we see that the loading is greatly enhanced in the region where the Nd : YAG laser intersects the CO$_2$ laser lattice.

The enhanced loading observed in the overlap region cannot be explained simply by the fact that the trap is deeper in this region. To demonstrate this we have reduced the CO$_2$ laser power by a factor of four such that the depth in the combined CO$_2$ plus Nd : YAG trap is less than a
Figure 4. Column density of $^{85}\text{Rb}$ trapped in a CO$_2$ laser lattice without the Nd:YAG laser (—-—-), and for a shallower CO$_2$ laser lattice with the Nd:YAG laser (———). The overall ground state light-shift in the overlap region of the shallow combined trap ($-27 \text{ MHz}$) is less than the maximum light-shift for the CO$_2$ laser lattice alone ($-36 \text{ MHz}$), but loading into the combined trap is still significantly more efficient. Both profiles are for a molasses detuning of $-20 \text{ MHz}$.

Figure 5. A surface plot of the column density for cooling laser detunings (a) $\Delta = 2\pi(-20 \text{ MHz})$ and (b) $\Delta = 2\pi(+2 \text{ MHz})$. The on-axis density is shown on the back plane. For blue-detuning (b) only the light-shift engineered region, where the CO$_2$ and Nd:YAG laser beams overlap, is loaded. Similar results are obtained for both $^{85}\text{Rb}$ and $^{87}\text{Rb}$.

CO$_2$ lattice alone at full power. Typical column densities are shown in figure 4. We see that the density in the combined trap is still significantly higher than for a deeper CO$_2$ lattice.

Remarkably, if we detune the cooling light slightly to the blue of the unperturbed atomic resonance such that neither the CO$_2$ nor the Nd:YAG laser beams alone trap any atoms, then we still observe that the region where the two beams intersect is efficiently loaded, see figure 5(b).
This spatial selectivity provides a very clear demonstration of the power of light-shift engineering using an auxiliary laser field. In addition, it demonstrates that the enhanced loaded observed in figures 3–5(a) cannot be explained by a ‘dimple’ effect, where atoms from neighbouring regions rethermalize in the overlap region [34].

Although the main purpose of this paper is to demonstrate enhanced and spatial selective loading produced by light-shift engineering, we have also performed temperature measurements on trapped atoms by switching off the dipole trapping beam and observing the ballistic expansion of the atomic cloud. By fitting the width of the atomic distribution for atoms originating in the light-shift engineered region, see figure 6, we estimate a temperature of $380 \pm 75 \, \mu$K, or $\sim 0.2U_0$, figure 6. We do not expect to achieve sub-Doppler temperatures in the light-shift engineered region as the trap and the engineering beam are not mode matched so the light-shift cancellation is only achieved over a very limited volume, and even then only for two of the nine magnetic sublevels. Improved mode-matching and adjusting the relative polarizations will be the focus of future work.

From figures 5 and 6 (inset), we estimate that the density in the light-shift engineered region is an order of magnitude larger than in the lattice region during the optical molasses phase (taking into account the volume overlap and the observed enhancement). This implies an initial phase space density of order $10^{-3}$. We observe a difference in the lifetime of $^{85}$Rb and $^{87}$Rb in the light-shift engineered region which suggests that the phase space density is limited by collisional loss.
5. Conclusion

To conclude, we propose a technique where an auxiliary laser beam is used to tune the differential light shift between any two states for multilevel atoms trapped in an optical dipole trap. We have performed theoretical calculations of the atomic polarizabilities in order to select an appropriate wavelength and power for the light-shift engineering beam. We describe an experiment on rubidium atoms trapped in a CO₂ laser lattice and demonstrate how light-shift engineering using an auxiliary laser field can be used to implement spatially selective loading. Temperature and density measurements show that the phase-space density is preserved in the light-shift engineered region. The technique could be applied to load a single-site in three-dimensional CO₂ lattice, with the interesting prospect of BEC in the limit of high-trap frequency. In addition, one could adapt the technique to directly pattern load thermal atoms into an optical lattice.

Acknowledgments

We thank E Riis, I G Hughes and S L Cornish for stimulating discussions, M J Pritchard for experimental assistance and EPSRC for financial support.

References

[1] Stamper-Kurn D M, Andrews M R, Chikkatur A P, Inouye S, Miesner H-J, Stenger J and Ketterle W 1998 Phys. Rev. Lett. 80 2027
[2] Anderson B P and Kasevich M A 1998 Science 282 1686
[3] Barrett M, Sauer J and Chapman M S 2001 Phys. Rev. Lett. 87 010404
[4] Weber T, Herbig J, Mark M, Nägerl H-C and Grimm R 2003 Science 299 232
[5] Takasu Y, Maki K, Komori K, Takano T, Honda K, Kumakura M, Yabuzaki T and Takahashi Y 2003 Phys. Rev. Lett. 91 040404
[6] Kinoshita T, Wenger T and Weiss D S 2005 Phys. Rev. A 71 011602 (R)
[7] Granade S R, Gehm M E, O’Hara K M and Thomas J E 2002 Phys. Rev. Lett. 88 120405
[8] Loftus T, Regal C A, Ticknor C, Bohn J L and Jin D S 2002 Phys. Rev. Lett. 88 173201
[9] Ott H, de Miranda E, Ferlaino F, Roati G, Modugno G and Inguscio M 2004 Phys. Rev. Lett. 92 160601
[10] Köhl M, Moritz H, Stöferle T, Güter K and Esslinger T 2005 Phys. Rev. Lett. 94 080403
[11] Katori H, Ido T and Gonokami M K 1999 J. Phys. Soc. Japan 68 2479
[12] Schlosser N, Reymond G and Grangier P 2002 Phys. Rev. Lett. 89 023005
[13] McKeever J, Buck J R, Boozer A D, Kuzmich A, Nägerl H-C, Stamper-Kurn D M and Kimble H J 2003 Phys. Rev. Lett. 91 133602
[14] Scheunemann R, Cataliotti F S, Hänsch T W and Weitz M 2000 Phys. Rev. A 62 051801
[15] Mandel O, Greiner M, Widera A, Rom T, Hänsch T W and Bloch I 2003 Nature 425 937
[16] Schrader D, Dotsenko I, Khudaverdyan M, Miroshnichenko Y, Rauschenbeutel A and Meschede D 2004 Phys. Rev. Lett. 93 150501
[17] Kaplan A, Andersen M F and Davidson N 2002 Phys. Rev. A 66 045401
[18] Thomas J E and Wang L J 1995 Phys. Rep. 262 311
[19] Kuppens S J M, Corwin K L, Miller K W, Chupp T E and Wieman C E 2000 Phys. Rev. A 62 013406
[20] Scheunemann R, Cataliotti R S, Hänsch T W and Weitz M 2000 J. Opt. B 2 645
[22] Cennini G, Ritt G, Geckeler C and Weitz M 2003 Appl. Phys. B 77 773
[23] Angel J R P and Sandars P G H 1968 Proc. R. Soc. A 305 125
[24] Schmieder R W 1973 Am. J. Phys. 40 297
[25] Klapisch M 1967 CR Acad. Sci. Ser. B 265 914
[26] Dalgarno A and Lewis T J 1955 Proc. R. Soc. A 233 70
Schwartz C 1959 Ann. Phys. (NY) 6 156
[27] Potvliege R M 1998 Comput. Phys. Commun. 114 42
[28] Safronova M S, Johnson W R and Derevianko A 1999 Phys. Rev. A 60 4476
Magnier S and Aubert-Frécon M 2002 J. Quant. Spectrosc. Radiat. Transfer 75 121
Zhu C, Dalgarno A, Porsev S G and Derevianko A 2004 Phys. Rev. A 70 032722
[29] Safronova M S, Williams C J and Clark C W 2004 Phys. Rev. A 69 022509
[30] Cox S G, Griffin P F, Adams C S, DeMille D and Riis E 2003 Rev. Sci. Instrum. 74 3185
[31] Griffin P F, Weatherill K J and Adams C S 2005 Rev. Sci. Instrum. 76 093102
[32] Pearman C, Adams C S, Cox S G, Griffin P F, Smith D A and Hughes I G 2002 J. Phys. B: At. Mol. Opt. Phys. 35 5141
[33] Adams C S, Lee H J, Davidson N, Kasevich M and Chu S 1995 Phys. Rev. Lett. 74 3577
[34] Stamper-Kurn D M, Miesner H-J, Chikkatur A P, Inouye S, Stenger J and Ketterle W 1998 Phys. Rev. Lett. 81 2194
Ma Z-Y, Foot C J and Cornish S L 2004 J. Phys. B At. Mol. Opt. Phys. 37 3187

New Journal of Physics 8 (2006) 11 (http://www.njp.org/)