Chapter 2

Lasers and Laser Stabilisation

2.1 Introduction

The use of diode lasers has become commonplace in atomic physics [30, 31, 32]. As the field has advanced rapidly, [4], it has become more important to have laser systems that are highly stable and capable of remaining ‘locked’ to a particular spectral line for long periods. A general requirement is to stabilise the lasers to less than the atomic linewidths, $\Gamma$ [33], which for the alkalis is of the order of 10 MHz (6 MHz for $^{85}$Rb). Although an extended cavity diode laser (ECDL) can have a short-term stability of less than 1 MHz, it can drift over 100 MHz in a few minutes due to thermal fluctuations [34]. To prevent this drift the lasers can be stabilised by referencing to a narrow spectroscopy signal, e.g. saturation absorption spectroscopy [30, 35].

Chen et al., [36] examined the number of atoms trapped, and optimal trapping conditions of $^{87}$Rb with lasers of linewidth 10 MHz and 1 MHz. The overall effect of the increase of the linewidth by an order of magnitude was a reduction in the trapped number by 40 percent, while still trapping more than $10^7$ atoms. This shows that by careful frequency stabilisation of the laser the number of trapped atoms can be significantly increased and fluctuations in the number of trapped atoms supressed. A further argument for frequency stabilisation is to keep the lasers on the desired frequency for as long as possible. This means that there can be confidence in the repeatability of experiments and reduces the amount of time spent tuning lasers.
2.2 Extended Cavity Diode Lasers (ECDLs)

Free running diode lasers have linewidths of up to 100 MHz and drift in frequency due to thermal vibrations and changes in the operating parameters of the diode, such as noise in the driving current. Tuning of the frequency is achieved mainly through the temperature of the diode, and to a lesser degree the driving current. However this tuning is a hit–an–miss affair that varies very much between different laser diodes. The output wavelength shows discrete jumps, on the order of 0.35 nm (∼100 GHz at 780 nm) with varying temperature due to mode hops in the laser cavity. See Wieman et al. for an excellent review of the use of diode lasers in atomic physics [37].

Diode lasers are very susceptible to optical feedback, a technique that can be used to create a tunable, narrow–linewidth laser source. A frequency dependent reflector - e.g. a diffraction grating - provides such a method of feedback while still coupling out a significant amount of laser power. In the ‘Littrow’ geometry a blazed grating diffracts the low power first order laser beam back into the laser diode cavity, with the zeroth order being outcoupled. This, and similar schemes are what are know as ECDLs. The external cavity allows the selection of a single mode of the diode chip. This simple set–up causes narrowing of the laser linewidth by two orders of magnitude and also allows tuning of the operating wavelength [30, 31].

To counteract the effect of mechanical vibrations and temperature fluctuations some kind of active stabilisation is required. In the ECDL scheme a grating is used to select a frequency, through the first diffracted order, and to feed this back into the diode laser cavity. This technique reduces the linewidth of the laser to <1 MHz. The zeroth order diffracted beam is then used as the laser output. The increased cavity length is a factor in the reduction of the linewidth. Adjustment of the angle of the grating with a piezo–electric actuator provides a mechanism for the feedback to the laser - if the laser frequency is lower than required, the angle of the grating can be increased or correspondingly opposite.

The temperature control of the laser and extended cavity determines the quality of the long term stability of the laser, i.e., how repeatable the performance of the laser is over the days, weeks and months that a experiment is in use. Temperature changes will cause changes in the cavity lengths of the diode and
the ECDL, which drastically affect the mode. For this reason the diode and external cavity must be actively temperature stabilised.

Experimentalists using Rb have the lucky advantage of having the cooling transition at 780 nm being virtually the same as the wavelength used in CD players [38]. Consequently considerable research has been conducted into the development of low cost and high power laser diodes in this spectral region. For example, it is now possible to buy a single 120 mW diode (Sharp GH0781JA2C) for less than £14 [39], or equivalent to less than £155/Watt.

2.3 Details of ECDLs

The lasers used in Durham atomic labs are based on the Littrow configuration [30, 31]. The laser diode (Sharp GH0781JA2C) and a collimating lens ($f = 4.5$ mm) are contained within a collimating tube (Thorlabs LT230P-B), giving good alignment of these optical components. The collimation tube is clamped into an aluminium mount which acts as a thermal reservoir for the laser diode. A gold–coated, holographic diffraction grating with 1800 lines/mm is used for frequency selective feedback. These gratings, from Richardson Grating Laboratory are used as they diffract less from the zeroth order and so can out–couple up to 85% of power out from the diode. The grating is mounted at 45° relative to the laser beam upon two piezo-electric actuators (Thorlabs AE0203D04) which are glued to another aluminium mount which is clamped in an adjustable mirror mount (Thorlabs KC1). The mirror mount allows for accurate alignment of the feedback into the laser diode. The entire external cavity is mounted inside an aluminium insulating box which is screwed to the brass base plate. The box is then mounted upon a heavy foam base to reduce vibration and then placed inside a second larger box. Anti-reflection coated windows are glued into both boxes to allow the laser beam to exit. The two boxes isolate the laser and extended cavity from air movement and temperature changes in the lab.

A Peltier cooler is in thermal contact with the collimating tube clamp. A second, larger cooler situated beneath the base plate to control the cavity temperature. Two 10 kΩ thermistors, mounted above the laser diode and between the Peltier
coolers, are connected to separate temperature controllers (Wavelength electronics TEC5000). By this arrangement the temperature of the laser diode and the cavity are actively controlled to 25°C and 24°C respectively. Previously we had kept the coolers at 19°C, approximately room temperature, but found that changes in the temperature of the lab above the set-point temperature of the laser diode caused run-away heating of the diode. This was due to the trapping of the heat generated by the Peltiers in keeping the laser diode cool within the two insulating boxes. Keeping the laser diode and cavity above the temperature range of the lab has proved to eliminate the problem.

2.4 Spectroscopy and Laser Stabilisation

In a history of hydrogen, Rigden writes, “The experiments themselves – saturation spectroscopy, polarization spectroscopy . . . – were magnificent in their design and execution.” [40].

2.4.1 Introduction

A considerable amount of time has been spent within the Durham group in stabilising the lasers used in our cold atom experiments. The goals of these stabilisation experiments were to have an accuracy as high as possible on an atomic transition line centre, to increase the precision and reduce the linewidth as much as possible (generally sub MHz), to have a very stable ‘lock’, and to have a repeatable response to the previous points. Another feature that is very desirable is ease of use when the technique is used in a full, cold atom experiment. Various methods of stabilising diode lasers to a frequency have been examined: dither locking through current modulation, dither locking through AOM modulation, level locking against Doppler broadened hyperfine features, dichroic atomic vapour laser locking (DAVLL) [41] and polarisation spectroscopy [42]. Only the latter was used in these experiments so only this will be described in detail here. However, for interest we compare the methods in terms of the goals listed above and also experimental complexity.
Comparison of Locking Methods

All of the methods for locking lasers have advantages in one of optical simplicity, electronic simplicity, accuracy, precision or robustness. Firstly we compare the methods as regards accuracy, precision and the recapture range - the frequency range over which the laser will return to the lock point if the laser is disturbed.

<table>
<thead>
<tr>
<th>Name</th>
<th>Accuracy</th>
<th>Precision</th>
<th>Recapture Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dither Locking</td>
<td>&lt; 1 MHz</td>
<td>≤ 1 MHz</td>
<td>Small, ≈ 50 MHz</td>
</tr>
<tr>
<td>DAVLL</td>
<td>≈ 250 MHz</td>
<td>≈ 1 MHz</td>
<td>Very large, ≈ 1 GHz</td>
</tr>
<tr>
<td>Level Locking</td>
<td>≈ 100 MHz</td>
<td>≈ 1 MHz</td>
<td>&lt; 10 MHz</td>
</tr>
<tr>
<td>Polarisation Spectroscopy</td>
<td>≈ 2 MHz</td>
<td>&lt; 1 MHz</td>
<td>≈ 100 MHz</td>
</tr>
</tbody>
</table>

Table 2.1: Comparison of the most common laser locking methods in terms of the accuracy and precision of the locking frequency and also the recapture range.

The values in Table 2.1 have been measured within the group. The table shows that polarisation spectroscopy is a precise technique that does not appear to compromise on other desirable characteristics.

The other consideration to be looked at is ease of implementation, and optical and electronic complexity. The main optical component required is the reference vapour cell, which is essential for all locking schemes. However a setup such as DAVLL requires an additional vapour cell for saturation absorption spectroscopy as the features it measures are GHz wide and the accuracy is low, as indicated in Table 2.2. The techniques all require essentially identical circuitry for feedback to the laser.

2.4.2 Basic Principles of Polarisation Spectroscopy

Polarisation spectroscopy was proposed and demonstrated by Wieman and Hänsch as an advancement on saturation absorption spectroscopy. The use of polarisation spectroscopy to stabilise an ECDL has been described previously [43]. This work has been further advanced to create a technique for frequency stabilising ECDLs on a zero-crossing of an error signal without modulation of the laser frequency [42].
<table>
<thead>
<tr>
<th>Name</th>
<th>Optics Required</th>
<th>Electronics Required</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dither Locking (Current)</td>
<td>1× Vapour cell</td>
<td>1 × Photodiode</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lock-in amplifier</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Current modulator</td>
</tr>
<tr>
<td>Dither Locking (AOM)</td>
<td>1× Vapour cell</td>
<td>1 × Photodiode</td>
</tr>
<tr>
<td></td>
<td>AOM</td>
<td>Lock-in amplifier</td>
</tr>
<tr>
<td>DAVLL</td>
<td>2× Vapour cell</td>
<td>2 × Photodiodes</td>
</tr>
<tr>
<td></td>
<td>Magnets</td>
<td>Differencing circuit</td>
</tr>
<tr>
<td>Level Locking</td>
<td>1× Vapour cell</td>
<td>1 × Photodiode</td>
</tr>
<tr>
<td>Polarisation Spectroscopy</td>
<td>1× Vapour cell</td>
<td>2 × Photodiodes</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Differencing circuit</td>
</tr>
</tbody>
</table>

Table 2.2: Comparison of the additional optical and electronic components, aside from standard mirrors and lenses, required for standard laser locking methods.

Polarisation spectroscopy is method of high resolution spectroscopy, similar to saturation absorption spectroscopy $^{30, 35}$ in many ways. The medium is pumped and probed with two beams created from the same laser, with the pump beam more intense than the probe. See Fig. 2.1 for experimental setup. The differences between the spectroscopic methods are in the pumping and probing mechanisms. The theory concerning polarisation spectroscopy is examined in depth in $^{35, 42, 44, 45}$.

![Figure 2.1: Schematic for polarisation spectroscopy based spectrometer.](image-url)
2.4.3 Model of Polarisation Spectroscopy

Consider a circularly polarised, $\sigma^+$ laser beam passing through an atomic gas sample. If the beam is resonant with a particular transition of the atom then the atoms will be optically pumped towards increasing $m_F$, following from the selection rule that $\sigma^\pm$ light causes $\Delta m_F = \pm 1$ transitions. This pumping will cause a nonuniform population of different Zeeman levels. A linearly polarised probe beam will observe any anisotropy of the medium as a birefringence, due to differential absorption of orthogonal components of the probe beam. This birefringence will be observed in a rotation of the plane of polarisation.

2.4.4 Experimental Implementation

The probe and pump beams are taken from the same laser with intensities of 1.2 mW/cm$^2$ and 3.6 mW/cm$^2$, respectively, typically used. The probe beam is arranged so that it is linearly polarised, if necessary using a linear polariser. In general this is not required as the beam emitted by the ECDL is already linearly polarised. We arrange that the plane of polarisation is at $\pi/4$ to the horizontal using a half-wave plate. The probe beam is analysed by passing it through a polarising beam splitting (PBS) cube which separates the beam into its linear horizontal and vertical components. Each of these components is detected by a separate photodiode. A good check that the angle of the polarisation is at $\pi/4$ is to ensure that the intensities coming from the PBS are identical. It is to be noted that linearly polarised light can be considered as a combination of left- and right-circularly polarised light, with the angle of the plane of linear polarisation being a function of the relative phases of the circular components. The pump beam is passed through a $\lambda/4$ waveplate so that it is circularly polarised when it pumps the medium.

The circularly polarised light will induce $\sigma^-$ or $\sigma^+$ transitions in the absorbing atoms; i.e., it will cause changes in the magnetic sub-levels of the atom of $\Delta m_F = -1$ and $\Delta m_F = +1$ respectively. The type of transition caused will depend on the polarisation of the beam relative to external magnetic fields. The circularly polarised light will cause saturation of some transitions within the atoms, and can pump some of the atoms into states that are dark to the pumping
light if these states are available. The net result is that the medium now has a non-uniform population in the different magnetic sub-levels. The medium will now absorb the $\sigma^+$ and the $\sigma^-$ components of the probe beam differently. Thus one of the components will emerge retarded and with a different relative phase to the other circular component as it had when it entered the medium. The effect is for the plane of polarisation of the probe beam to be rotated. This will be observed by an increase of intensity in one of the photodiodes analysing the resolved components of the probe beam and a corresponding decrease in the other. The differential absorption of the orthogonal circularly polarised components of the probe beam is observed by inserting a $\lambda/4$ waveplate before the analysing PBS. The result can be seen in Fig. 2.2 which clearly shows the significant enhancement and decrease of absorption about the closed transition.

Fig. 2.3 (top and middle) show saturated absorption and polarisation spectra recorded simultaneously on a single frequency scan for $^{87}$Rb and $^{85}$Rb cooling transitions. The signal produced for Fig. 2.3 (middle) used the set-up shown in Fig. 2.1 with an angle of 5.5 mrad between the pump and probe beams. In our set-up this requires a distance of over half a metre between the vapour

![Figure 2.2: Polarisation spectra with a quarter-wave plate before the analysing PBS. (a) Absorption profile for the component of the probe driving $\sigma^-$ transitions, showing an enhanced absorption in the region of the closed transition. (b) Absorption profile for the component of the probe driving $\sigma^+$ transitions, showing a decreased absorption in the region of the closed transition.](image-url)
Figure 2.3: Saturated absorption (top) and polarisation (middle, bottom) spectra of, from left to right, the $^{87}\text{Rb}$, $F = 2 \rightarrow F'$ and the $^{85}\text{Rb}$, $F = 3 \rightarrow F'$ features recorded on a single frequency scan. top) and middle): Pump and probe were counter-propagating at an angle of $\approx 5$ mrad and with intensities of 3.6 mW/cm$^2$ and 1.2 mW/cm$^2$ respectively. bottom) Same setup but with pump and probe were counter-propagating at an angle of 72.5 mrad.

...
decrease in signal height.

### 2.4.5 Magnetic Sensitivity of Polarisation Spectroscopy

The effect of a cancelling magnetic fields about the vapour cell was examined by placing the cell within a Mu–metal shield. Careful positioning of the cell within the shield was found to remove a non–linear background offset, Fig. 2.5. The figure shows that the magnetic shield decreases the size of the observed signals, whereas previously Pearman had measured increased signals with a shield \[44\]. In general it was found that slight changes in the Mu–metal shield position caused the observed signal to change. Also, the shield is inconvenient to use as it is bulky.

A pair of coils were used to produce a bias field along the vapour cell. The coils were approximately 5 cm in diameter and separated by approximately 8 cm. The coils produced a maximum B–field of 1.3 G at the centre of the vapour cell. This longitudinal bias field caused the polarisation spectroscopy

![Figure 2.4: Effect of increasing the pump–probe angle in the polarisation spectroscopy setup. The spectrum is that of the $^{85}\text{Rb} F = 3 \rightarrow F'$ transition. The angles and peak–to–peak signals are, a) 37 mrad, 320 mV, b) 58 mrad, 262 mV, c) 80 mrad, 170 mV.](image)
Figure 2.5: Spectra taken with (bottom) and without (top) a Mu-metal magnetic shield about the vapour cell in polarisation spectroscopy. The figures show spectra with and without the pump beam.

features to increase in size. Fig. 2.6 shows this increase as observed on the $^{85}\text{Rb}$ $F = 3 \rightarrow F' = 4$ feature.

For laser locking it is essential to know to what frequency the laser is being locked. Increasing the bias B-field also changes the position of the features. To monitor this effect a separate saturation absorption spectroscopy setup was added to monitor the position of the features that were to be locked to. The position of the zero-crossing initially varies quickly with varying bias B-field up to approximately 0.2 G, as shown in Fig. 2.7. The offset from ‘true’ line centre is actually decreased up to this point. These results agree with measured spectra of calcium taken over a greater B-field range [46].

In the setup the position of the bias coils was well defined by the vapour cell. Small changes in the position of the coils were not observed to have an effect on the spectroscopy signals produced. The offset of the zero crossing was monitored
Figure 2.6: Plot of the variation of the peak-to-peak signal on the $^{85}$Rb $F = 3 \rightarrow F' = 4$ polarisation spectroscopy feature with increasing longitudinal, bias B-field. A field of 1.3 G causes a signal increase by a factor of 2.7

regularly but was not found to drift over days or months.

### 2.4.6 Locking with Polarisation Spectroscopy

An integrator circuit based on that of Rovera et al. [47] was used, Fig. 2.8. Following the integrator section a DC bias voltage was added. This was to bring the voltage on a gross scale to the voltage corresponding to the required locking point. The output from the adder was connected to the piezo and also to the oscilloscope to monitor the feedback signal.

The laser was locked as follows: the laser current and the piezo scan were adjusted until the required transitions were observed in the saturation absorption spectrum. The zero-crossing of the polarisation spectroscopy difference signal was observed and the corresponding piezo voltage was recorded. The piezo was disconnected from the signal generator and connected to the output of the locking circuit, ensuring that the ‘Lock’ was set so that the integrator acted as a
Figure 2.7: Plot of the variation of the zero crossing of the $^{85}\text{Rb } F = 3 \rightarrow F' = 4$ polarisation spectroscopy feature with increasing longitudinal, bias B–field. The error bars are due to uncertainty in defining the line center in the reference saturation spectroscopy.

voltage follower. The recorded piezo voltage was added on at the DC bias stage and was fine tuned so that the saturation spectroscopy signal was observed to follow the pattern of the hyperfine transitions in the region required and the difference signal was seen to move as expected and to move to its zero crossing. The ‘Lock’ switch was then used and the gain adjusted until oscillation was observed. The gain was then reduced, indicating a lock with a large gain but below the oscillation threshold. External disturbances, such as loud noise (provided by a radio that was tuned to the noise between stations) and striking of the table caused oscillations in the feedback signal which died quickly when the disturbance was removed. The laser was then observed to remain on resonance.
2.5 Frequency Stability and Beat Measurements

The trapping and hyperfine repumping lasers have been locked without interruption for days using polarisation spectroscopy, limited only by the lifetime of the batteries in the photodiode circuits.

To monitor the frequency stability of the locking scheme, the trapping and repumping lasers were both locked to the $^{85}\text{Rb}, F = 3 \rightarrow F' = 4$ feature using polarisation spectroscopy and feedback to the grating piezo. A frequency offset of $\sim 5$ MHz was introduced between the lasers by using the $\lambda/2$ waveplate (see Fig. 2.1) to shift the zero of the error signal on one of the lasers. The beams were combined on a 50/50 beam-splitter and then focussed onto a photodiode. The photodiode, a Siemens BPX-65, has a quoted frequency response of up to 100 MHz when used with a 50 \, \Omega resistor. The data were recorded on an 300 MHz bandwidth oscilloscope, terminated at 50 \, \Omega for impedance matching.

If each laser is well described by a Lorentzian frequency line shape then the combined line shape should be also be described as a Lorentzian. The FFT of the beat signal was fitted with back-to-back exponentials as the Fourier
transform of a Lorentzian is an exponential, Fig. 2.9. The full-width-half-maximum (FWHM) was estimated as 625 kHz. If we assume that both lasers have similar, though uncorrelated linewidths we then estimate the individual laser linewidths as $\sim 310$ kHz.

Figure 2.9: FFT of measured beat spectrum between two lasers frequency stabilised using polarisation spectroscopy (grey) with a back-to-back exponential fit. The FWHM is measured to be 625 kHz.

If the lasers drift in a correlated way, say due to temperature changes in the lab, this would not be evident from the measurement described above. We have monitored the individual error signals feedback to the piezo while the error is in lock and observe that the RMS value of this signal, typically 300 kHz, agrees with the beat measurements.

It has also been shown that the ‘recapture’ range of the polarisation spectroscopy signal is at least a factor of 3 larger than that of the saturation spectroscopy method. The saturation spectroscopy error signal has zero crossings separated by 60 MHz, giving a range of $\sim \pm 30$ MHz on the locking point. This is due to the fact that each peak in the spectrum has a zero crossing. The polarisation spectroscopy signal gives of a range of $\sim -50$ MHz $\sim +300$ MHz...
on the lock point, see Fig. 2.3. This value was found by direct measurement of
results. With a larger angle between the pump and probe beams the details of
the polarisation spectrum were reduced. This increased the range on the lower
frequency side of the lock point.

Fig. 2.10 shows the increased captured range and simpler error signal produced
by polarisation spectroscopy when compared to dither locking, for the $^{85}\text{Rb}$,
$F = 2 \rightarrow F'$ transitions. Using polarisation spectroscopy gives zero crossings
at $-520 \text{ MHz}$ and at $+60 \text{ MHz}$, relative to the lock point, with the lower limit
being off the scale of the figure. The dither method gives zeros at $\approx 10 \text{ MHz}$ on
either side of the desired lock point.
Figure 2.10: Saturated absorption spectrum (top), the corresponding error signal produced by a dither on the laser drive current (middle), and polarisation spectrum (bottom) of the $^{85}\text{Rb}$, $F = 2 \rightarrow F'$ hyperfine features. The polarisation spectrum has fewer zero-crossings and a greater capture range than the dither-produced error signal. The zero crossing is close to the $^{85}\text{Rb}$, $F = 2 \rightarrow F' = 1/2$ crossover feature, $-78.1$ MHz detuned from the repumping transition, $F = 2 \rightarrow F' = 3$ which is referenced as 0 MHz. For the polarisation spectrum the same setup as Fig. 2.3 (bottom) is used.