Injection locking of a diode laser for use in an ultra-cold strontium experiment

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Abstract. Injection locking of a Nichia NDB7675 blue “slave” laser diode at 461nm was achieved using a “master” laser system with an injection locking range of 2GHz and a maximum power output of 178mW from a seed power of 0.5-10mW. Higher power seeds showed better suppression of unwanted frequency modes and resolved a ‘Lamb dip’ in a saturated absorption spectroscopy experiment. However, it is still unclear whether the injection locking is suitable for use in ultra-cold strontium experiments.

1. Introduction

Gravimeters are devices that can detect the variation in force due to gravity. They have many geophysical and industrial applications including: prospecting for natural resources, navigation, the detection of earthquakes, testing of general relativity and the study of global warming [1,2]. A gravimeter based on a cold or ultra-cold cloud of atoms is called an atomic gravimeter.

The Strontium group at the University of São Paulo in São Carlos is interested in developing an atomic gravimeter which can measure the Bloch oscillations of ultra-cold strontium atoms that are confined in a vertical standing light wave. The frequency of the Bloch oscillations is directly proportional to the force due to gravity. The measurements are achieved by constructing a high-finesse ring cavity which is loaded with laser-cooled strontium atoms that are trapped in the antinodes of a unidirectionally pumped laser beam [3]. The interaction of the atoms with the ring cavity allow for in-vivo measurements of the Bloch oscillations without perturbing the atomic dynamics. This project is of interest to the group as it’s main aims are to better understand collective scattering of light from ultra-cold atoms and to cool strontium atoms to quantum-degenerate temperatures and to trap them in optical lattices.

To successfully develop a high precision gravimeter, high power coherent lasers are necessary to cool and trap atoms. Strontium atoms are cooled and trapped using a number of laser transitions. Initially atoms are cooled to a few mK in a magneto-optical trap (MOT) operating on a dipole allowed $(5s^2)^1S_0$ -$(5s5p)\ ^1P_1$ transition, at wavelength 461nm, linewidth 32MHz [4]. The saturation intensity of the transition is large, so laser power of the order 100mW is required. To save resources, rather than purchasing a dedicated 461nm laser, it is possible to use a small amount of power of an existing laser system through a process known as “injection locking”. Injection locking utilizes the coherency and stability of a narrow-band, low power laser system and combines it with the desired high power output of a broad-band, high power diode laser. The low power, low noise laser is referred to as a "master laser" and the high power, high noise laser is referred to as a "slave laser". If the master and slave frequencies are sufficiently close then the slave laser is compelled to act on the injected frequency with low noise. [5]

The master laser used in this experiment is a 'Toptica' TA/DL-SHG pro Frequency Doubled High Power Laser system and the slave laser used in this experiment is a 'Nichia' NDB7675 blue diode laser. The master laser has a frequency of 650.5040THz (wavelength 461.1809nm). The slave laser diode has maximum power output at 459.9nm according to previous results obtained by the group.

2. Theory

For injection locking to be achieved and sustained, two criteria needed to be met. Firstly, the slave frequency must match the master frequency, this requires good frequency control using temperature and current controllers. Secondly, the slave has to have a matching spatial distribution, i.e. its beam size and shape must match the master's.

2.1. Frequency control

The natural frequency of the slave laser diode in the free-running mode is 652THz at room temperature which is close to the desired frequency of 650.5040THz but not close enough for injection locking to occur. This means that the frequency of the slave needs to be adjusted by using coarse temperature control and finer current control. The temperature is controlled with 10mK precision by using a temperature feedback loop which consists of a thermoelectric cooler (TEC), a thermistor and a electronic feedback circuit, called a temperature controller. A thermistor's resistance is dependent on temperature and so it gives a reading of temperature when placed next to the diode. The controller can be used to set the desired temperature and then the TEC will cool or heat the diode until equilibrium is reached. The TEC works by utilizing the 'Peltier' effect. This is when current passes between two dissimilar conductors in a circuit where heat flux appears and thus heat can be generated or removed from the system [6,7].

The speed at which the temperature of the diode settles on the set temperature is determined by a PID (Proportional-Integral-Derivative) feedback circuit. The circuit contains three operational amplifiers (op-amps) which separately amplify, integrate or differentiate the error signal, i.e. the difference between the desired temperature and the actual temperature. By changing resistance close to each one of the three op-amps, the gain on each one of the effects - P, I and D - can be optimized in order to improve the speed and stability of the controller.

2.2. General optics theory

In this experiment multiple mirrors, waveplates and polarizing beam splitters (PBS) are used. The mirrors are coated for blue light so that they have high reflectivity and they are used to redirect and contain the laser light on the optical table and for aligning light into various optical apparatus. Beam-walking utilizes two mirrors to guide the light to a specific point in space with a specific angle. The first mirror the beam encounters primarily controls the position of the beam and the second mirror primarily controls the angle. By following an iterative procedure of adjusting the mirrors the optimal path can be achieved [8].

Waveplates alter the polarization state of light that passes through them. The waveplates used in this experiment are half waveplates which alter the polarization direction of linearly polarized light. A waveplate consists of a birefringent crystal that retards the polarization of either the horizontal or vertical axis so that there is a phase change between the two axes. The material and length of the crystal is chosen so that this phase change is 180°. PBS's can split a laser beam into two beams because they consist of a partially transmissive reflective surface for a specific wavelength. The amount of light that is reflected or transmitted depends on the polarization state of the laser beam and so the proportion of splitting can be controlled by using waveplates.

It was necessary to include an optical isolator (Thorlabs IO-3-460-HP) in the experiment to prevent high power optical feedback from damaging the diode and to assure different paths for the incoming and outgoing injection locking beams. An optical isolator utilizes the Faraday effect: an applied magnetic field rotates the polarization of a beam of light. Only light of a specific polarization angle can enter and exit the ends of the isolator. Using a waveplate before the isolator allows the maximum amount of light to enter the entry port. This light's polarization is rotated 45° by the isolator and it leaves the exit port which is at 45° with respect to the entrance port. However, light that enters the isolator from the other direction will be rotated so that it is 90° out of phase and thus is deviated from the optical axis at the entrance PBS.

The size of laser beams in the horizontal orientation can be adjusted by using anamorphic prisms. Lasers transverse anamorphic prisms according to Snell's law, i.e. a beam entering a medium of higher refractive index will refract towards the normal of the interface, magnifying the beam. After the beam has been magnified in one prism it is de-magnified in another prism which also corrects its direction so that it is the same as the incident beam. However, depending on the media involved and the prisms' relative angles there can be an overall magnification greater than unity. [9]

2.3. Fabry Perot, modes and cavities

The most common laser resonator is one which has two spherical or flat facing mirrors with one of the mirrors being partially transmitting to allow light out of the resonator. A trapped optical beam becomes a cavity mode which forms a standing wave in the cavity. Cavities allow for high directionality and well defined frequencies [10].

A Fabry Perot interferometer is a confocal cavity with a high finesse (the number of times that light is reflected before being lost). The higher the finesse, the higher the sensitivity of the Fabry Perot cavity to the measurement of the linewidth of the laser source and so it is more frequency selective. The two mirrors have some transmissivity with sharp resonances. The resonant frequencies can be tuned by changing the cavity length with a piezo actuator.

3. Experimental method

3.1. Coupling light to a fibre

Before injection locking could be attempted, some of the laser light from the one experiment needed to be taken to the other laboratory. The easiest way to achieve this was by using an optical fibre. Some of the laser light used in the existing experiment was obtained for this experiment by using a PBS and a half waveplate. The obtained light was then guided on a new optical path by using a series of mirrors and directed on to the mounted end of an optical fibre. The diameter of the beams were matched by using lenses. To maximize the amount of light passing through the fibre, the polarization and spatial positioning of the beam was optimized. The polarization was optimized by using a half waveplate and the positioning was optimized by using beam-walking.

3.2. Setting up temperature and current control

To keep the slave laser acting on the master frequency, good temperature and current control were needed. A TEC was attached beneath the slave diode and a thermistor was attached close to the diode using thermally conductive epoxy glue. The positive and negative bias wires of the TEC and the two wires of the thermistor were soldered to a D-subminiature connector which was fixed to the back of the previously assembled plexiglas slave laser casing. More wires were then soldered to connect the outside of the casing to the Toptica temperature controller. A BNC cable was attached between the temperature controller and an oscilloscope so that the feedback signal could be visualized. The PID circuit was considered optimized when the time taken to reach equilibrium was minimized, and with the fewest and smallest overshoots. To avoid damaging the diode the temperature was kept within the region 15-50°C

A positive and a negative wire were soldered to the diode and similarly connected to the current controller via D-subminiature connectors. The threshold current of the free-running laser was 176mA and the maximum current the controller could supply was 500mA.

3.3. Setting up the optical table

The final experimental setup is shown in figure 1.

The optical fibre carrying the master light was clamped to the table at a height of 50mm. The output laser beam was collimated using a collimation lens and then fixed. The height of both the master and slave beams were kept at a constant height of 50mm around the optical table to allow for good vertical matching. The slave laser casing was clamped to the table and similarly the beam was collimated using a collimation lens.

The optical table setup required that light exiting from the optical fibre be redirected so that it impacted on the slave laser output. The combined, injected laser light would then need to pass along a different path to be used for further experiments. In addition, light needed to be redirected to both a home-made Fabry Perot interferometer with a finesse of 50 and a wavemeter, so that the modal behaviour and frequency could be observed, respectively.

Light from both the master beam and the slave beam was guided into the Fabry Perot cavity using beam walking. Two mirrors were used for the slave, two for the master. To improve the finesse of the cavity and to mode-match the incident laser beam to the cavity's geometry a lens of focal length 250mm was used with its focus halfway along the Fabry Perot. The Fabry Perot's piezo-actuator was connected to a function generator which produced a sawtooth waveform with a frequency of 20Hz. As it scanned, a photodetector at the output of the interferometer detected the resonant frequencies which formed a trace on an oscilloscope that showed the spectrum of the optical cavity.

The remaining light was coupled to a multimode fibre which was attached to a 'HighFinesse' WS-6 wavemeter. The wavemeter gave a continuous reading of the frequency (with an accuracy limited to 100MHz) during the experiment indicating how the frequency of the slave should be adjusting using temperature and current controllers to achieve injection locking.

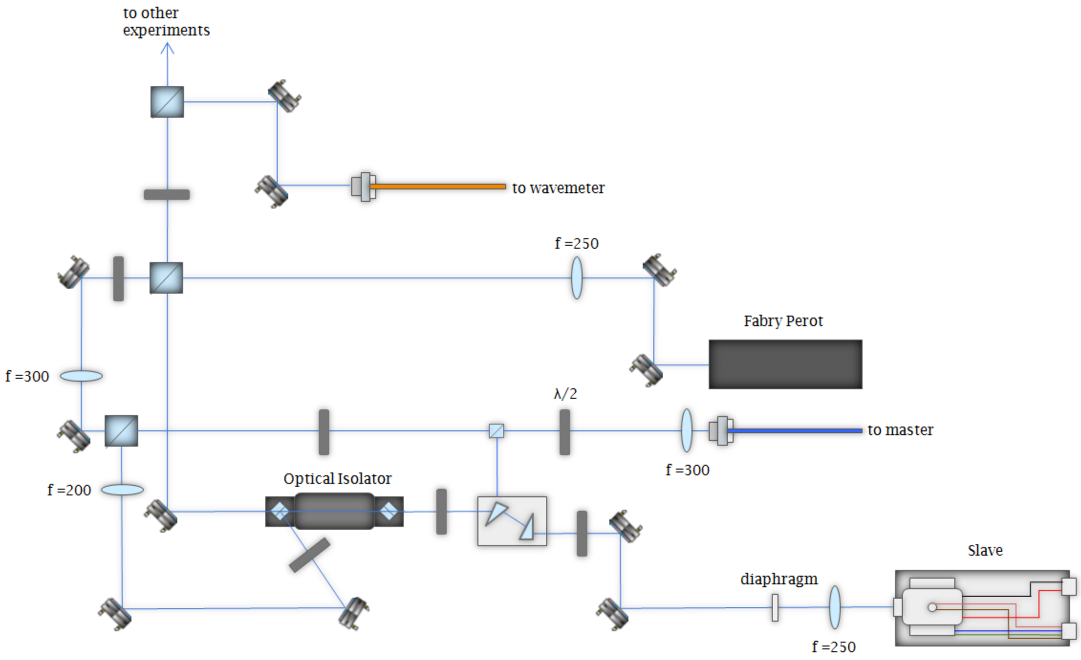

Figure 1. Experimental setup

3.4. *Achieving injection locking*

The slave beam was very broad in the horizontal axis even when collimated, so anamorphic prisms were utilized to reshape the beam to make it match the more circular master beam. In addition, because the prisms are linear optical devices, the master light entering the prisms from the other side was widened to match the size of the slave up to the diode. This allowed good spatial-matching in the entire injection locking region.

The optical isolator had side ports which allowed the passage of master light without it being extinguished. The slave light that passed through the isolator was polarized so that a minimum amount exited the side ports. The optical isolator was set up so that the reflective surfaces of the PBS's within were at 45° to the side ports, meaning that light had to be introduced at an angle of 45°

Results were taken until the beam became too multimodal for the master to lock, even if the shape was changed by removing the prisms. Next, the glass plate within the diode casing was removed and an instant improvement in injection locking was observed. This was because the glass created feedback on the slave diode which competed with the injection locking effect because it increased the gain of the free-running modes of the slave diode. Data was taken up to almost the maximum limit of the current controller. Measurements of the modal behaviour were taken monitoring the Fabry Perot and data of the spectrum was obtained using a spectrum analyzer (HighFinesse LSA). The variation of injection with different seed powers was also recorded.

3.5. Saturated Absorption Spectroscopy

To give a frequency reference of the $(5s^2)^1S_0$ -(5s5p) $^1P_1$ transition a strontium cell was employed. This can be used with locking electronics to stabilize the frequency of a 461nm laser. The strontium cell was heated to 300°C to obtain a high strontium partial pressure. Two counterpropagating beams, the 'probe' and the 'pump' beams, were passed through the cell and superposed. The pump beam has a much higher intensity than the probe and causes 'spectral hole burning' by saturating the intensity at close to resonance. After passing through the cell the probe impacts on a photodiode which allows analysis of the Doppler free absorption spectrum. [11]

To indicate the accuracy of the injection locked frequency of the slave laser, the saturated absorption spectroscopy signal created by the slave beam was observed. If the injection acted on the right frequency, the probe transmission would show an increased intensity near resonance and a local minimum at resonance called a 'Lamb dip' because of the absorption due to the pump beam.

4. Results

A maximum of 60% coupling efficiency through the fibre was achieved. At room temperature the Nichia diode begins lasing at 176mA current and has proportional power as current increases up to the maximum safe power of 1.1W (limited to just over 400mW with new Toptica controller because of current constraints). This means that any of the proportional region would be suitable for attempting injection locking.

It was possible to injection lock the central lobe of the master laser with the slave laser window installed. In the single mode lasing region (176mA to 190mA) injection locking was achievable with a maximum carrying region of 2GHz and a maximum power output of 20mW. In the multimodal region it was possible to achieve injection locking up to 216mA with a power output of 55mW before the Fabry Perot signal became too noisy and large side bands appeared which could not be suppressed.

With the glass on the diode removed, side peaks still developed but the injection signal was much more stable with seed power of 0.5mW. The current was increased up to 480mA giving a power output of 439mW with injection region stable. 178mW of this power exited the optical isolator for use in strontium experiments. The Fabry Perot signals, figure 2, show the modal behaviour of the injection locking as current through the diode was increased.

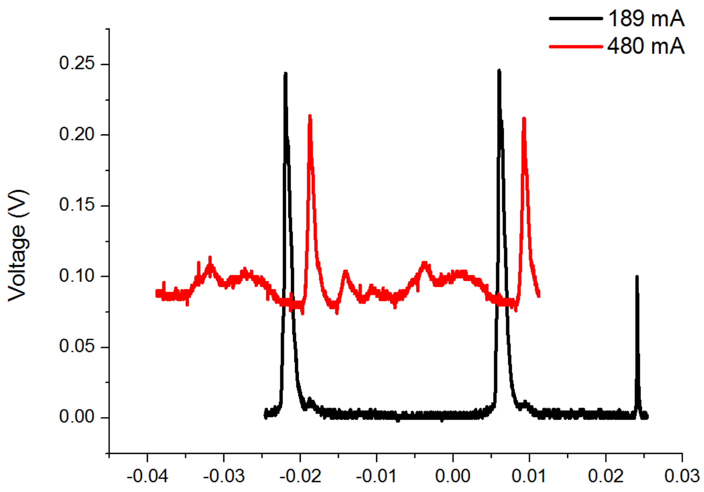

Figure 2. Emission spectrum of Fabry Perot cavity (1.5GHz free spectral range, 50 finesse) for injection locked beams at two different currents with a seed power of 0.5mW

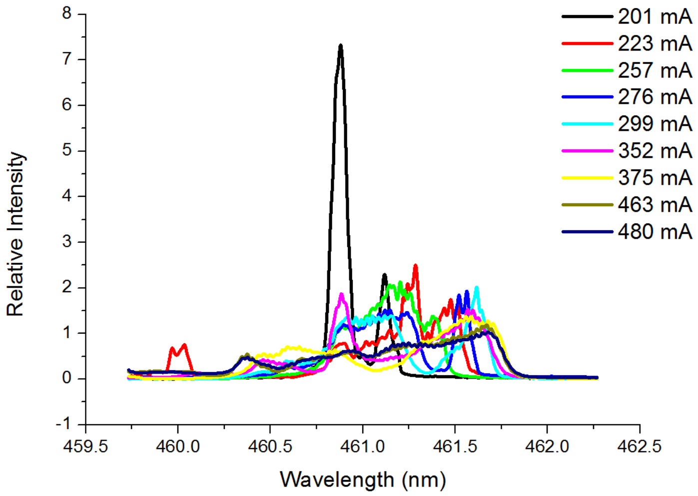

Figure 3. Relative intensity of emission spectrum of free-running diode measured at different currents using a spectrum analyzer.

A Toptica optical spectrum analyzer was used to see the various frequencies of the slave laser and to assess whether injection locking suppressed the unwanted frequencies as well as to see the optimal power to seed the slave laser. The results are shown in figures 3-5. For the vast majority of the current measurements taken, the spectrum exhibits injection locking on the master frequency with unwanted side bands. By increasing the seed power the side bands can be suppressed. This was necessary for using the diode in a strontium experiment.

4.1. Saturated Absorption Spectroscopy

The saturation absorption spectroscopy of a 300°C cell of strontium gave the relative absorption profiles of the probe beam with different seed powers, figure 6. Figure 6 shows the

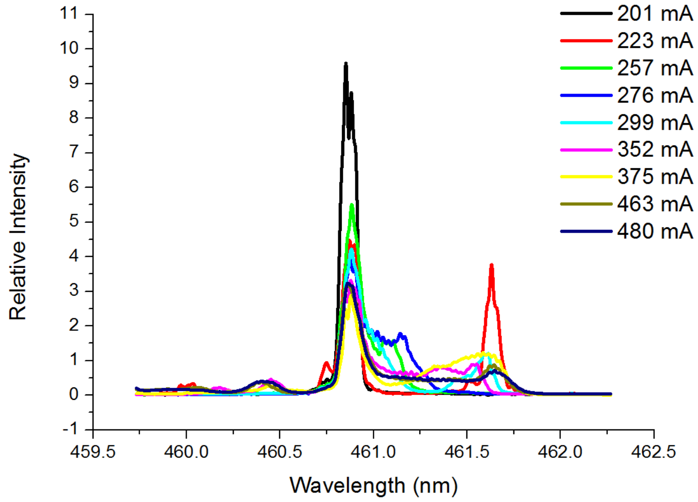

Figure 4. Relative intensity of emission spectrum for injection locked diode measured at different slave currents using a spectrum analyzer.

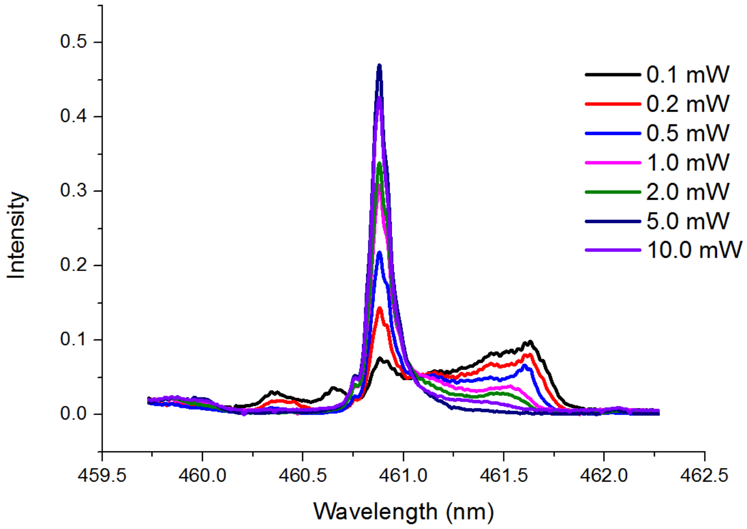

Figure 5. Intensity of spectrum of wavelengths for injection at 477mA, varying injection power. A greater intensity acts on the injection wavelength as seed power increases.

maximum absorption in the cell of the injected beam compared to the master beam is 50%. The transmission profiles of the master and injected slave beams of the probe beam in figure 7 show that the injected beam has higher transmission but both show the Lamb dip.

5. Discussion

5.1. Coupling light to a fibre

Achieving a satisfactory coupling efficiency was a lengthy and time-consuming process. Compared to typical fibre-coupling values, the current efficiency of around 60% can be

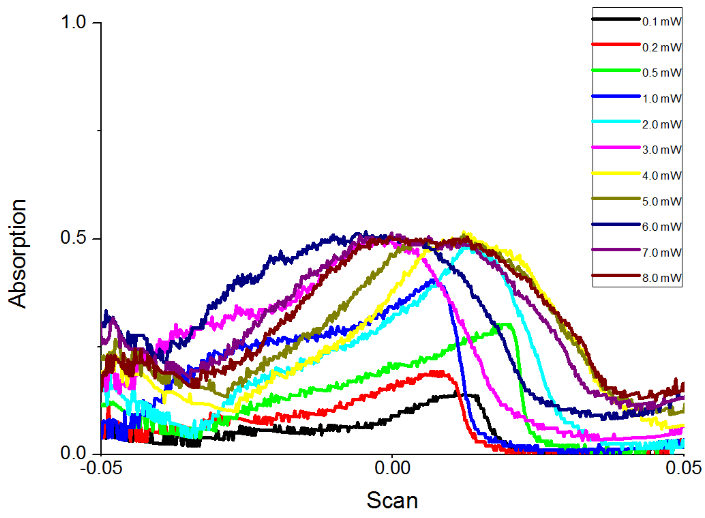

Figure 6. Ratio of injected absorption profile to master profile in a strontium cell, varying injection power

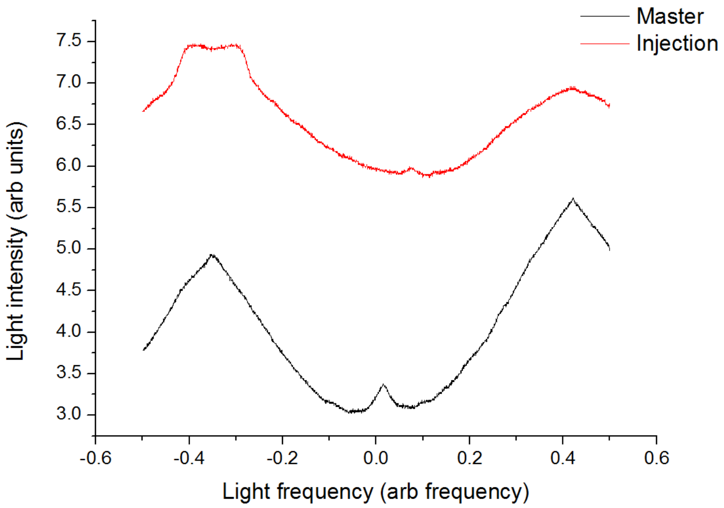

Figure 7. Transmission profile of strontium cell, comparing master and injected beam

improved upon. The efficiency was low due to the following reasons:

(i) The coupling was very sensitive, and disturbing the fibre could easily disrupt the beam. This could be because of the collimation lens or damage to the fibre. This problem was suppressed but not fully resolved by clamping the fibre to the table close to the fibre ends so that it was more rigid and less susceptible to disturbance.

(ii) Polarization entering the fibre was not optimized and this reduced efficiency. Optimization is necessary because the fibre has slow and fast polarization axes. The polarization was optimized by adding a half waveplate and using a Schäfter and Kirchhoff polarization analyzer to generate a Poincaré sphere which visualized the direction of polarization.

(iii) There was flickering in the output beam due to variations in the polarization which disrupted injection locking. This was prevented by using a PBS before and after the fibre to 'clean' the beam with the consequence of slightly reducing the power.

5.2. Frequency Control

There were unexpected problems and unexplained defects with a number of controllers before the Toptica controller was used. It was time-consuming to install each new controller because its behaviour had to be characterized and optimized. However, once the Toptica controller was installed it made the experimental process much easier because it controlled both current and temperature at the same time and it had a visual display which made it much easier to quantitatively characterize the temperature and current regions where injection locking occurred. Both the controllers had 10-point potentiometers incorporated which allowed much finer control than before, making finding and stabilizing injection locking vastly easier.

One difficulty in controlling the frequency was optimizing the PID circuit in the temperature controller. Increasing P increased the settling speed, but if it was set too high it made the system oscillate about the desired value. Increasing I increased the acceleration to the set temperature, but, if it was too high, the phase change became too great. This meant that instead of compensating for oscillations about the desired value, it actually enhanced the oscillations preventing the signal from settling. It took several minutes for the temperature to settle which made it difficult and time-consuming to quantitatively measure whether the PID was being optimized. The optimization was made more difficult because there were three co-dependent variables and each PID circuit was different for each new temperature controller.

5.3. Injection Locking

It was difficult to collimate the slave beam because the laser exhibited astigmatism so that if one orientation was collimated then the other would be divergent. There was no way to resolve this focussing problem using optical equipment in the laboratory. To compromise, the beam was partially collimated in both directions with the aim of keeping the beam as collimated as possible within the locking region.

Anamorphic prisms were utilized to match the shape of the two beams but because the slave was much wider than the master it was not possible to completely match their widths. This could be resolved in the future by using two sets of prism pairs. Initially a lot of power was lost through the anamorphic prisms (up to 75%). This was believed to be because they were not coated for blue light. This problem was later resolved because it was realized that the loss was associated with the polarization of the light entering the prisms. The transmission was more efficient with p-polarized light (parallel to plane of incidence) so a half waveplate was added and the transmission efficiency increased to a maximum of 75%.

The orientation of the PBS's within the optical isolator meant master light had to be sent in at a 45° angle. The result of this was that some of the light would get clipped and distorted if the master beam was too large, negatively affecting injection locking. Making the beam smaller using lenses resolved this issue, and the use of beam-walking maximized the output through the end of the isolator.

The main difficulty in achieving injection locking was matching the spatial profile of the beams in such a way that injection locking would be maintained as the current was varied. This was because as the current increased the slave spatial profile developed multimodal behaviour. Initially, diameters of the central lobes were matched by decreasing the size of the master beam using the telescope effect. A diaphragm was used to cut the side lobes of the slave beam but it was found that this resulted in unwanted diffraction interference. To resolve this, the beams were matched as closely as possible with the diaphragm when closed, and then the diaphragm was opened prior to attempting locking. It was found that the collimation of the central lobe did not match the collimation of the beam overall, i.e. the lobes diverged from one another. Instead of adjusting the collimation lens another lens was added with its focal point at the diode laser's source. A lens of f = 250 mm was used and collimated the central lobe to sufficiently match the master beam.

When the current was increased above the single mode region the frequency signal on the wavemeter displayed high levels of noise and exhibited mode-hopping. This was not ideal as consequently finding the correct frequency for achieving injection locking had to be done 'blind', i.e. by using the characteristic changes in frequency when current and temperature were varied in the single mode region. In the future, continuously monitoring the spectrum using a spectrum analyzer would make it easier to visualize the dominant frequency.

The results obtained indicate much better injection locking with the glass window in the diode removed. At low currents the diode output power is not high enough for the transition and at high currents increasingly more power goes into the unwanted modes. Figure 2 shows that as the current increases, even though the total power output increases, an insufficient amount of power acts on the desired mode. At low current (189mA) the spectrum is single mode whereas at high currents (480mA) the spectrum is broad meaning a majority of power acts on the unwanted region causing a large offset. The spectrum of wavelengths of the free-running slave diode, figure 3, shows that at low current the power concentrates in a few spectral regions and at high current the spectrum is very broad. This is improved when injection locked, figure 4, with low current spectra becoming almost single mode near the master wavelength but still for higher currents there is spreading in the spectra and a peak at around 461.7nm. By increasing the seed power, figure 5, the spectrum is narrowed as the other frequencies are suppressed within GHz of the injection frequency.

5.4. Saturated Absorption Spectroscopy

The results from the strontium cell suggest that the injected beam acting on the master frequency is responsible for the Lamb dip, however, the injected spectrum exhibits a large offset due to a large transmission of light, figure 7. At low injection power the spectrum is broad so more is transmitted, figure 6. As seed power increases, the spectrum concentrates near resonance so that more power is absorbed. As seed power increases, the spectrum peaks at 50% absorbed power indicating that there are non-resonant frequency components responsible for the offset in figure 7. Even though injection power improves the desired frequency within GHz, figure 5, it does not seem to improve within MHz of the correct frequency.

6. Conclusions

It was possible to achieve injection locking with a cheap blue diode laser with a suitable locking range for strontium experiments of 2GHz. By removing the glass plate in the diode it was possible to improve the stability of the injection locking and increase the power of the locked beam to the limits of the current controller, 439mW. Of this power a maximum of 178mW was available for use in strontium experiments. The power lost through other modes was limited by increasing the seed power. It was possible to observe a Lamb dip in the saturated absorption spectrum of the injected beam which indicates some of the injected light acts within MHz of the correct frequency but increasing the seed power did not improve the result. The limited availability of power means that unfortunately, in its current setup, the beam could not be used for the $(5s^2)^1S_0$ -(5s5p) $^1P_1$ transition necessary for trapping strontium atoms in an atomic ring cavity, however, the group at São Carlos are continuing the experiment with the prospect of improving the efficiency of the optical setup; testing the experiment with other cheap diodes; and using the current setup for other strontium-based experiments.

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