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

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We report on a method of light–shift engineering where an auxiliary laser is used to tune the atomic transition frequency. The technique is used to selectively load a specific region of an optical lattice. The results are explained by calculating the differential light–shift of each hyperfine state. We conclude that the remarkable spatial selectivity of light–shift engineering using an auxiliary laser provides a powerful technique to prepare ultra-cold trapped atoms for experiments on quantum gases and quantum information processing.

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Optical dipole traps and optical lattices are finding an ever increasing range of applications in experiments on Bose-Einstein condensation (BEC) [1, 2, 3, 4], optical clocks [5], single–atom manipulation [6, 7], and quantum information processing (QIP) [8, 9]. In many applications, one is interested not only in the light–shift of the atomic transition frequency. The technique is used to selectively load a well defined region of an optical lattice. The results are explained by calculating the differential light–shift of each hyperfine state. Specifically, we consider the case of loading \(^{85}\text{Rb}\) atoms into a deep \(^{133}\text{Rb}\) laser lattice is carried out as follows: the ground state light–shift gives an intensity of \(I = 335 \alpha_0^3 \) at \(1.064 \mu\text{m}\) in atomic units. A Nd:YAG laser beam (propagating at +45° to the \(x\) axis in the \(x\) \(y\) plane) with power 7.8 W is focussed to form a waist (1/e² radius) of 70 \(\mu\text{m}\) at the center of the chamber. The beam is collimated and retro–reflected to form a 1D optical lattice. The intensity of the CO\(_2\) laser is controlled using an acousto-optic modulator (AOM). The intensity at the center of the lattice, \(I_0 = 5.5 \times 10^5 \text{ W cm}^{-2}\), gives a ground state light–shift \(U_0 = -\frac{1}{2}\alpha_0 I_0/(\epsilon_0 c) = h(-36 \text{ MHz})\), where \(\alpha_0 = 722 \alpha_0^3\) at 1.064 \(\mu\text{m}\) in atomic units. The CO\(_2\) laser and Nd:YAG laser beams are linearly polarized along the \(x\) and \(z\) axes, respectively.

Loading of a CO\(_2\) laser lattice is carried out as follows: The CO\(_2\) and Nd:YAG laser beams are left on throughout the loading stage. We load a magneto-optical trap (MOT), centered on the dipole trap, with \(2 \times 10^7 \text{ \(^{85}\text{Rb}\)}\) atoms in typically 3 seconds. After the magnetic field is switched off, the cooling laser beam intensities are reduced from 55 mW cm\(^{-2}\) to 10 mW cm\(^{-2}\) and the detuning is increased to \(\Delta = -8\Gamma\), where \(\Gamma = 2\pi(6 \text{ MHz})\) 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 \(\mu\text{K}\), measured by time–
of-flight. During the molasses phase the hyperfine re-pumping laser intensity is lowered from 6 mWcm$^{-2}$ to 200 $\mu$Wcm$^{-2}$ and then switched off completely with a shutter for the final 5 ms such that atoms are pumped in the lower hyperfine state. 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 fluorescence to give a spatial profile of the trapped atoms. A typical atom distribution viewed approximately perpendicular to both the CO$_2$ and Nd:YAG laser propagation directions.

Finally, we should add that 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 CO$_2$ lattice alone at full power. Typical column densities are shown in Fig. 3. We see that the density in the combined trap is still significantly higher than for a deeper CO$_2$ lattice.

To explain the spatially selective loading for blue-detuned cooling light, we have calculated the polarizability of the 5s ground and 5p excited states as a function of wavelength. The details of the calculation will be explained elsewhere. Briefly, 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 of the \(5p\) state. In addition, there is a tensor polarizability \(\alpha_2 = (\alpha_{xx} - \alpha_{zz})/3\) which lifts the degeneracy of different \(m\)-states. In order to obtain these quantities, we represent the interaction of the valence electron with the core by the model potential proposed by Klapisch. The polarizabilities are calculated by the implicit summation method. Thus \(\alpha_{xx}\) (and similarly for \(\alpha_{yy}\) and \(\alpha_{zz}\)) is obtained as

\[
(\varepsilon_0 \pm \hbar \omega - H_0)|\pm 1\rangle = e\mathcal{F} x|0\rangle.
\]

Here \(H_0\) is the Hamiltonian of the field-free model atom and \(E_0\) 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 wave functions on a discrete basis of radial Sturmian functions and spherical harmonics. The zero-frequency limit, the resulting values of \(\alpha_0[5s], \alpha_0[5p]\) and \(\alpha_2[5p]\) converge towards \(333a_0^3, 854a_0^3\), and \(-151a_0^3\), respectively, in satisfactory agreement with previous experimental and theoretical work. The dynamic polarizabilities as functions of wavelength are shown in Fig. 4. We find that \(\alpha_0 = 722a_0^3\) at 1.064 \(\mu\text{m}\), which agrees well with experiment and other theoretical work.

For our purposes the most important result of Fig. 4 is that the polarizabilities of the \(5s\) state at the \(5p\) laser wavelength (\(\lambda = 10.6 \mu\text{m}\)) and the Nd:YAG wavelength (\(\lambda = 1.064 \mu\text{m}\)) have the same sign, whereas the polarizabilities of the \(5p\) state have opposite signs. It follows that one can use a combination of \(CO_2\) and Nd:YAG lasers to tune the differential light-shift between the \(5s\) and \(5p\) states through zero. To calculate the light-shift experienced by atoms in the combined \(CO_2\) plus Nd:YAG trap we calculate the eigenvalues of the matrix

\[
U = U_0 - \frac{1}{2\varepsilon_0 c} \sum_{i=1,2} \langle \alpha_i \hat{I} + \alpha_i^2 Q^i \rangle I_i ,
\]

where \(U_0\) is a diagonal matrix with components corresponding to the hyperfine splitting, the index \(i\) denotes the \(CO_2\) and Nd:YAG lasers, and \(Q^i\) is a matrix with components \(\langle F, m_F | Q_i | F', m_F' \rangle\) with \(Q_i = [3J^2 - J(J + 1)]/J(2J - 1)\) and \(J\), being the electronic angular momentum operator in the direction of laser field \(i\). The differential light-shift between the ground state and the \(5p^2 P_{3/2}(F = 4)\) state for the \(CO_2\) laser alone is shown in Fig. 5(a). As a single laser beam splits the states according to the magnitude of \(m_F\), there are five

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**FIG. 3:** Column density for a \(CO_2\) laser lattice without the Nd:YAG laser (dashed line), and for a shallower \(CO_2\) laser lattice with the Nd:YAG laser (solid line). 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 \(-20 \text{ MHz}\).

**FIG. 4:** 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, \(\alpha_0 = \alpha_{xx} = \alpha_{yy} = \alpha_{zz}\).

**FIG. 5:** The 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 sub-levels of the \(5p^2 P_{3/2}(F = 4)\) minus that of the ground state state in \(^{85}Rb\) for atoms in (a) the \(CO_2\) laser lattice only, and (b) in the combined \(CO_2\) plus Nd:YAG trap.
The levels are far blue-detuned (positive differential shift) at the centre of the lattice, making laser cooling ineffective unless the cooling light is detuning to the red by an amount larger than the differential light-shift. Adding the Nd:YAG laser produces the shifts shown in Fig. 5(b). The Nd:YAG laser lifts the degeneracy between the ±mf components, although two pairs of states remain close to degenerate. More importantly, one pair of states is pulled down into the region of negative differential shift. This allows efficient laser cooling in the center of the overlap region, even when the cooling light is slightly blue-detuned relative to the unperturbed resonance frequency. Note that, efficient loading for blue-detuning can only be explained if one includes the tensor polarizability term α2. Although α2 is smaller than the scalar polarizability (by a factor of 4 or 5), it dramatically alters whether states see the cooling light as red or blue detuned and therefore completely determines whether the trap is loaded or not.

As light-shift engineering allows laser cooling to work as efficiently as in free space one might expect to load atoms at lower temperature than in conventional loading schemes. To address this issue we need to increase the sensitivity and the resolution of our imaging system to allow accurate density and temperature measurements. This will be the focus of future work.

To conclude, we have shown how light-shift engineering using an auxiliary laser field can be used to implement spatially selective loading of deep far-off resonance optical lattices. We have performed theoretical calculations of the atomic polarizabilities and have shown that the addition of a second laser field induces a splitting of the excited state which is crucial in determining the efficiency of loading into the combined trap. The technique could be applied to load a single-site in 3D CO2 lattice, with the interesting prospect of BEC in the limit of high trap frequency. In addition one could adapt the technique to perform patterned loading of optical lattices for applications in QIP experiments.

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