kHz linewidth lasers using polarisation spectroscopy

J. S. J. Torrance[1], B. M. Sparkes[1], and R. E. Scholten[1]

[1]School of Physics, The University of Melbourne, Melbourne, Victoria 3010 Australia

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Abstract

Due to polarisation spectroscopy being a refractive index based technique it is not limited by the lifetime of atomic states unlike similar techniques such as saturated absorption spectroscopy. We demonstrate a laser system stabilised with polarisation spectroscopy achieving spectral linewidths of order 1 kHz.

1 Intro

Laser frequency stabilisation to atomic references is essential to numerous applications including the cooling and trapping of atoms [1–3], atomic clocks [4], high resolution spectroscopy [5] and metrology [6–8]. Narrow linewidth lasers are also important to blah blah.

Current techniques for minimising laser linewidths range from laser stabilisation with saturated absorption spectroscopy, which can achieve linewidths in the region of 150 kHz [9], to elaborate experiments involving extremely high finesse cavities that are able to achieve sub-Hertz linewidths with diode lasers using the Pound-Drever-Hall technique [10].

Polarisation spectroscopy (PS) [8, 11] has much in common with saturated absorption spectroscopy [12–14] as both techniques provide frequency stabilisation to an atomic reference however PS relies on the circular birefringence of optically pumped atoms rather than absorption. PS is shown here to be able to reduce diode laser linewidths to kHz levels.

It has been shown previously that PS can be used to reduce the linewidth of a distributed feedback diode from 2 MHz to 20 kHz [15] and of diode lasers to 65 kHz [16]. Our PS locking system utilises high bandwidth feedback to the laser diode to achieve linewidths of order 1 kHz.

2 Pol Spec Theory

PS uses counterpropagating pump and probe beams from the same laser to induce circular birefringence in an atomic sample which produces a frequency dependent rotation in the polarisation angle of the probe beam. This rotation is used to generate an error signal ideal for laser locking [8, 11].

The polarisation rotation of the probe can be monitored using a balanced polarimeter which consists of a quarter-wave plate, polarising beam splitter (PBS) and two detectors. By taking the difference between the signals from the two detectors the balanced polarimeter provides a background-free signal which is ideal for laser locking [17]. A schematic of polarisation spectroscopy with a balanced polarimeter is shown in figure 1 and an example of a PS error spectrum for rubidium 85 $5^2S_{1/2}$ to $5^2P_{3/2}$ transition is given in figure 2.

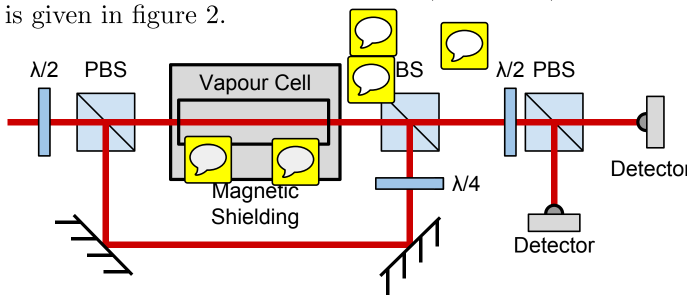

Figure 1: A schematic of polarisation spectroscopy with a balanced polarimeter. The power balance between the probe and pump beam is controlled with the leftmost $\lambda/2$ waveplate and PBS. The $\lambda/4$ waveplate is used to make the pump circularly polarised and the non-polarising beamsplitter (BS) is used to counterpropagate the beams through the atomic sample without altering the polarisation of the circular pump or linear probe. The final $\lambda/2$ waveplate and PBS form the balanced polarimeter which monitors the polarisation rotation of the probe.

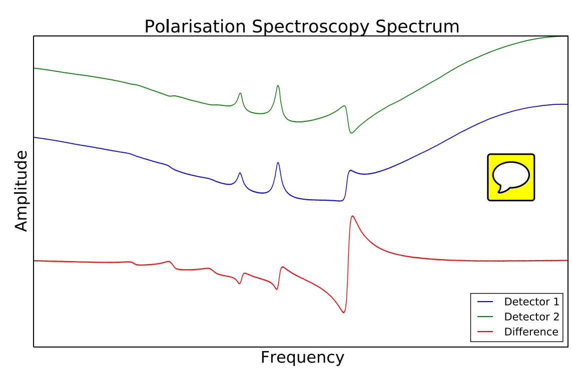

Figure 2: An example of the polarisation spectrum of the Rb85 $5^2S_{1/2}$ to $5^2P_{3/2}$ transition. This is a stand in image. One showing pol spec vs sat abs would probably be more useful. Label the various transitions too.

The error signal is the difference between the signals from the two detectors which in turn are the intensity of the horizontal and vertical polarisation components of the probe beam. The rotation of the polarisation of the probe beam as it passes through the atomic sample changes the ratio of light on the detectors and is given by [18]

$$\Delta\theta = \frac{\pi L}{\lambda}(n_+ - n_-) \tag{1}$$

where L is the length of the atomic sample and $n_\pm$ are the refractive indices for the circularly polarised components of the linear probe beam, $\sigma^\pm$.

Due to the optical pumping of the pump beam the refractive indices for $\sigma^\pm$ are different since the refractive indices are given by[citation or derivation needed]

$$n_\pm = 1 + N\frac{\sigma\lambda}{4\pi}\frac{\Gamma}{\Omega_{ge\pm}}\rho_{ge\pm} \tag{2}$$

and $\rho_{ge\pm}$ and $\sigma_{ge\pm}$ are very different with a circularly polarised pump. In equation 2, N is the atomic density of the sample, σ is the optical cross-section, λ is the wavelength of the light, $\Omega_{ge\pm}$ is the Rabi frequency for the transition in question and $\rho_{ge\pm}$ is one of the off-diagonal elements of the steady-state density matrix for the atoms.

The complicated energy levels can be simplified to a three level V-system where the two excited levels have the same energy but different couplings to the $\sigma_\pm$ light. Optical Bloch equations (OBEs) for a three level system can be used to calculate $\rho_{ge\pm}$. To simulate PS one of $\Omega_{ge\pm}$ must be larger to represent the probe beam. After integrating over a typical velocity distribution the rotation of the probe beam over a range of detuning from atomic resonance is shown in figure 3.

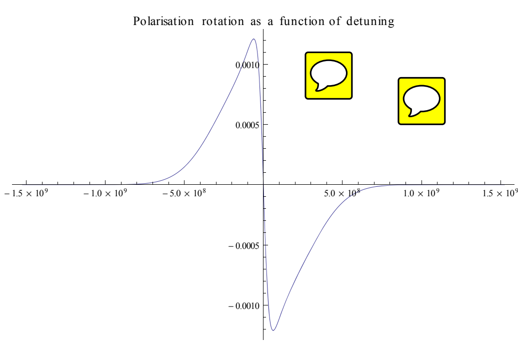

Figure 3: The rotation of the probe beam as it passes through an atomic sample pumped by the pump beam as the detuning of the laser is quickly scanned over the atomic resonance. More simulation parameters.

The error signal from the rotation of the probe beam is not temporarily limited by atomic processes unlike some other locking techniques such as saturated absorption which are limited by the excited state lifetime[citation]. This means that PS is technically and noise limited.

Bandwidth theory?

3 Setup

~~The experiment was constructed in order to measure the practical linewidth of a diode laser locked with PS and~~ the setup is depicted in figure 4. Two separate external cavity diode lasers (ECDLs) were individually locked using PS and high bandwidth feedback. A heterodyne measurement was then made to determine the lasers' spectral linewidths. 780 nm laser diodes (product code?) were used to target the rubidium 85 $5^2S_{1/2}$ F=3 to $5^2P_{3/2}$ F=4 transition.

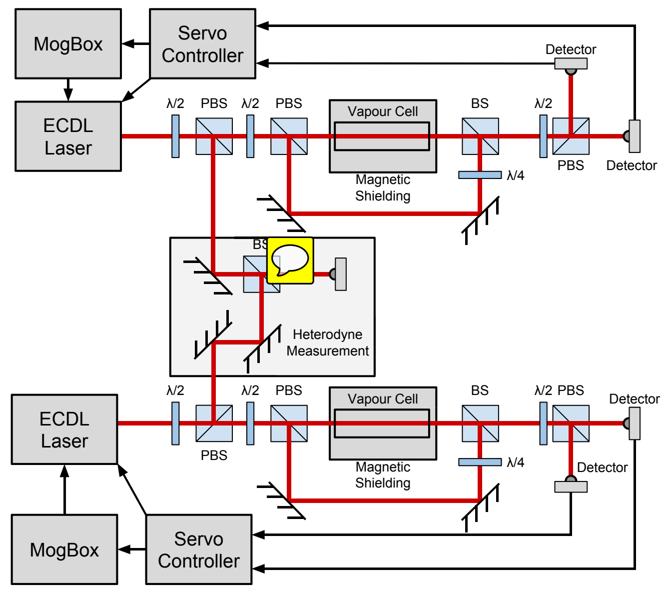

Figure 4: A schematic diagram of the PS setup. This is pretty ugly. Needs work.

The two lasers used were a Toptica DL Pro and a MOGLabs ECDL with modulation bandwidths of 100 MHz and ??? MHz respectively. Each laser was split with some light going to the PS locking and the rest going to the heterodyne measurement. The PS detectors were 100 MHz bandwidth photodiodes (ThorLabs PDA10A) the outputs of which were connected to 14 MHz bandwidth servo controllers (NewFocus LB1005). The servo controllers handle the subtraction of the error signals for the balanced polarimeter as well as locking parameters such as gain. The output of the servo controllers is connected to the fast modulation inputs of the lasers.

Something something new headboard. How much detail? Isolating the laser diode from the electrical ground plane, via some arcane arrangements of FETs as shown in figure 5, is essential in order to reduce the noise in the current feedback to the diode.

Figure 5: A simplified schematic diagram of the MOG laser FET setup. May not be 100% accurate.

The heterodyne measurements are made by first frequency shifting one of the lasers with an acousto-optical modulator (AOM) and then combining the two beams to be copropagating and coincident on to a high bandwidth detector (NewFocus 1621 with a bandwidth >100 MHz). The output of the heterodyne detector is given to the spectrum analyser (Rohde & Schwarz FSP with a 40 GHz bandwidth) and the heterodyne signal can be measured centred around the the AOM frequency.

4 Results

4.1 Bandwidth

The bandwidth of each device is going to be measured hopefully with the network analyser function of the Rohde & Schwarz spectrum analyser and hopefully all the bandwidth will make sense when the entire system's bandwidth is also measured. If I'm lucky I'll get something like figure 6.

This bandwidth means that this setup is capable of achieving linewidths of what? How do I work this out?

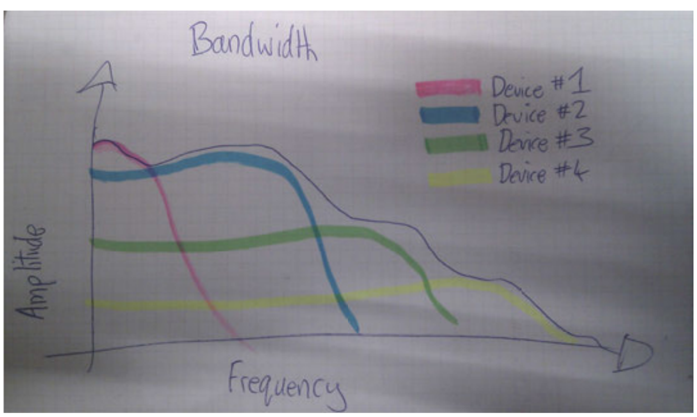

Figure 6: Bandwidth measurement of the Toptica PS setup. This figure needs prettifying

4.2 Heterodyne Measurements

A heterodyne measurements of the signal produced by the two lasers is shown figure 8. The full-width half maximum (FWHM) width of the beatnote shown is 2.0 kHz. If Gaussian linewidths and identical lasers are assumed then there is a factor of $\sqrt{2}$ between the beatnote FWHM and the lasers' FWHM which corresponds to a laser FWHM linewidth of 1.4 kHz.

Diagnostics measurements performed with a high-finesse cavity indicated that the frequency jitter of the MogLabs laser setup was significantly larger than that of the Toptica laser setup. Unfortunately the resources were not available to produce two lower jitter identical setups. If we estimate that the spectral linewidth of the MogLabs laser was double that of the Toptica then the linewidth of the Toptica would be 1.15 kHz.

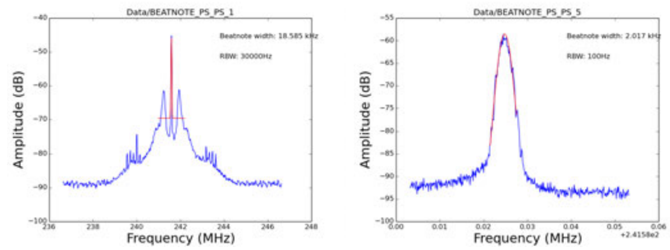

Figure 7: Typical heterodyne beatnotes for the two lasers locked with PS. Both measurements are 50 shot averages taken consecutively.

Figure 8: Something like this.

5 Conclusion

The spectral linewidth achievable with PS is demonstrably lower than previously indicated. It is likely that with additional work into vibrational and optical isolation combined with higher bandwidth electronics that the linewidth could be further reduced to 10s or 100s of Hz. The current experimental setup is an example of a low cost, low linewidth and relatively simple laser source.

6 Other Stuff

- let's not bother mentioning the fibres except perhaps in passing if long term drift is mentioned
- I haven't mentioned some of the details like the calcite prisms or beam expantion

- Transient temperature/frequency drift - possible solution with intensity stabilisation.
- What about phase lead? I didn't end up using any.
- Things that perhaps should be mentioned:
  - cost advantage
  - broad locking range
  - good signal to noise

7 Acknowledgements

- Funding sources.
- Alex for electronics help (or should he be an author?)
- Rory for sanity checking of code (hrm... probably not going to be using those results in the paper after all. Remove acknowledgement?)
- Andre Luiten for equipment and advice

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