

Chapter 7

Optical lattices and experiment design

“Every contrivance of man, every tool, every instrument, every utensil, every article designed for use, of each and every kind, evolved from a very simple beginning.” Robert Collier

Having studied magnetic manipulation, attention is returned to optical manipulation and the second aim of the thesis. The goal of which is to load cold atoms into a 3D optical lattice for use in quantum information processing (QIP) experiments. An optical lattice is a periodic array of potential minima created by the interference of laser beams. Cold atoms can be loaded into these minima, and what results is a periodic array of sites containing a miniature cold atom cloud. Manipulation of single-sites has been experimentally demonstrated in a 1D CO₂ laser lattice [93, 94]. To achieve QIP requires high oscillation frequencies in all directions to avoid decoherence; a strong motivation to move to three dimensions.

This chapter introduces optical lattices and describes the creation of a face-centred cubic lattice made from CO₂ laser beams. From this, design criteria for an experiment are outlined. In the proceeding chapters the construction, operation and optimisation of the cold atom experiment is described. Work presented in these chapters has been done in collaboration with C. S. Adams and K. J. Weatherill.

7.1 Optical lattices

It is imperative to take the light's polarisation into account when calculating the dipole force introduced in Chapter 2. The first reason is that the individual laser beam's electric fields must be added as vectors. The resulting total electric field vector can then be used to calculate the intensity, $I(\mathbf{r}) = \epsilon_0 c |\mathbf{E}|^2 / 2$; a scalar quantity. The second reason is the polarisation affects the allowed atomic transitions. For example, in Chapter 2 the Q -matrix was given for an electric field aligned along the quantisation axis. The calculation of the excited state polarisability is more complicated for multiple laser beams.

Although linked, it is possible to construct lattices that have just a spatial variation of either the polarisation or intensity. A simple example of the former is the interference pattern resulting from two counter-propagating laser beams that have orthogonal linear polarisation (lin \perp lin). For a thorough discussion of this scheme and its use in sub-Doppler cooling see refs. [105, 127].

This thesis will concentrate on lattices created by the spatial variation of intensity. The simplest example is two counter-propagating laser beams that have parallel linear polarisation (lin \parallel lin). Figure 7.1 shows the standing wave interference pattern of two focused CO₂ laser beams. Each lattice site is separated by half the wavelength of the laser light. This illustrates a major advantage of using a CO₂ laser as the large wavelength ($\lambda_T = 10.6 \mu\text{m}$) makes it possible to resolve optically individual lattice sites.

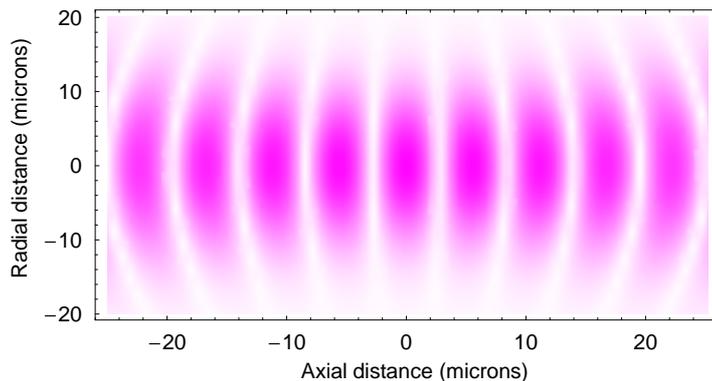


Figure 7.1: The contour plot shows the potential minima generated from the interference of two counter-propagating laser beams that have parallel linear polarisation. The $10 \mu\text{m}$ beam waist used in the simulation highlights diffraction's influence.

The standing wave can be turned into an optical conveyor belt. If there is a small frequency difference, δ , between the two laser beams, the position of the potential wells will move in time (with velocity $v = \delta/k$, where k is the wavevector of the laser). In practise this could be implemented with an acousto-optical modulator (AOM). A second method is to vary the phase of one of the beams, which could be implemented using technology based upon a liquid crystal device (LCD).

Lattices more exotic than the 1D standing wave can be created by the interference of multiple laser beams, see [161] for the crystallography of optical lattices. A N -dimensional lattice requires a minimum of $N + 1$ laser beams. One problem with the topography of lattices is that they can be changed by fluctuations in the phase of the individual laser beams. Certain geometries with exactly $N + 1$ beams have phase independent topography, as outlined in [161], whereby any phase change just results in a translation of the lattice sites. Adams *et al.* showed how to create a face-centred cubic lattice that is phase independent [162]. It is this design that we plan to use to trap Rb atoms. Figure 7.2 shows a diagram of the laser geometry.

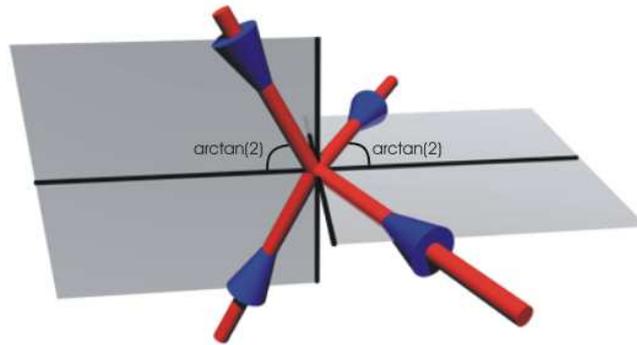


Figure 7.2: A face-centred cubic lattice is created if the laser beams are at an angle of $\arctan(2)$ degrees from the common plane axis, and the polarisations are linear and in the plane. The six MOT beams are the thin black lines.

A pair of laser beams propagate in a plane, and a further two lasers are counter-propagating with respect to the first pair in a plane orthogonal to the first. All beams are at angle of $\arctan(2) \approx 63.43^\circ$ to the common plane axis. The foci of all four beams overlap at the centre of the co-ordinate system. Furthermore, all beams are linearly polarised in the plane of propagation. The arrangement outlined has the added advantage that it fits in well with MOT cooling beams along the Cartesian axes.

Calculations of the resulting dipole potential have been performed based on CO₂ laser beams being focused to a beam waist of 50 μm . The dipole potential has been scaled in units of the potential well depth of a single Gaussian beam (For 65 W of laser power: $U_{\text{Dip}}(0)/k_{\text{B}} = 1.2 \text{ mK}$). Figure 7.3 shows a 1D slice through the lattice. The interference pattern is evident in the overall Gaussian profile of the laser beam. The trap depth is 12.8 times greater than that of a single focused Gaussian beam. The lattice constant is: $\lambda_{\text{T}}/\sin(\arctan(2)) = \lambda_{\text{T}}\sqrt{5}/2 = 11.85 \mu\text{m}$. Figure 7.4 shows the interference pattern in the $z = 0$ plane of the lattice. The face-centred cubic structure is evident. It is expected that it will be possible to create ~ 1000 lattice sites loaded with cold atoms.

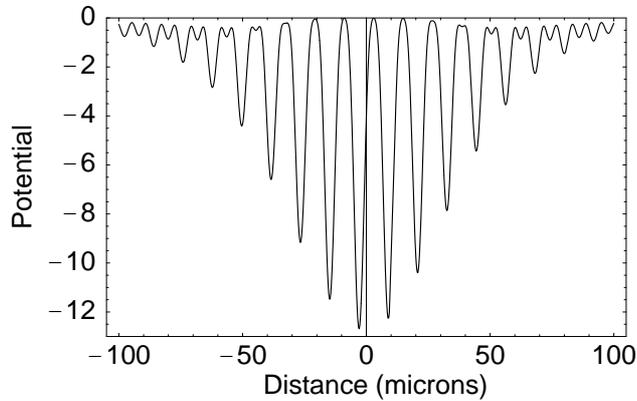


Figure 7.3: A 1D slice through the centre of the four beam interference pattern. The dipole potential has been scaled in units of the potential well depth of a single Gaussian beam. In this simulation the beam waist of the lasers is 50 μm .

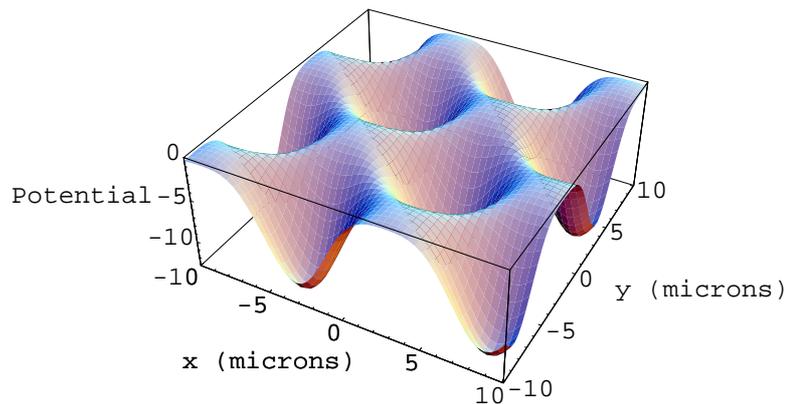


Figure 7.4: The potential energy surface along the $z=0$ plane of the four beam interference pattern. The face-centred cubic structure is evident. The dipole potential has been scaled in units of the potential well depth of a single Gaussian beam. In this simulation the beam waist of the lasers is 50 μm .

7.1.1 Single-site addressability

Once the atoms have been loaded into the periodic array, a technique is needed to address individual lattice sites. A single laser beam can be used to probe a line of atoms held in a 3D lattice. To probe just one site requires two crossed laser beams, centred on the site of interest, see Figure 7.5. This has the added advantage that the lasers can be used to perform two-photon stimulated Raman transitions. The transfer of atoms in just one lattice site to a different hyperfine ground state has the effect of “marking” them for subsequent operations.

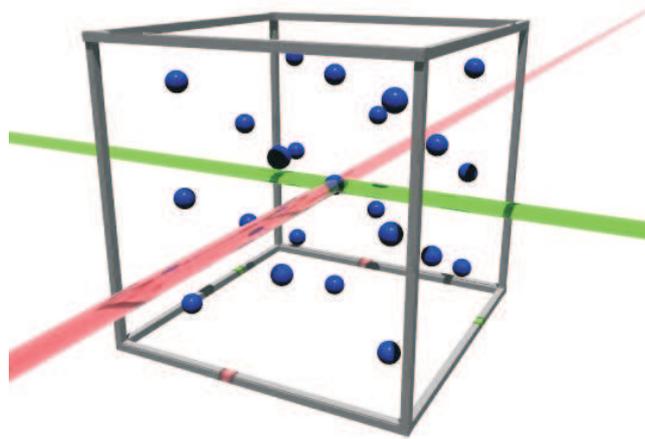


Figure 7.5: The principle of using two laser beams to select a single site in a 3D optical lattice is illustrated.

In theory it is possible to construct state-selective optical tweezers to move the contents of the marked site. An optical tweezer can be constructed from a highly focused laser beam, which acts as a moveable dipole trap. It is made to be state-selective by ensuring that the light shifts of the unmarked sites exactly cancel. A more controlled method of transport would be to use an optical conveyor belt to move one qubit state without disturbing the other state.

7.2 Experiment: design criteria

To construct a 3D lattice experiment requires the vacuum chamber to have three main features:

- Extremely low background pressure to reduce collisions with background gas that result in decoherence.
- Good optical access. The CO₂ laser needs to enter and exit the chamber 8 times, and a further 6 windows are needed for the cooling beams. Extra ports will be needed for probing and imaging the cold atoms. An added complication is the CO₂ laser requires the use of window material that will not be shattered by the high powers. ZnSe is a material that meets this requirement.
- A method to align the CO₂ laser safely and accurately to the required angles. Ideally the laser should be incident normally to the window, to avoid dangerous off-axis reflections.

With these criteria in mind, a differentially pumped two chamber vacuum system was constructed. The first chamber operates at a higher pressure and cools the Rubidium atoms. These atoms are then moved to the second lower pressure chamber. The custom designed chamber has 22 viewports which are machined at the required angles to make the optical lattice. By aligning the CO₂ laser to the window centres simplifies what could be a difficult setup. The next chapter describes in detail the construction of the experiment.

Chapter 7 summary

- Optical lattices were introduced and the importance of including polarisation was explained. The 4 beam geometry for constructing a face-centred cubic lattice was presented along with slices through the potential surface. Techniques for addressing single-sites in the lattice were outlined.
- Design criteria for building a 3D lattice experiment were given.