

DEVELOPMENTS IN QUANTUM TECHNOLOGY FOR PORTABLE STRONTIUM ATOMIC SYSTEMS

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ABSTRACT

Cold atomic experiments have reached a level of maturity where they are no longer required to be contained in a laboratory environment. This opens up the opportunity to develop portable quantum systems for use in science and industry but there is still a requirement to improve the methodology and technology to decrease the size and/or increase the performance to allow useful deployment in the field. Portable optical clocks are moving towards the prospect of remote frequency comparison where optical fibres links cannot be established [1], and measurements of gravitational redshift utilising the change in clock frequency with height [2]. This thesis focuses on systems utilising neutral strontium, detailing work on a portable strontium lattice clock, compact laser systems and an alternative atom source to current methods for next generation systems.

The clock detailed in the thesis is designed with tophat beams and prisms to generate the 6 orthogonal directions of light for cooling and trapping of atoms; allowing a compact and robust atomic package to be designed. The progress in the experiment from a blue to a red magneto optical trap (MOT) is shown and it is described how the results found affect the future of the experiment. This work also inspired research into future technologies for portable strontium systems. Specifically, lasers of dimensions $77 \times 34 \times 57$ mm (length $\times$ width $\times$ height) were built and used to trap and cool atoms.

These stable and compact lasers offer a low cost alternative to commercial lasers while providing the performance required for the trapping of atoms. Of note is the 461 nm laser that was constructed, producing 40 mW of single frequency light.

The final experimental section covers the novel MOT loading with optically activated, strontium oxide powder that is successfully used as a atomic source for a cold atomic experiment. The source is held within the science chamber and sublimated to a gas with a focused 405 nm emission laser. This allows unique and compact designs be made as the source no longer needs be held and heated outside of the chamber, requiring line of sight from the point of release to capture. The flux released from the source has proven to trap twice as many atoms in the blue MOT compared to a commonly used dispenser, both without pre-cooling. The characterisation and limitation of this source is presented with considerations of how it will be used within an experiment.

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Chapter One

Introduction

1.1 Introduction to time

Time is the fourth dimension with the first three being the orthogonal directions of space. Defining time is difficult thing to do and is a subject of much discussion. A popular definition is “what a clock measures”[3], however this quickly leads into a circular argument when then attempting define a clock. A better understand of time can grasped by examining the first human concept of a unit of time. The day/night cycle, due to the rotation of the Earth, created two events separated by the passage of time which moves an observer from past to future. Our SI unit of time originates from this event based definition; the second being historically defined as $\frac{1}{86400}$ of a day.

Since then the definition of a second has progressed to a more reliable standard which is universal throughout both space and time. In addition, our definition of time has become more precise; allowing an ever greater ability to

resolve and measure event shorter duration due to clocks having the ability to measure the second with a lower level of uncertainty. The ability to measure time allows scheduling to occur, both of events and information with an increased timing resolution allowing smaller time difference to be measured, rapid communication due to time stamping of information, more accurate global navigation satellite system (GNSS) and improved understanding of fundamental physics.

1.2 Principles of a clock and measuring time

A clock is a device that can measure the progression of time and help us know what time it is, i.e the duration between the present and the zero point in time of your choosing. Although a clock as a whole may be hard to define, the fundamental components required to make a clock are easier to understand..

Three components are required, an oscillator, a reference, and a counter. The oscillator is required to change in a periodic manner and its frequency is locked to the reference for the clock. A counter then counts the number of periods that the oscillator undergoes, this may need to be converted in order to be counted. The counter also needs to output the result in a useful way so the time being measured can be understood. To aid this explanation two examples will be given; the simplest being the grandfather pendulum clock. Here the oscillator is a fixed length pendulum which swings under simple harmonic motion (SHM). The frequency of this is determined by gravity,

thus the mass of the Earth acts as our reference. The counter is the clock face which displays a useful output to the user, this required gears and cogs to convert the period of the pendulum into a one second “tick” on the clock face.

Another example is the day/night cycle where the components are less obvious. Here the oscillator is a fixed point on the Earth. The period of this oscillation is determined by the angular moment of the Earth, acting as the reference and determining the duration of the rotation of the Earth. Finally the converter is anything that can observe this rotation and record this event. This could be a state of the art telescope or a human drawing marks on a wall each time the Sun rises. It is clear to see from these examples that there is a range of reliability in these clocks and it is therefore important to characterise the performance of the clock.

1.2.1 Clock specifications

A clock needs to be accurate and measure a second at our current definition of time which is based off the ground state hyperfine transition frequency of caesium-133. This can be measured directly or indirectly if the correct conversion is known. As well as having the correct measurement, we require a low uncertainty on this measurement. Uncertainty determines the range of possible values being measured by the device, this will include the precision of the measurement in addition to errors in the conversion factor. A high output stability, defined as the consistency of results over time, allows a lower

uncertainty to be reached faster as there is less shot to shot correction needed to be compensated for. There also needs to be low sources of instability which can cause longer timescale drift to the measured result, perturbing the frequency and increase the uncertainty over time. Finally, a clock needs to be reproducible so that it can be recreated by others, checked for accuracy and be useful to society. This includes the easy of production of the clock as well as its consistency in performance at different locations and environments. We can apply these terms to help understand why atomic clocks, specifically strontium optical clocks, are a very good candidate for a high performance clock.

1.2.2 Designing a clock

The oscillator in the system is required to have highly stable periodic behaviour to increase the stability, and to be high frequency so the precision is also high. The previous examples of the grandfather clock and day/night cycle are both fairly stable in the short term, however a pendulum will never be frictionless or without external perturbation, and requires external energy to keep moving which will effect the period. The day/night cycle is also not stable over the course of the year due to the tilt of the Earth causing seasons. Choosing the point where the Sun is the highest in the sky will mitigate this partly.

Both of these examples also have a low frequency, although in the case of the grandfather clock this can be increased with a shorter pendulum. A

low frequency means lower measurement precision, analogous to fewer measurement marks on a ruler. Although we can split these periods up, as is done with a sundial for example, this will not have a smaller uncertainty as measuring a shorter period directly would. A better oscillator would be electromagnetic radiation, specifically microwave or optical radiation which will be focused on here. Optical radiation has a frequency ranging from 300 GHz to 3000 THz, and this high frequency means the oscillator is not currently the limiting factor in the uncertainty of our modern optical clocks [4]. This radiation can be induced to be extremely stable which is characterised by the linewidth of the laser. In optical clocks, an optical cavity is used to lock the frequency of the laser to the more stable cavity length using feedback loops. Unfortunately, direct measurement of the frequency of the light locked to the cavity to the precision level required can not be undertaken so a known reference frequency is required to add a secondary lock to the laser, allowing the frequency to be determined.

A potential reference needs to have a low range of possible values and to be consistent over time, otherwise this will limit both the stability and uncertainty of the clock. Additionally, a universally constant reference that is also accessible to many devices will increase the accuracy and reproducibility of the system. This thesis has a focus on portable clocks, thus having a constant reference in space is extremely important otherwise the value will change in different locations ¹ [2]. Another factor that is crucial to a portable

¹Height will effect the clocks frequency which has been observed in strontium clocks

clock is low sensitivity to external perturbation which can be a source of instability for the clock. The previous examples of the grandfather clock and the day/night cycle are also both examples of systems that have poor references and this is why the period of a day is no longer used to define a second. Although both values can be known at one space and time, gravity is not uniform over the surface of the Earth and Earth's angular momentum is changing over time, thus both have a high uncertainty and are not easily reproducible. Atoms provide a better basis for high performance clocks. The electron transitions of these atoms are used, with transitions of high frequency and low linewidth chosen to offer the best reference for the oscillator. This is quantified by the Q (or quality) factor which here is the ratio between the transition's frequency and linewidth. A higher value is more desirable but additionally it has to be able to interact with the chosen oscillator so these parts of the clock can be locked to one another. Although atoms are sensitive to many external factors, such as electromagnetic fields, work can be done to isolate the atoms from these effects. Factors that can not be completely systemically removed can be compensated for numerically, for example the black-body radiation (BBR) emitted from the surroundings of the atoms which perturb the transition frequency being probed. These effects are measured and the user can calculate how the reference is affected. This allows a correction to the measured frequency from theoretical perfect conditions thus allowing others to undertake the same process and achieve the same result.

Lastly, we consider the counter which simply needs to induce as minimal additional uncertainty between measurement of the oscillator and the output. As stated previously, this stage may also involve a conversion to relate the output to the accepted definition for a second. This conversion needs to be known to a high accuracy to ensure a high accuracy clock. The examples being used have potential issues to undertake this procedure. The cogs and gears of a clock may become worn over time or manufacturing tolerances could cause an error on the output. The observer of the day/night cycle may induce an error when determining current rotation of the Earth, for example difficultly measuring when theis at the highest point. Optical clocks use a frequency comb to output a lower microwave frequency so the periods can be counted by electronics. The frequency of optical light is too high to be directly counted due to limitations in current technology but the comb allows a conversion with negligible induced error so the uncertainty is maintained while the precision of the output is reduced. The theoretical frequency is known as well as the perturbations to the measured frequency and these are used to output “ticks” at a known time interval.

Optical clocks are now the best performing clocks that we have available. Their fractional frequency uncertainty is unparalleled and comparison measurements against caesium clocks have shown them to be accurate and provide two to three orders of magnitude less frequency uncertainty. The limiting factor to our uncertainty in measuring time is the Q factor of the transition being used to define the second. To decrease the uncertainty a

redefinition of the second is needed and using an optical transition is a possible candidate for this, a full discussion of this can be found references [5], [6], [7] and the International Bureau of Weights and Measures (BIPM) have published their requirements that are needed to be observed before a redefinition is considered [8]. These focus on laboratory based systems but in order to distribute this time effectively, in addition to optical fibres which are already being successfully used [9], portable clocks will play a key role. Portable systems allow for a holdover low uncertainty clock in locations or situations where fibre or satellite comparisons are unavailable. My work and this thesis focuses on the development of a portable strontium lattice clock and the technology required to reduce the size, weight and power (SWaP) of strontium system.

1.3 Strontium optical clock

For the clock transition to be probed, strontium atoms are required to be held in an optical lattice where the Doppler shift is sufficiently low that the narrow linewidth, doubly forbidden, $5s^2\ ^1S_0 - 5s5p\ ^3P_0$, “clock” transition can be observed. In order to trap the atoms in a lattice they need to be moving sufficiently slow enough to be trapped in the optically induced potential well. Strontium atoms are released as a gas into a vacuum chamber and are trapped in a magneto optical trap utilising laser cooling. This technique used photon scattering to slow atoms by exciting an electronic transition,

transferring the moment of the absorbed photon to the atom. By directing the light counterpropagating to the trajectory of the atom and detuning the frequency to match the Doppler shift caused by velocity, slowing in one direction can be achieved. A cooling transition with a rapidly decaying excited state is selected to allow many photons to be absorbed quickly. When the decay occurs and a photon is released in a random direction and thus over many cycle does not effect the overall slowing of the atom. This technique needs to be allied in all directions, usually in the form of three pairs of counterpropagating, orthogonal beams, allowing slowing of the atoms in every direction, thus cooling and trapping the atoms. To increase the amount of atoms that can be captured by the trap, a quadrupole magnetic field created by a pair of anti-Helmholtz style electromagnetic coils, produces a spatially varying magnetic field which is zero at the trap centre. This induces a Zeeman shift on the atomic transition frequency, allowing single frequency light to be resonant with a range of atomic velocities at different locations in the trap. This has the additional effect of aligning the electron spin axis of the trapped atoms to the magnetic field and circular polarised light is needed to match the handedness of the spin to stimulate the transition. There are many parameters which need to be set to optimise cooling in the MOT including: the intensity of light which affects the scatter rate of the photons, the physical area where the cooling beams overlap which determines the region where light matter interaction can occur to sufficiently slow atoms to capture, the detuning of light from resonance and the gradient of the magnetic field. A

detailed explanation of this technique can be found in chapter 9 of the book Atomic Physics by C. Foot [10].

For strontium, atoms may have been initially slowed using a Zeeman slower to increase the rate at which the atoms are loaded. This is a technique which applies the above method in a single direction over a distance of a few centimetres, increased the number of atoms with a velocity which can then be captured in the MOT. Then, initial trapping is undertaken using blue 461 nm light stimulating the $5s^2\ ^1S_0 - 5s5p\ ^1P_1$ transition, see figure 1.1. Once stimulated these atoms will spontaneously fall into the ground state or indirectly fall into the metastable $^3P_2$ state, where two repump lasers (707 and 679 nm) are used to stimulate the atoms to fall back to the ground state. Due to the blue cooling light being used this is called the “blue” MOT and cools the atoms to below 1 mK temperatures. Due to the finite trapping depth of an optical lattice, further cooling is required for sufficient atoms to fall into the optical dipole trap. A second cooling transition $5s^2\ ^1S_0 - 5s5p\ ^3P_1$ is stimulated using 689 nm light forming a “red” MOT. This process cools the atoms further to approximately 10 μ K where they can be trapped in a high intensity, counter propagating 813 nm beams. This is the “magic wavelength” for strontium where the first order AC Strack shift on the ground and clock states are equal and the transition frequency has no first order perturbation due to the laser intensity [11].

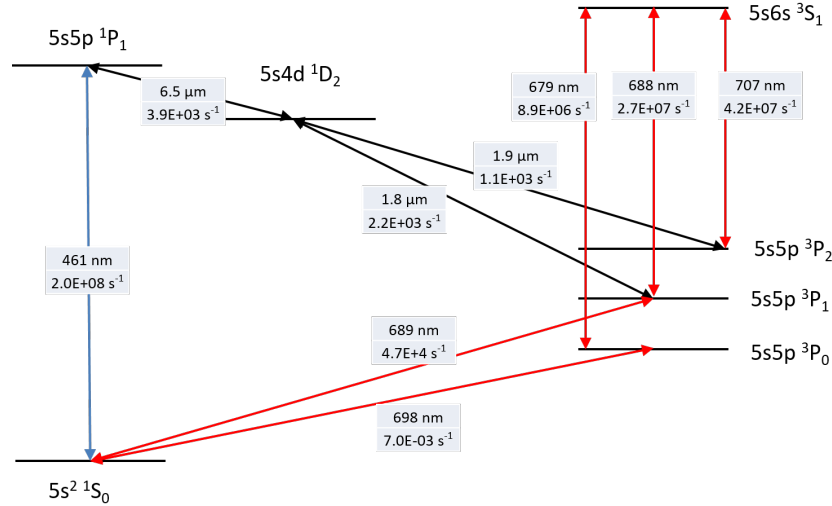


Figure 1.1 The relevant energy levels and transitions in strontium. For each transitions the wavelength (top) and decay rate (bottom) are shown for each transition, these values are taken from references [12][13].

1.3.1 Clock spectroscopy

Once the atoms are held in the optical lattice, spectroscopy of the clock transition can be observed. Due to the long lifetime of the clock state, spectroscopy cannot be undertaken directly and the $^1S_0 - ^1P_1$ “blue transition” is used to determine whether the clock laser is at the correct frequency. This process involves a π pulse stimulating the atoms to transition into the clock state, a 461 nm pulse which acts as a destructive measure of the atoms remaining in the ground state, a pulse from the two repump wavelengths so the atoms return to the ground state and a final destructive measurement. This allows knowledge of if the atoms have successfully transitioned into the clock state and thus if the laser is at the correct frequency. However in order to

precisely set the frequency at the centre of the transition linewidth additional information is required to know how to adjust the frequency appropriately.

To understand how the frequency of the clock laser needs to be adjusted two measurements are required, one either side of the transition centre so the measurements can be compared. This is done by use of an acoustic or electro optical modulator which can accurately shift the frequency by a small amount, moving the frequency away from maximum but still allowing a signal to be detected. Each measurement is destructive and removes the atoms from the trap, thus loading and cooling has to occur each experimental cycle and hence it is critical that this process occurs quickly. At least two measurement cycles are required to make a correction to the frequency of the clock laser so the laser has to be extremely stable to keep the laser frequency constant during these measurements.

1.3.2 Acquiring a frequency reference

Achieving clock spectroscopy achieves a precise knowledge of the the frequency of the clock laser but to achieve a time output from the system requires more work. In order to maintain precision in the laser frequency between clock measurements the laser has to remain stable. To achieve this a second, fast feedback loop is required which is undertaken with a high finesse, ultra low expansion (ULE) glass spacer [14], silicon [15] or similarly suitable materials [16].

Once a stable and precise frequency is acquired, the next procedure is to

gain accurate knowledge of the frequency. The frequency of the laser matches that of frequency of the atomic transition for the atom in the environment it is currently being held which will induce shifts on the transition. The magnitude of this perturbation needs to be characterised and controlled to provide a known, stable frequency output additionally allowing the performance of different clocks to be compared. Knowledge of the atomic energy levels is used to find the frequency of transition in “perfect” conditions where no shifts are induced due to electric or magnetic fields, the atoms are held at absolute zero and there is no systematic shifts caused by the measurement. There are many sources of perturbations to the frequency [17], but only two are described here as they have relevance within this project.

Firstly the black-body radiation from all sources of heat cause the perturbation to the clock frequency, this is usually the largest source. To overcome this, accurate thermal knowledge of the chamber and the surroundings are required in addition to it being kept very stable. Once achieved, the effect can be modelled and an accurate shift calculated. Secondly, background gas collisions of the atoms from the vacuum on atoms trapped within the lattice cause a loss rate of atoms which acts to shift the frequency [18]. Accurate knowledge of the lifetime of the lattice can be used to account for this shift however reduction of the collisions will decrease the required correction and thus likely reduce the error in this correction [19]. This is important as it is not the size of the perturbation that is the limitation to the clock but the uncertainty in the correction. The total effect of the perturbations are calcu-

lated and an uncertainty budget acquired for the frequency shifts occurring to the clock frequency. This shift sets the fractional frequency uncertainty of the clock and sets the limit of the performance of the clock.

1.3.3 Clock measurement

cannot be directly measured as its value is too high to be counted,

Once a frequency output is obtained, it is usual to use a frequency comb to compare the clock to either the cesium standard or another optical clock to determine if the performance is as expected [20]. However, this process compares frequencies and not a clock output and additional steps are required if a user wants to use an optical clock as a stand alone clock reference. This will also require the use of a frequency comb, where one “tooth” of the comb is locked to the clock frequency and the measurable microwave outputs of the clocks are measured and compared to produce the “tick” of the clock [21]. The conversion to lower frequency is known, so it is possible to determine how many ticks of the clock correspond to a 1 second interval, if the clock has previously been well characterised and is kept at controlled conditions. As will all clocks, the total error will increase over time and will need periodic correction to the “correct” time.

1.4 Thesis overview

The reminder of this thesis will explain the practical work that was undertaken during my Ph.D. This work has focused on the development of portable technology for both current and future generations of systems. Although the focus is on strontium lattice clocks, the information presented here can be applied to all strontium based atomic systems for field applications. An outline of each chapter is given below.

1.4.1 Portable strontium optical lattice clock - Mini-Clock

The miniature strontium lattice clock or “MiniClock” project aimed to take the strontium lattice clock techniques and implement it within a portable package. The systems used within this clock are the same as a laboratory based one but each part is reduced in size to fit in a total volume of 180 l with a mass under 100 kg and power consumption less than 400 W [22]. A reduction in stability is expected but purposed SWaP is a large decrease compared other experiments utilising the same technology. After a introduction to the project and the progress of made before I joined, the chapter 2 will discuss the work I undertook on the development of the experimental procedure and the confirmation of the “red” MOT in the system. The optics required to achieve this second stage of cooling are discussed with an initial characterisation of the required parameters.

1.4.2 Portable lasers utilising an interference filter in an ECDL

Chapter 3 describes the building and characterisation of a range of compact lasers with an interference filter within an extended cavity diode laser. These lasers offer stable performance in a small and robust package and are ideal for portable applications. The initial design for these lasers was already developed, and I present the improvements to design I developed. This predominately was improvements to the optical feedback alignment into the diode. Lasers at 4 different wavelengths were built by myself and used within atomic physics experiments. The 461 nm laser built is of note as this laser provides up to 40 mW and was able to successfully trap atoms in a blue MOT.

1.4.3 Optically activated atomic strontium source for portable systems

Developments in a novel atomic source for strontium cold atom systems are discussed in chapter 4. A 405 nm emission laser is used to heat a strontium oxide powder, stimulating the release of a strontium atomic flux which can be captured in a MOT. Here improvements to the reliability of the system are demonstrated, indicating how such a loading technique could be implemented within portable quantum technology. This work was undertaken solely by myself and forms the main experimental chapter of the thesis.

Chapter Two

Portable strontium optical lattice clock - MiniClock

The “MiniClock” experiment aimed to build a portable strontium clock and is a joint project between the University of Birmingham, Defence Science and Technology Lab (dstl) and National Physics Lab (NPL). This aimed to produce an optical frequency standard based on the $^1S_0 - ^3P_0$ “clock” transition in strontium 88 [23], within a target volume of 180 l with a mass under 100 kg and power consumption less than 400 W [22]. The motivation for this project was aimed at achieving a much smaller size strontium optical clock at the sacrifice of stability and uncertainty. The clock would be the first of its kind and be able to be moved without mechanical assistance and achieve a stability of 1×10^{-15} per $\sqrt{\tau}$ at 100 s [24]. The equipment produced here would act as a demonstrator of a land based frequency standard for deployment on transportable platforms in a compact package which could be used by a

knowledgeable operator once the platform is stationary.

The system is split into three subsections; the atomic module, the clock laser module and the control module. These would be built and designed separately with the clock laser module being produced by NPL. The atomic module would house the vacuum chamber, distribution and shaping optics, and some lasers when power constraints meant that a fibre coupled input into the system were not possible. The clock laser consisted of a laser to probe the clock transition and a high finesse ultra low expansion (ULE) spacer cubic cavity to lock the laser [14] and produce an very stable oscillator for the clock. Finally the control and lasers package contains the remaining laser in the system as well as the computer control, another ULE transfer cavity to lock the laser and transfer the stability from the clock laser, and voltage and frequency generation which is distributed throughout the system for control of the clock experiment cycle.

The work in this thesis focuses on the atomic module of the clock. Progress in the characterisation of the science chamber and development in the operation was undertaken to move the experiment towards the final goal of spectroscopy of the clock transition and inform on the design considerations for the system to become portable. This chapter looks at the experimental data taken to progress the experiment from first to second stage cooling and the parameters of the lasers and vacuum chamber needed for successful operation. For easier reference, the relevant energy levels in strontium are again include in this chapter in figure 2.1.

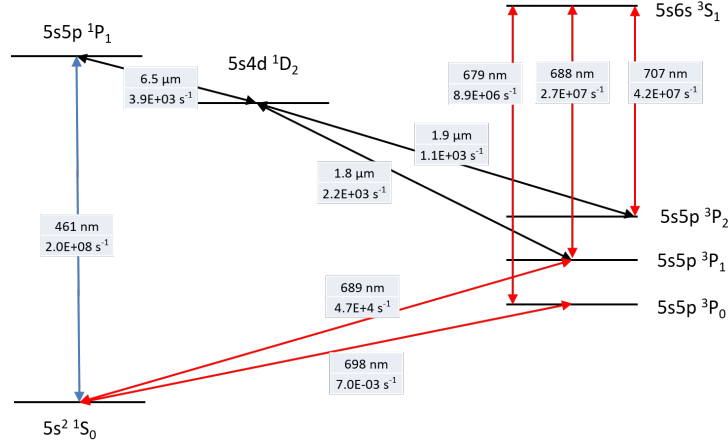


Figure 2.1 The relevant energy levels and transitions in strontium. For each transitions the wavelength (top) and decay rate (bottom) are shown for each transition, these values are taken from references [12][13].

2.1 Science chamber characterisation

The design and building of the science chamber is detailed in references [25], [26] and [27]. When I joined the project the aim was to confirm and characterise the broadband red MOT, and to produce the result reliably with optics similar to those to be used in the final experimental set up to understand the requirements of the lasers to be used in the system. Due to the portable nature of the experiment it is extremely difficult to produce a sufficient amount of 461 nm light to operate the system without the use of large laser systems due to the limited output power of laser diodes at this wavelength. The science chamber consists of four right-angle prism mirrors and an external quarter waveplate and flat mirror to provide the light to

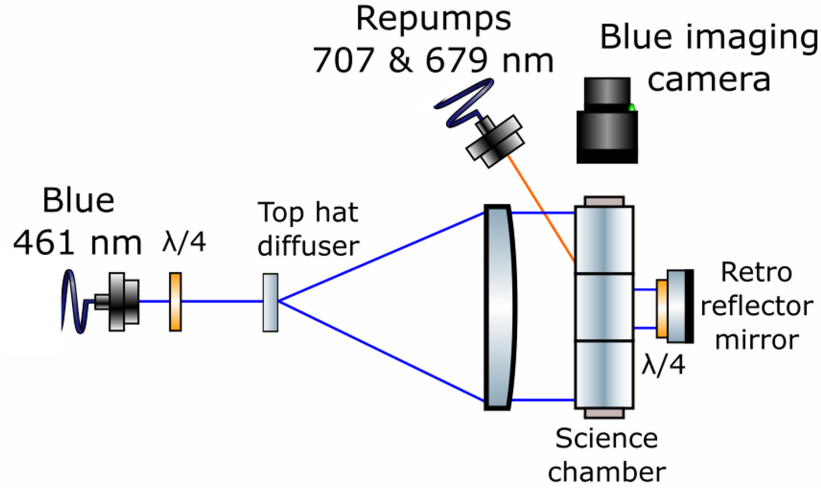


Figure 2.2 The optics required to achieve a blue MOT within the science chamber of the experiment. This view is taken from the side of the system and atoms enter the chamber by propagating in a direction out of the page. Viewports are located on either side of the chamber as well as the top and bottom, these allowing optical assess for the cooling light and for a camera to view the atoms for monitoring purposes. The top and bottom viewports will later be used for optical lattice and clock lasers to enter the chamber. The prisms are mounted inside the science chamber and are shown in figure 2.3.

create a MOT as shown in figure 2.2 and figure 2.3. Although this is a compact and stable way to produce the required beams, this method requires a higher total amount of power than the transitionally used 3 beam MOT which retro-reflectors on each beam due to light not being used in areas between the prisms.

The first stage of trapping in this clock was the blue MOT which captures atoms released from a dispenser. There is no initial slowing of the atoms, usually preformed by a Zeeman slower in strontium system as this allowed the

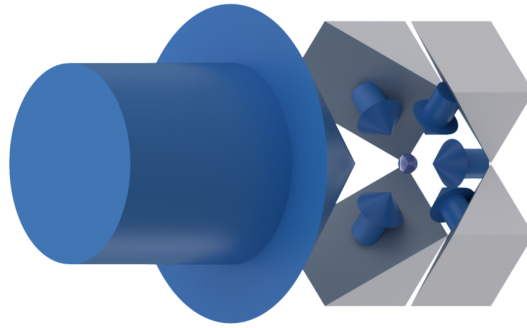


Figure 2.3 The diagram shows the 4 right angle prism mirrors that are mounted within the science chamber. A large, collimated, circularly polarised incoming beam, directed from left to right in the figure, is partially reflected from each prism to generate 4 additional beams crossing at the centre of the chamber. The central part of the incoming beam passes between the prisms and reflects from a mirror, additionally undergoing a double pass through a quarter waveplate. Both mirror and waveplate are mounted externally to the science chamber. The prisms, waveplate and mirror allows the generation of 6 orthogonal beams of light with the correct polarisation in a simple and compact design.

conservation of power and space in the system. This means however that the loading time to reach the required atom number is much longer as there are fewer atoms at the required velocity to be trapped in the system. The aim of this part of the experiment is to reach approximately 1 million trapped atoms at an average temperature of 1 mK or less. These numbers are a common aim of clocks of this type and this goal wants to be achieved as quickly as possible to reduce the down time of the clock in which the clock laser is not probing the transition and correction can be made to correct frequency drift. To compensate for this, there are a few parameters to tune in the MOT, the frequency detuning, magnetic field gradient, capture volume and optical power. The frequency detuning and magnetic field gradient can only be detuned slightly as these need to be set to give the atomic temperature around the 1 mK target which is required to transfer a large percentage of atoms into the second stage of cooling. The capture volume for this design has a set upper limit due to using prisms, however a decrease in the capture volume by reducing the beam size would act to increase the intensity of light for the same input power. Ideally the power would be increased, as the intensity, I , used is far below saturation intensity, I_{sat} , so increasing the power would help to increase the loading rate of the MOT but as stated, this is very difficult to achieve in a portable system. However, it is shown in figure 2.4 that increasing power would have a great affect on increasing the maximum number of trapped atoms. Here the load time is long enough for the trap to saturate at each power.

We can find the relationship between the intensity of the light and the number of atoms, N , by considering the rate of change of atoms in the cloud,

$$\frac{dN}{dt} = R - \frac{N}{\tau} - \beta \int n_{MOT}^2(d, t) d\mathbf{V}, \quad (2.1)$$

where, R is the load rate, N/τ is loss rate due to hot background gases which scale with the number of atoms and a constant loss coefficient τ . The final term is the loss rate due to two body collisions in the MOT characterised by a loss coefficient β and the atom density n_{MOT} , however this loss term negligible compared to losses due to background atoms [28]. Here we are interested in the number of atom at equilibrium N_{eq} , where atom number is maximum, hence,

$$N = N_{eq}, \text{ when } \frac{dN}{dt} = 0. \quad (2.2)$$

This give the following equation which can be written in terms of the cross section area of the trapping region A , the cross section for collisions between background and trapped atoms σ , the capture velocity v_c , and the peak velocity of the thermal distribution on incoming atoms to the trap, v_p .

$$N_{eq} = R\tau = 0.1 \frac{A}{\sigma} \left(\frac{v_c}{v_p} \right)^4 \quad (2.3)$$

In this equation, only v_c has an dependency on I . v_c is defined at the maximum velocity an atom can have prior to trapping and still be captured

in the MOT. To find this we can use the force equation,

$$F = \frac{mv^2}{2d}. \quad (2.4)$$

For this equation, F is the force from the photons being absorbed, m is the mass of the strontium atoms and d is the capture volume, the distance over which a travelling atom is could be resonant with the light [29]. Rearranging this for velocity gives,

$$v_c = \sqrt{\frac{2Fd}{m}}. \quad (2.5)$$

The rate at which photons can transfer momentum, $\hbar k$, to the atoms is dependent on how often electron excitation occurs as there is a finite time for the atom to decay back to the ground state and then a photon be available to cause a further excitation. This is determined by the photon scatter rate R_{sc} which for the steady state of a two energy level cooling scheme is,

$$R_{sc} = \left(\frac{\Gamma}{2}\right) \frac{(I/I_{sat})}{1 + 4(\Delta/\Gamma)^2 + (I/I_{sat})}. \quad (2.6)$$

Here Γ is the decay rate from the excited state and Δ is the detuning of the light from resonance [30]. This gives the relationship between capture velocity and intensity,

$$v_c = \sqrt{\left(\frac{\Gamma \hbar k d}{m}\right) \frac{(I/I_{sat})}{1 + 4(\Delta/\Gamma)^2 + (I/I_{sat})}}. \quad (2.7)$$

Finally this is can be used in equation 2.3 to give the proportionality between atom number and intensity,

$$N_{eq} \propto \left(\frac{(I/I_{sat})}{1 + 4(\Delta/\Gamma)^2 + (I/I_{sat})} \right)^2. \quad (2.8)$$

This is only an approximation, predominately as this applies for a 2 level system whereas for strontium there is other decay paths from the excited state in the first stage of cool. It can however still be a useful tool to characterise the experiment and show that the intensity is limiting the atom number in the blue MOT.

Instead of expanding the blue beam which will come into contact with the prisms using Gaussian optics we employ the use of an engineered diffuser optic from Thorlabs. This creates a tophat beam profile in an diverging beam, forming a circular beam profile with an even power distribution across the beam. This acts to give a even intensity distribution over the area of the beam profile giving even trapping on each side of the MOT. This works to increase the atom number and increase the loading rate. Although there is only 90% transmission for this optic, usually the Gaussian beam has to be expanded much larger than area of the prisms to achieve enough power in the sides of the MOT but this also wastes a lot of power. When the power in the beam is 60 mW, the intensity in the enlarged beam is 4.89 mWcm^{-2} after 10% power loss. This compares to an I_{sat} of 42.5 mWcm^{-2} for the blue strontium transition.

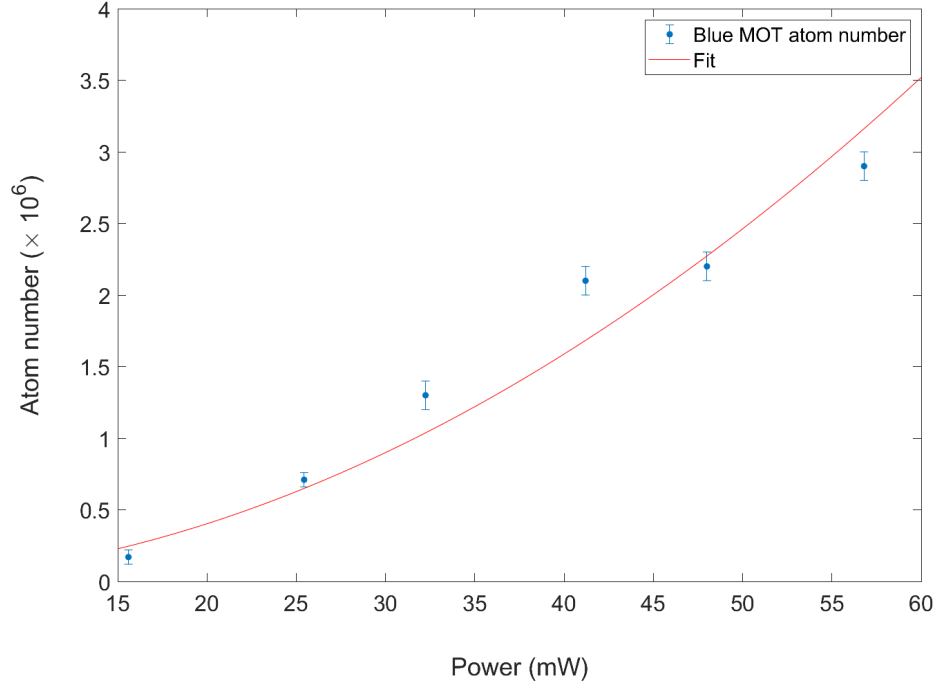


Figure 2.4 The maximum blue MOT atom number in the Mini-Clock system with increasing total power in the beam. Each data point is taken once the atom number in the trap has reach maximum. The added fit using equation 2.8 follows the data with reasonable accuracy indicating that the atom number is limited by the power in the beam. Increasing the power will increase the capture velocity and thus the load rate of trapped atoms as shown in equation 2.7 and 2.3, allowing a sufficient atom number to be reached quicker leading to less time between clock spectroscopy measurements.

The optics for the second stage cooling were incorporated into the setup in addition to the electronics to modulate the frequency of the laser and broaden the laser spectrum to address more atoms, increasing the transfer rate between the blue MOT and broadband red MOT. The frequency of the beam is required to oscillate by 2 MHz to address a wider range of atomic velocities and is set to oscillate over this range of frequencies at a rate of 7 kHz. This is undertaken by modulating the electronic input of an AOM in the beam path of the light by ± 1 MHz, causing the frequency of the first order diffracted beam to sweep over this range. The amplitude of the modulation is controlled by an additional frequency at 7 kHz triangle wave signal to sweep over all frequencies in the range evenly. The beam is tuned to the correct frequency to address the $^1S_0 - ^3P_1$ transition in ^{88}Sr . The wavelength of this light is 689 nm and is in the red region of the visible spectrum, hence the term “red” MOT. The broadening of the laser frequency increases the transfer of atoms from the blue trap as a wider range of velocities will be resonant with the light. This is followed by a reduction of the broadening, cooling the atoms further and allowing their capture in an optical lattice.

Ideally, a top hat diffuser would be also used to expand the red beam with the 2 beams being overlapped and expanded by the same diffuser. This will make the telescope more compact and require less optics. However, it was unknown if a top hat diffuser could be used for a red MOT as this had previously not been tested. It was possible that consistency of the polarisation across the beam would not be good enough effectively capture the atoms.

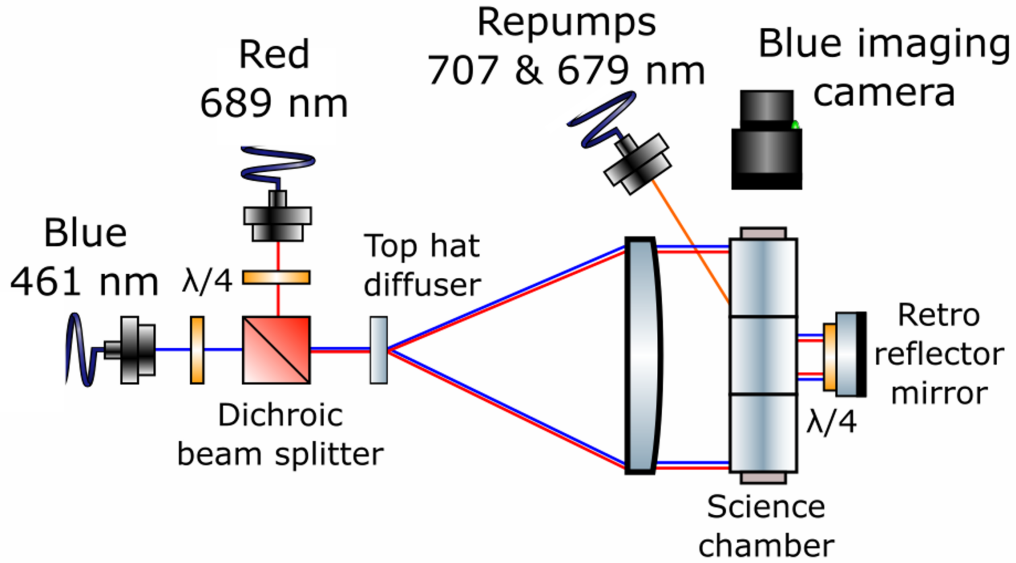


Figure 2.5 The optics required to achieve the red MOT in the MiniClock system. The combination of the beams before the top hat diffuser allows fewer and smaller optics to be used, thus decreasing the overall space required.

For this test, the blue and red beams would expand on different optics and combine on a large dichroic mirror before being collimated by the same lens. This allowed the red MOT to first be confirmed using a lens in the place of the diffuser that would provide the same 20% expansion as seen in the diffuser. This allowed a quick swap between the two optics and using either the lens or diffuser yielded a similar atom number in the red MOT stage. Finally, the system was tested combining the light before a single diffuser and the atom number was maintained. This allowed a more simple and compact optical arrangement as seen in figure 2.5.

Measurements were taken 50 ms after the blue light had been turned off

so it was certain the atoms were being trapped by the red light and not the remnants of the blue MOT. The effect of increasing the power in the red beam was tested as shown in figure 2.6. For the case of the $^1S_0 - ^3P_1$ transition the I_{sat} is only $3 \mu\text{Wcm}^{-2}$ which for the beam size being used would only require a power of 0.03 mW in the beam, however laser frequency is being modulated for the broadband red MOT the power needs to be increased to compensate for this.

The dispenser current is adjusted to test the effect of the atom number in both the blue and red MOTs. Increasing the dispenser current will increase the flux of atoms released into the chamber having the due effect of increasing the number of atoms available for trapping and increasing the number of atoms that could cause collisions with trapped atoms, removing them from the trap. In addition, the dispenser does not contain pure strontium so increasing the current also raises the background pressure in the chamber, again causing more collisions that could remove trapped atoms. The correct current is required to be found where there is high flux without it being too high to remove trapped atoms. Figure 2.7 shows the effect of the MOT numbers with dispenser current.

The lifetime of the red MOT is also important to characterise. This is a measurement of how long the atoms are contained within the trap and is found by taking images of the remaining atoms in the trap over longer periods of time where the atoms are held in the red MOT. An example at 7 A dispenser current is shown in figure 2.8. To extract the lifetime, the

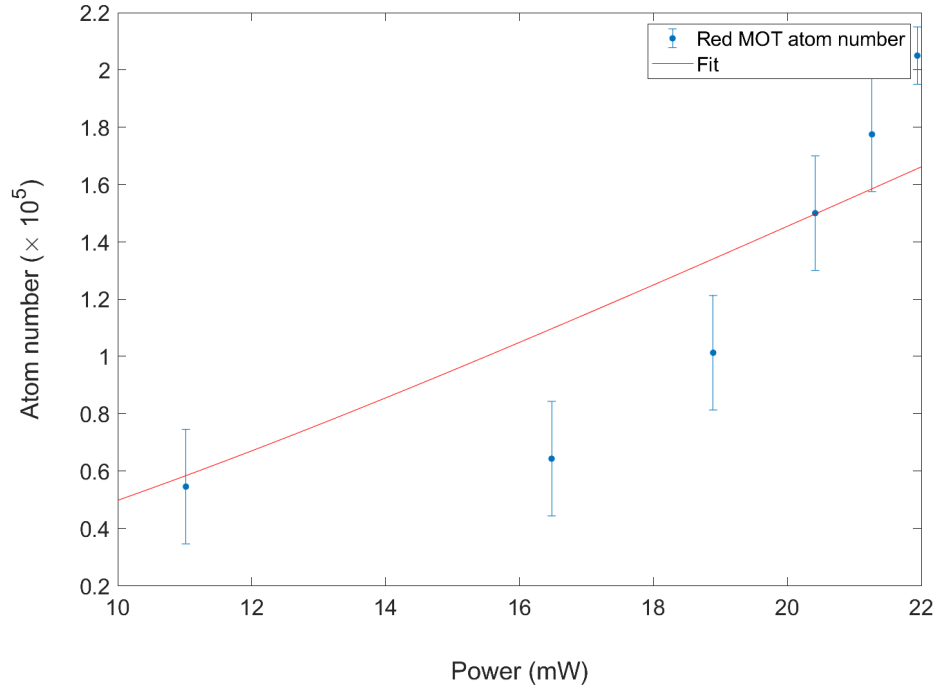


Figure 2.6 The change in red MOT atom number with change in optical power of the beam. The equation 2.8 does not fit the data well for the case of the red MOT. This indicates that although increasing the power will increase the transfer of atoms into the red MOT, power alone is not the limiting factor. It is likely that either the alignment of the beam onto the atoms or polarisation purity over the beam's wavefront is also limiting the ability to trap atoms effectively.

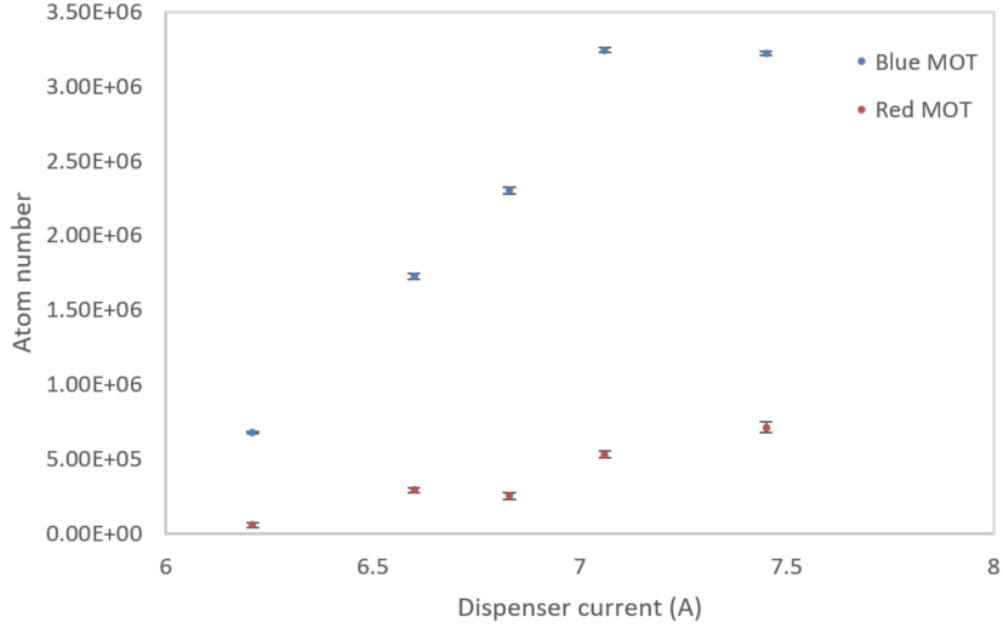


Figure 2.7 Blue MOT and red MOT atom number with changing dispenser current. Both show that atom number increases with increasing dispenser current within this range. The final data point on the blue MOT curve shows no increase, this was due to the camera saturating at the exposure time being used, not due to the atom number no longer increasing. Although this data indicates that increasing the dispenser current further may be desirable for both traps, keeping the current as low as possible while achieving sufficient atom numbers is desirable to reduce loss of trapped atoms due to collision.

exponential decrease in atom number is fitted using equation 2.9.

$$N = N_0 e^{\frac{-t}{\tau}} + N_\infty. \quad (2.9)$$

Here, N is the number of atoms, N_0 is the number of atoms at the beginning of the red MOT stage and N_∞ is the background count which should be close to zero. The lifetime, τ , for the data was found to be 33(3) ms, a value much lower than is desirable. The rapid loss of atoms would mean fewer atoms will remain once attempting to load the optical lattice later in the experimental cycle.

These initial results showed that improvements to the cooling of the atoms was required to increase the lifetime of the atoms in the red MOT to allow time for further cooling and trapping in an optical lattice. Although only relatively few atoms are required in the optical lattice, around 1000, a high density of cold atoms is required to load the lattice effectively. A lifetime of only 33 ms is similar to the time required for each stage of cooling after the blue MOT, a lifetime much longer than the total cooling time is preferential so the atoms can be reduced in temperature without significant atom loss so it can be ensured cold atoms remain trapped and a high density achieved to lose the lattice. It is possible the short lifetime is due to poor cooling of the atoms and the tophat diffuser being used for the 689 nm cooling beam is not ideal for this stage. Although this allowed more atoms to be captured in the blue trap, it is possible the polarisation across the beam not good enough

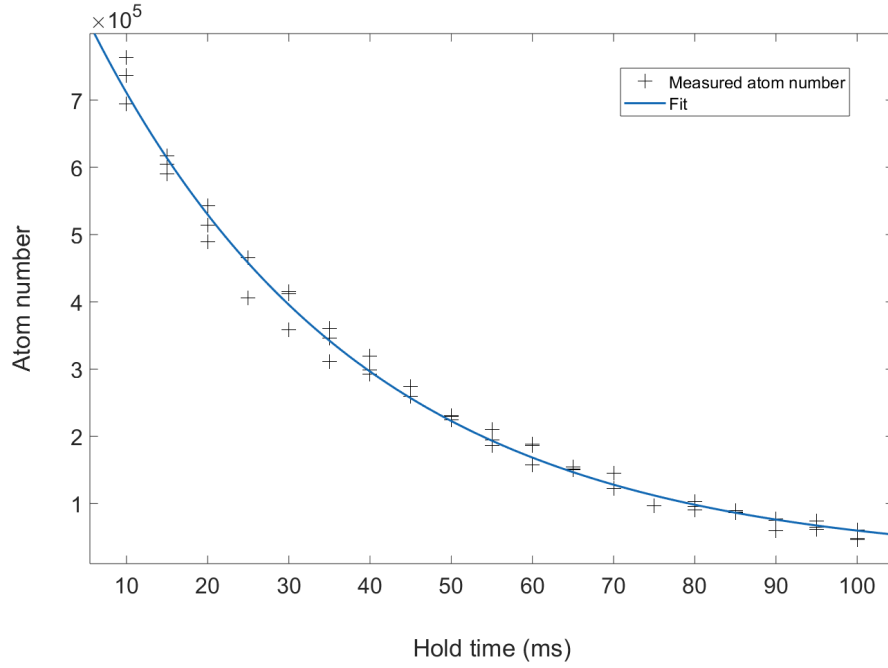


Figure 2.8 A graph of the decay in atom number trapped in the red MOT with longer hold times before measurement. Measurement was taken at 7A supplied to the dispenser and 22 mW in the red MOT beam. This shows the characterising trend for this measurement as equation 2.9 is fitted to the data.

to cool the atoms effectively in the red trap. It was shown in figure 2.6 that power alone was not the limiting factor for the red MOT and other factors were contributing to low atoms number. Another method to improve the lifetime would be to reduce the background gas collisions with trapped atoms. Increasing the pumping speed into the science chamber would decrease the pressure and could lead to a less atoms being lost, this could be achieved with a second ion pump being attached to the system. Finally, an atomic shutter could also contribute to increasing the lifetime. This would act as a physical block to the atomic flux once loading of atoms in the the blue MOT was completed with the purposes of reduce collisions between fast moving atoms released from the dispenser and trapped atoms.

2.2 Improving the tophat diffuser

The tophat diffuser has proven to be very effective for the blue MOT due to the better power distribution exciting the atoms from each side of the MOT compared to a Gaussian beam. It was noted that a lot of power was still wasted where the light would not strike a mirror or a prism in the system and potential improvements could be made. A plus shaped beam would be ideal to match the prisms arrangement but an option could not easily be sourced where the power loss was not greater than would be gained from the improved shape. However, Thorlabs also sold a tophat engineered diffuser that would produce a square shaped beam. If this square is orientated such

that the corners of the square are pointing to the centre of each prism, i.e. the side of the square are at a 45° angle to the prism edges, this would require approximately 20% less beam size and still obtain the light in all the same areas as shown in figure 2.9. As the optic has the same transmission efficiency, the available optical power could be distributed over a smaller area, leading to an increased optical intensity and potential improvement in atomic trapping. This was tested by capturing atoms with both diffusers and comparing the results as shown in figure 2.10. This leads to an increase atom number of 16%, a significant increase when blue MOT atom number and load rate is already limited due to the blue optical power being well below I_{sat} for the transition.

2.3 Conclusion

The work undertaken on the MiniClock was insight to the current technology and methods used to achieve a portable clock using strontium atoms. The results here only cover the experimental progress to the broadband red MOT stage and work has continued on the system since this point. The data taken and shown here gave knowledge that was used while designing the atomic package. The measurements set lower limits on the optical power that was required in the blue and red cooling lasers, meaning these lasers were required to have free space beams upon emission until the atoms. Fibres would allow more flexibility in the design but too much more power be lost in the coupling

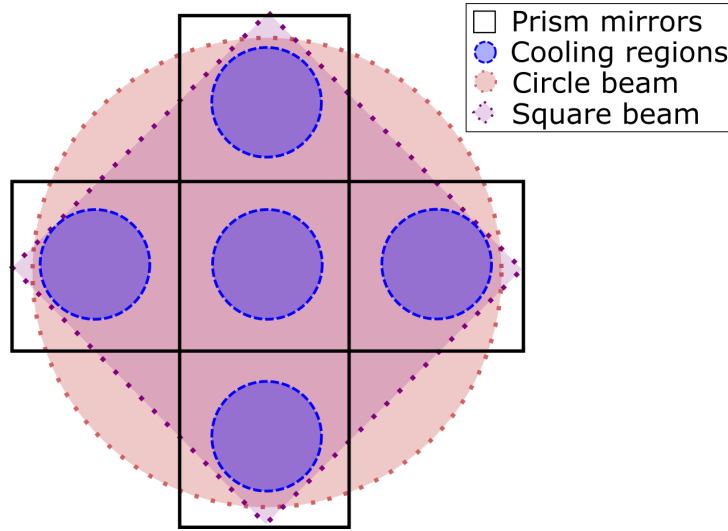


Figure 2.9 The image shows how the use of a square beam shape could allow for a smaller beam to be used. The view is along the line of the cooling beam so the prisms are seen as black squares. The blue circles represents the regions where cooling light will strike the atoms either directly or via reflection and provide the most effective cooling as it is these sections of the beam that overlap at the trap centre. It is then clear by comparing the larger circle and square, the square is smaller while still overlapping the key cooling regions. The square shaped beam would lead a higher intensity of light when the same laser power is being used.

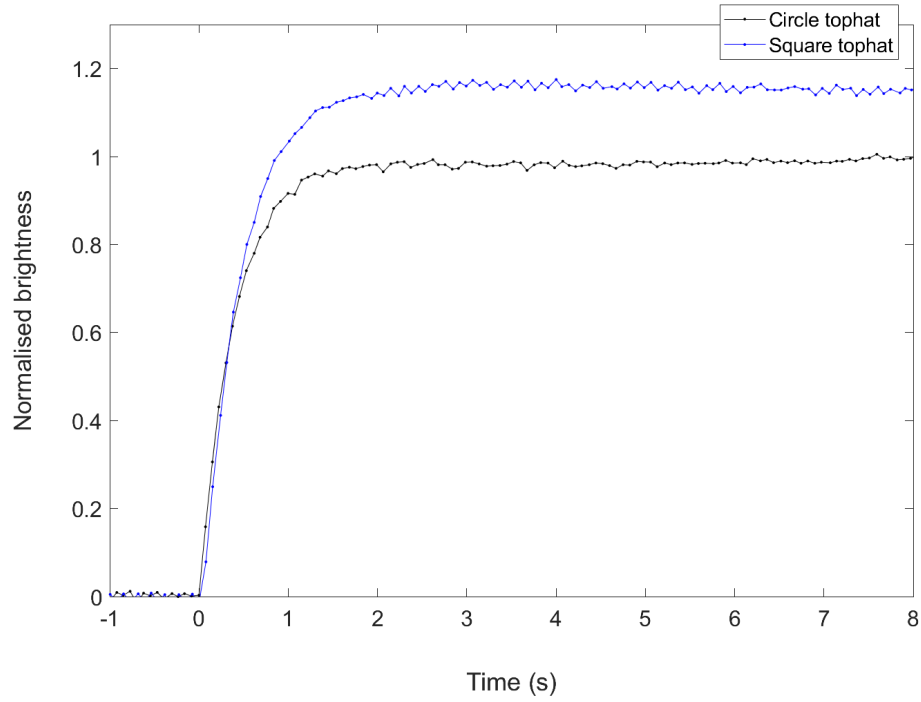


Figure 2.10 A comparison of the atom number captured in a blue MOT using a circle and square tophat diffusers from Thorlabs. Both results were taken on the same science chamber, with the same power in the beam but there is a clear increase in brightness released from the MOT when using a square beam, thus a high number of captured atoms.

process. One area for improvement was the pressure in the science chamber and it was planned to further decrease this with an additional ion pump to allow a longer lifetime of the red MOT in the system.

Additionally, the information gained in this experiment motivated the following two chapters of work which focus on technology for future generations of optical strontium clocks. Two key areas were the lasers and the atomic source, both of which work within the current system but are large in size or do not have ideal performance. These chapters will explain the issues identified and detail the efforts to improve the technology to reduce size and improve performance.

Chapter Three

Portable lasers utilising an interference filter in an ECDL

Optical atomic clocks, as the name implies, utilise light to cool and trap atoms as well as probe the atomic transition which forms the reference of the clock. The light required is produced by lasers which need to be well controlled and reliable to constantly produce the precise frequencies to manipulate atoms contained within a vacuum chamber. Laser light generation and stabilisation is one of the more technically challenging elements of producing an atomic clock and is the focus of this chapter.

Lasers operate using stimulated emission, where optical feedback within a gain medium causes the emission of photons identical to the photons passing the atoms, providing an electron can undergo a transition that would realise an equivalent amount of energy. This can be further amplified by trapping the photons within an optical cavity, creating standing waves thus increasing the

optical power passing through the gain medium stimulating more photons to be emitted. It is possible for stimulated emission to happen in multiple places within the gain medium, called a multimode laser. Additionally, the laser can lase at multiple different frequencies as more than one longitudinal mode can propagate in the cavity depending on the nature of the light entering the gain medium or the cavity that surrounds it. The work in this thesis solely focuses on visible and near infrared light and all utilise semiconductor laser diodes.

When considering portable quantum technology systems such as the strontium clock being developed at the University of Birmingham [31], which require stable, single frequency and compact lasers, the commercially available options are limited. Many companies can provide very high performance lasers however such systems are often very expensive and have high SWaP profiles. More experimental options are starting to become commercially available that use holographic gratings but from our testing have not been as robust and reliable as we would desire. Additionally the availability of frequencies is limited as only a few nanometers of tuning range can be achieved with this technology. Ideally we would be able to produce these lasers ourselves and exactly tune them to specifications required. I have worked on developing an extended cavity diode laser (ECDL), adapting the method first used by X. Baillard (et al.) at the Observatoire de Paris in 2006 [32]. This design uses a bandpass interference filter (IF) for wavelength selection of the light returning to a diode to stimulate the increase of amplification at

this wavelength and allows single frequency operation. The cavity is created with the use of a partially reflective mirror, reflecting around 20 % the light back to the diode and the remaining light is transmitted to form the output of the laser. Wavelength selection of the feedback is achieved by rotating the filter to allow different frequencies of light to transmit through the filter. The interference filter consists of multiple layers of differing refractive index causes destructive interference at the output for wavelengths outside of the bandpass region. Within a range of frequencies only a narrow section of light is transmitted with the rest being reflected as transmission would cause destructive interference. Decreasing the angle between the filter and the beam of light from normal decreases the effective length of the cavity in the filter allowing a shorter wavelength to be transmitted. This effect allows both a narrow range of frequencies to be built up within extended cavity and provides a method to select the stimulated frequency.

The standard design used for ECDLs and the method we will compare to is the Littrow design [33] where a diffraction grating selects the feedback frequency as well as allowing the formation of the extended cavity. The diffraction grating is placed at an angle where the 0th order mode reflects from the grating to form the laser output and the 1st order mode is diffracted back into the diode. Tuning is achieved by rotating the grating to select which frequency is diffracted back into the diode. Rotating the grating has the additional effect of changing the angle of the laser output. This is not the case for the IF ECDL as the output angle is independent of wavelength. This

means tuning the laser is much easier and forms one of the main advantages of this design. The other is the use of a “cat’s eye” retro-reflector in set up which decreases the likelihood of optical misalignment. This simple setup of a lens to focus the beam to a point on the reflective surface drastically increase the passive stability of the setup from mechanical noise as the angle sensitivity of the alignment is decreased. These factors make this laser design an ideal candidate for a tunable and stable laser for use in our system. The use of the cat eye configuration and IF remain as the key advantages within the design presented here; however, improvements are made on the supplementary optics in the cavity and the mounting each component so that the laser produced is compact, stable and easy to assemble and operate.

Figure 3.1 shows the design of the laser developed by X. Billard (2006)[32]. A few limitations have been identified with this design which we wish to improve on. The first is the requirement to change the reflectivity of the mirror to vary the amount of light which is fed back to the diode. The percentage of light returning to the diode may require adjustment during assembly to increase the range of frequencies the laser can be tuned to, or increase the power output if the desired frequency is easily reach. In order to change the reflectivity of the mirror output coupler to accommodate this, the mirror itself is required to be changed. This can be a timely and costly process as optical realignment is required each time the mirror is replaced and mirrors with a range of reflectivity are required. Additionally, having the lens outside of the cavity means the focus of the laser could change when

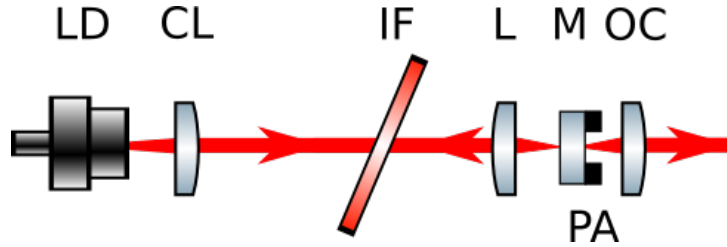


Figure 3.1 The schematic of the first ECDL which used an interference filter within the cavity. Published in 2006 by the Paris Observatory [32] the laser uses an interference filter (IF) for wavelength selection and a cats eye configuration to provide mechanically stable feedback light to the diode (LD). The mirror (M) in the cats eye is partially reflective allowing around 80% of the light to transmit through the mirror to form the output of the laser. The cavity length is controlled by a ring piezoelectric actuator (PA) mounted to the back of the mirror. The other components in the schematic are the collimation lens (CL) and output collimation lens (OC) both used to collimate the diverging beams, and the cat eye lens (L) used to focus the light on the mirror, increasing mechanical stability.

undertaking tuning and optimisation in the cavity as the position of the cat eye lens and mirror move. We also want to develop a stable base for the diode and optics to be mounted in which can provide a temperature control of the diode, a stable cavity length and a platform which allow ease of assembly and use. This design was first presented in Marco Menchetti's thesis, reference [27], but here a more in depth look at the laser is presented on updated version of the laser. The design and the components used within the laser are discussed and how each are used to achieve a stable frequency output.

3.1 Design and Assembly

The main adaptation in our system is the use of wave plates and a polarising beam splitter within the cavity which is formed between the diode and a mirror, as shown in figure 3.2. This allows precise and adaptable control of the amount of light leaving the cavity thus it is easier to optimise power output of the laser at the required frequency without the need for re-assembly. This has an additional benefit that the collimation of the output beam of the laser only depends on the position of a single lens in the system whereas previously all 3 lenses would require adjustment to achieve a collimated output beam. Other designs have used a non-polarising beam splitter [34] which also has this second benefit but again means optics have to be replaced to optimise the system. Replacing the beam splitter may be easier to undertake than replacing the mirror as the cavity alignment will not be affected as much however, the light reflected from the mirror will also be affected by the beam splitter which will cause 16% of power emitted from the diode to leave the cavity on the opposite side to the main output of the laser when a 80:20 beam splitter is used.

There are two configurations that can be used to operate the laser. The first is to use a half-wave plate before the PBS which can be rotated to control the amount of light leaving the cavity of the first pass of the PBS. Alternatively, the diode can be rotated which would allow the reduction in optics in the cavity but this could disturb the precise alignment of the feed-

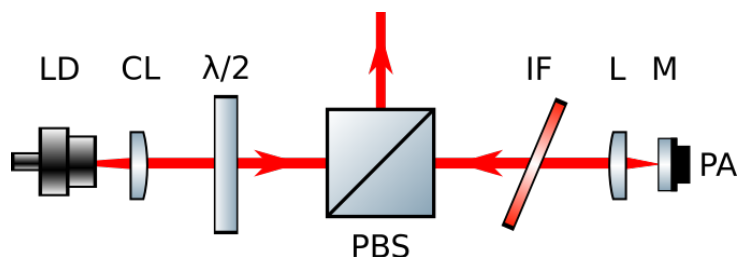


Figure 3.2 The schematic of the laser that has been used in this work. The output of the laser is at the first pass of the polarising beam splitter (PBS) with the amount of light leaving the cavity being controlled by the half wave plate ($\lambda/2$). The light remaining in the cavity passes through the IF which is rotated to control the exact frequency of the light passing through. The reflected light passes again passes through the IF and PBS but there is minimal loss at the PBS as the polarisation is unaffected and the light returns to the diode to cause stimulated emission at the desired frequency.

back or damage the diode which are quite fragile and often costly. As well as the advantages listed above, this allows most of the power to leave the cavity without passing through the IF which has a maximum transmission efficiency of 90% which causes 10% of the power to be lost from the system from reflection from the surface. It is then only the remaining light in the cavity that makes a double pass through the filter before returning to the diode. Although the output is not filtered we have used this design thoroughly and have had no issue in achieving a single frequency output. A worry for this design was the miss match of polarisation leaving and entering the diode, however this appeared to have no adverse effects of the power or frequency stability of the laser output. Alternatively, we can ensure polarisation matching and filtering of the output by using a quarter waveplate (QWP) on the

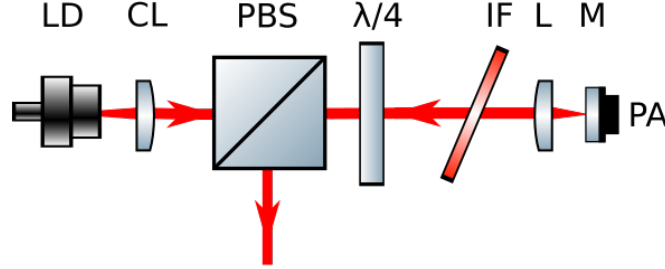


Figure 3.3 The QWP configuration where all light is transmitted through the PBS on the first pass and the percentage of power coupled out of the cavity is set by rotation the QWP.

other side of the PBS, see figure 3.3. The half-waveplate is set so all light is transmitted through the PBS and the double pass of the quarter-waveplate acts as half waveplate to rotate the light to adjust the amount of laser power leaving the cavity. This loses the benefit of the output beam only depending on the position of a single lens but the filtering of the output will ensure there is no remnant of any unwanted internal diode modes. As all optical power travels through multiple optics twice increasing power losses.

The choice between these configurations is mainly dominated by the power requirement of the laser compared to the power that can be supplied by the laser diode. If 5% of the light leaving the diode is required to return into the for feedback, the total losses from each optic would mean 76% out the power would form a useful output for the HWP configuration and 63% with the QWP.

For both designs there needs to be good quality optics to allow efficient

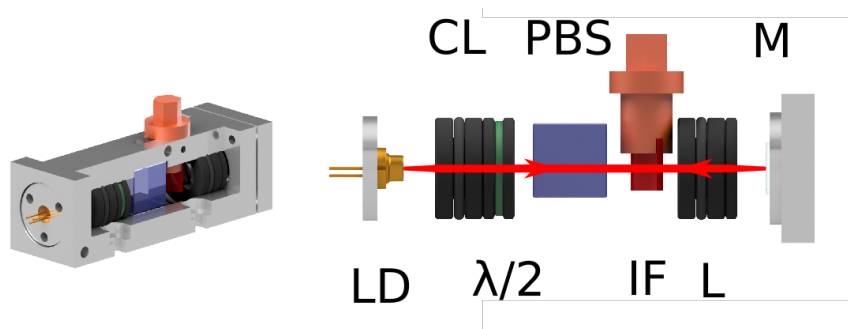


Figure 3.4 A render of the IF ECDL showing both the cavity and a labelled image of each of the optics and the mounts they are supported in.

polarisation rotation and a good extension ratio for the PBS. This helps to reduce the amount of light lost on the second port of the PBS where you desire no light to leave the cavity. However, light could be used for frequency and power monitoring of the laser thus not have as large of a negative impact.

The following section of the thesis gives a more detailed description of the components being used in the system. A render for the cavity which was produced can be seen in figure 3.4, a photograph in figure 3.5 and a drawing in figure 3.6.

3.1.1 Laser diode

A laser diode is a semiconductor device where a driving current converts electrical energy into light. Initially, the diode produces light via spontaneous emission with the electrical energy pumping electrons into higher energy levels which spontaneously fall back down into lower energy levels, releasing

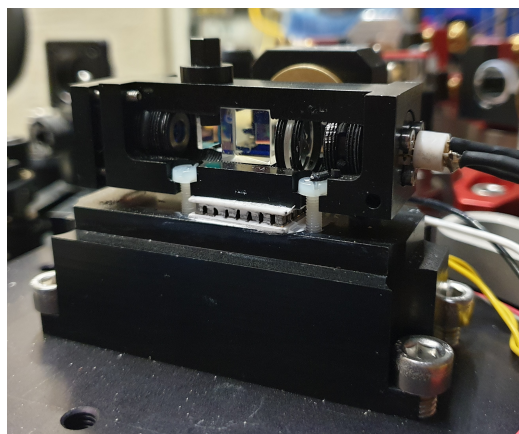


Figure 3.5 A photograph of the IF ECDL

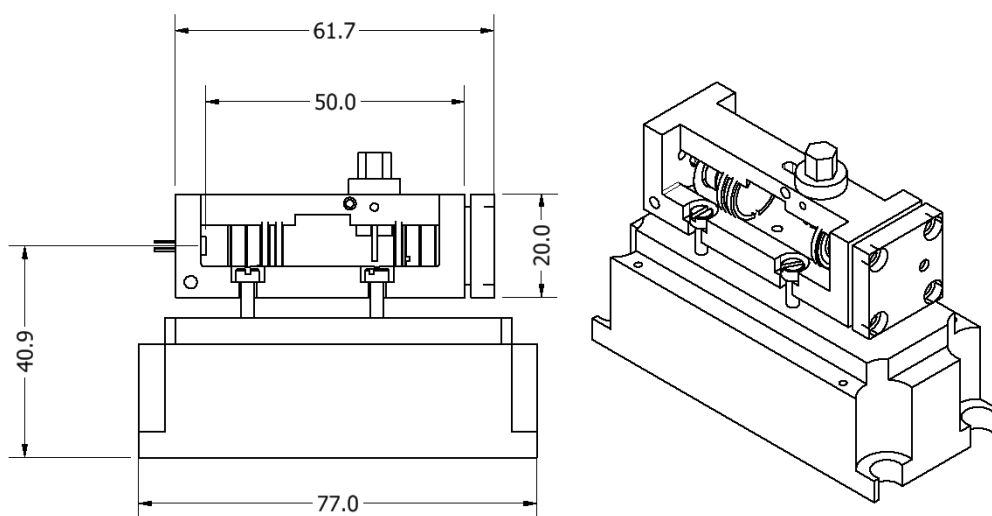


Figure 3.6 A technical drawing of the IF ECDL

light, this is the same process as a light emitting diode (LED). For a laser diode, a cavity is also created around the internal medium which is reflective on one side and partially reflective on the other which forms the laser output. This causes some light to remain in the gain medium of the diode, promoting stimulated emission causing the diode to promote light amplification by stimulated emission of radiation, i.e. to lase. The emitted wavelength of light is determined by the material properties of the gain medium and the length of the cavity inside so manufactured diodes can only produce light over a range of a few nanometers which can be extended to a few tens of nanometers with control of the temperature and the current to the diode, as well as wavelength of the feedback light. In addition one needs to consider if the diode requires an anti-reflection (AR) coating which can reduce the percentage of light reflected from the front facet of the diode into the gain medium. This gives more control of the frequency produced by the external feedback to the diode making it easier to tune the wavelength and produces a cleaner output spectrum. This coating can dramatically increase the cost of the laser diode and may not be required in lower performance lasers.

3.1.2 Collimation lens

The addition of a collimation lens is required to take the divergent light emitted from the diode and collimate the output into a beam. Here an aspheric lens is used which offers the best on-axis performance of the common lens types, as well allowing the collimation of highly divergence light. The

focal length of the lens can be chosen to select the size of collimated beam and it is desirable, as with all the optics in the cavity, to have an AR coating to stop additional standing waves forming between surfaces and creating competing cavities which will affect the optical feedback into the laser.

3.1.3 Polarisation wave plates and polarising beam splitter

Light emitted from the laser diode is linearly polarised and the angle of polarisation can be rotated using a half waveplate or converted to circularly polarised light using a quarter waveplate. This rotation is required in this design to adjust the amount of light leaving the cavity via reflection in a polarising beam splitter (PBS) which will reflect the horizontal and transmit vertical component of the light. If the wave plate is set so more light remains in the cavity, the wavelength of the laser can be tuned further away from the central frequency modes stimulated in the diode without feedback. Once the required frequency is achieved the wave plate can be rotated to increase the power output of the laser, reducing the light remaining in the cavity until only sufficiently above threshold to achieve single frequency output.

3.1.4 Interference Filter

The interference filter is a narrow band pass filter, transmitting only a narrow range of frequencies and reflecting other light. For this laser it is preferable to

have a filter with a transmission full width half maximum (FWHM) of a few tenths of a nanometer. This is in order to suppress competing modes from stimulating in the external cavity which can occur if there is not enough attenuation of the undesired modes created by the internal cavity of the diode. It was found a FWHM of 0.3 nm is sufficient to allow only one longitudinal mode to build in the cavity if the feedback alignment is optimised. Work has been done to get these cavities to work with wider filters [34] or multiple filters [35].

The interference filter works by reflecting light on its inner surfaces, forming constructive interference at the required frequency and destructive at others. The transmission wavelength, λ , can be tuned down from maximum, $\lambda_{\max}$, (achieved when the filter is normal to the laser beam) by rotating the filter which follows,

$$\lambda = \lambda_{\max} \sqrt{1 - \frac{\sin^2 \theta}{n_{\text{eff}}^2}}, \quad (3.1)$$

where θ is the angle of incidence and n_{eff}^2 is the effective index of refraction of the filter.

Ideally the filter would allow 100% transmission at maximum and completely blocks the surrounding frequency space, however at this time, filters with up to a transmission efficiency of 90% are available meaning some light is lost on both passes of the filter. The cost of the filters are comparable to other components, however the filters at the required frequency are usu-

ally not readily available and a costly manufacturing process may be needed. However, this produces many of these filters which are cut to a size of $7 \times 7 \times 1$ mm. These are mounted so they can be rotated and fixed in place once the correct angle is achieved.

3.1.5 Cat's eye retro-reflector

Instead of simply having a mirror at the end of the cavity, a lens and mirror are used in a cat's eye configuration to reduce the alignment sensitivity. Predominately this is done to decrease sensitivity to mechanical noise on the system as it acts to decrease the alignment sensitivity, however it makes achieving optimised feedback much easier as adjustments to the mirror angle affect the beam alignment to a smaller degree. The lens and mirror have to be exactly positioned so the lens is focused on the mirrors surface to achieve the desired effect. Here we used an achromatic lens with a focal length of 7.5 mm. The achromatic lens is not necessary but this lens type offers better performance for a beam that is not centred with the middle of the lens. This can happen within the cavity as the alignment between the diode and collimation lens is subject to machining tolerances and cannot be adjusted by the user. The achromatic lens helps to keep a higher beam quality and the focal length of 7.5 mm was found to ensure alignment was easily achieved and stable. The mirror used is a 7 mm diameter, 2 mm thick and is silver coated. This mirror type offers the best performance for maintaining the light polarisation, reducing losses on the second pass of the PBS. It is mounted on

a piezoelectric actuator which allows control the external cavity length.

3.1.6 Cavity length and temperature control

The filter allows coarse tuning of the output wavelength by selecting which internal diode mode is allowed to amplify in the external cavity. However we also want control of the properties of the external cavity to precisely control the frequency and ensure it remains stable. The interplay between the internal and external cavity determines the frequency within combined extended cavity which gives this type of laser it's name, i.e. extended cavity diode laser (ECDL). Control of the length of the cavity is achieved with the use of a piezoelectric actuator, a device that causes mechanical displacement in response to a voltage over the component. This device is affixed with glue between the cavity and the mirror and allows a displacement of $3.5 \mu\text{m}$ over supply range of 150 V. The length of the cavity is 50 mm meaning the free spectral range (FSR) of the cavity is 3 GHz which would be a FSR of 4.6 pm for the 679 nm laser. This displacement allows the free spectral range to be covered multiple times. This simple device allows precise control of the change cavity length, thus the precise adjustment of frequency of the standing wave within the cavity. Additionally the length of the actuator can be adjusted very quickly, important for fast feedback loops when looking the laser to an external reference.

To control both the temperature of the cavity and of the diode a Peltier device or thermoelectric cooler (TEC) is used to heat and cool the cavity

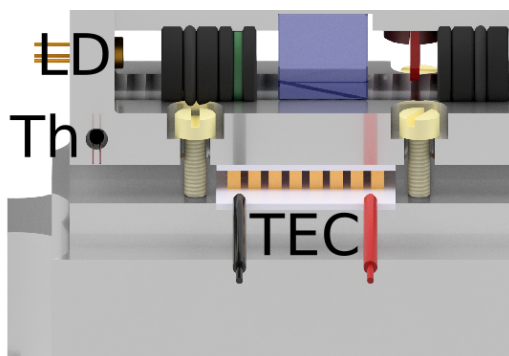


Figure 3.7 The TEC is placed at the centre of the cavity to provide temperature stabilisation to the entire cavity to reduce temperature induced length change which would affect the frequency output. The thermistor (Th) is placed close to the diode to ensure the least temperature fluctuations at this point. Additionally, the diode will produce heat and needs to be cooled, the placement of the thermistor will ensure the diode does not get too hot which can damage the diode.

which is measured by a 10 k Ω thermistor. This approach also allows the stabilisation of the temperature in response to thermal fluctuations. This is very important for the diode as small changes in temperature can cause large shifts to the output frequency but additionally controlling the temperature of the external cavity can reduce thermal expansion in the metallic structure of the cavity. Both work to help stabilise the output frequency of the laser. Figure 3.7 shows the placement of these components within the laser.

3.1.7 Heat shielding and mounting

A heat shield is placed around the cavity to reduce the effect that atmospheric temperature fluctuations have on the frequency of the laser, as shown in

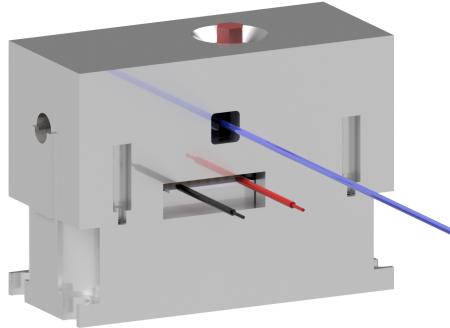


Figure 3.8 The heat shield for the ECDL provides both shielding from external temperature fluctuations and external sources of dirt and dust which could coat the cavity optics.

figure 3.8. The shield attenuates the heat transfer into the cavity allowing more time for the temperature feedback loop to respond to a change. The shield also helps to keep the optics in the cavity free from environmental contamination which could effect the optical beam. An extrusion from the top of the shield allows access to the IF mount thus the filter angle to be adjust while the shield is in place to reducing frequency fluctuation caused by the heat emitted from the hand. Additional layers of shielding could be added to improve the performance but it is expected that this laser will be placed within other assemblies which would have their own shielding. The laser is mounted on a base which acts as a heat sink for the TEC and thermal paste is used to increase thermal conduction between these parts. The height of the base can be modified to choose the height of the laser beam entering the system.

3.1.8 Cavity design and material

Other papers have presented laser schematics utilising the IF within their ECDL [32][35][34], however the design of the cavity holding the optics is not often discussed. As the lasers we wish to produce are for portable application, the desire of this cavity was to be thermally and mechanically stable and have a small form factor. For these reasons a cavity was designed so most of the optical components could be held in a single piece of metal which could be temperature controlled as was discussed in the previous subsection. The design centres around a custom lens tube where the diode is placed from one side with a back plate to hold it in position with the other optics being positioned by accessing the lens tube from the opposite side and a second piece attached to the end where the mirror and piezoelectric actuator are glued to form the extended cavity and provide adjustment to the mirror angle to optimise feedback alignment. A hole in the top of the cavity allows the filter to be held in place and the angle adjusted, a slit in the top of the cavity allows variable control resistance when adjusting the filter angle as this process is very sensitive and a lock screws is used once the filter angle is set. The optics in the cavity are mounted into half inch threaded optics mounts and the position is adjusted by rotating the holder and secured in place using retaining rings. The PBS is slid into the design from the side and can be held in place temporarily with a set screw and later glued to increase mechanical stability. A later design which was not built, placed a 5 mm PBS

within a custom threaded half inch optic holder which could also be screwed into the cavity, additionally making the cavity shorter and less complex. The cavity was designed to be as short as possible so it was easier to control the temperature and would give a longer the free spectral range increasing the spacing between external cavity frequency modes and reducing the likelihood of mode hops occurring during operation.

When the mirror mount is added to the design it is possible that the mirror will be aligned well enough to achieve good feedback to the diode by only adjusting the position of the lens but this was very rare. To allow adjustment to occur a rubber ring was placed between the mirror mount and cavity which would allow a small adjustment of the angle of the mirror by compressing the rubber ring using 4 screws through the plate. This may impair the stability of the laser but the ring is compressed as much as possible to decrease the effect. An alternative design was also produced where a kinematic mirror mount was added to the back of the cavity, figure 3.9. This design was successfully built but was much harder to initially assemble and provided no obvious benefits to ease of alignment or stability.

The material used to produce the cavities was aluminium as it was the most readily available material to use for prototyping the design. The choice material would be mechanically stiff, have a low thermal expansion and high thermal conductivity. Although optimisation of the material was never undertaken, aluminium proved adequate for the task. Unfortunately the cavity was not tested for mechanical, thermal or acoustic stability, however, the

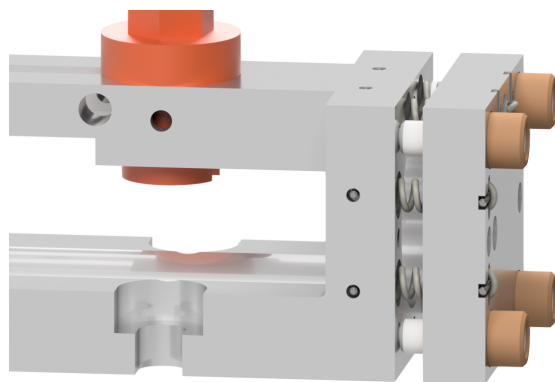


Figure 3.9 A IF ECDL was built using springs and fine adjustments screws to control the angle of the mirror in the cavity. The springs would hold the back plate under tension, pushing against the adjustments screws which could be rotated to control the angles. There were also holes added for lock screws which could secure the angle of the mirror once optimised feedback was achieved.

lasers remained very stable in the laboratory (as will be discussed in the section 3.3 of this chapter) and remained at a stable frequency while the breadboard the lasers were placed on were moved. The base and temperature shield are also made from aluminium however, the filter holder is made from brass to stop galling and allowing a smooth rotation. Steel screws are used throughout the exception of the 4 screws used to secure the cavity to the base where nylon screws are used to reduce thermal conduction between the cavity and the base.

3.1.9 Size, weight and cost

The final size of this laser with heat shield and base is $77 \times 34 \times 57$ mm (length $\times$ width $\times$ height) giving a volume of 0.13 l and the weight is 350 g. If the base is not required and the laser cavity is mounted directly to the breadboard the height is reduced to 30 mm giving a volume of 0.07 l. This is not the limit in size for this laser and it could be reduced further while maintaining a similar setup. Custom optic mounts and a 5 mm PBS would help to reduce the length of the cavity. Thinner structure for the cavity and temperature shield will allow all dimensions to be reduced but possibly at the cost of mechanical and thermal stability.

The low cost of this laser is one of the most desirable characteristics. The cost of the diode has the largest effect on the overall cost. This laser was built with diodes ranging from £1000 to £50 depending on frequency and the presence of an AR coating. The interference filter cost under £300 as stock was available with the required bandwidth and at the right frequency. If stock could not be found it is likely a manufacturing run would be required costing thousands of pounds but producing many filters. The cost of each filter would remain similar but this could increase the price drastically if only one laser needs to be produced. The cavity and mounting were built in house at the University of Birmingham so the cost of this is unknown. The rest of the optics, mounts for the optics and electronics in the package cost under £700 meaning the total cost of the laser is under £2,000. When

comparing this to commercial options with similar performance, this would cost upwards of £7,000 in a much larger form factor.

3.2 Operation and tuning of the laser.

There are four ways to tune the frequency output of this laser once single mode operation has been achieved. The assembly of the laser from its components is more difficult than is found for a Litrow laser, however once built has proven to require little mechanical adjustment for a periods of months to a year with minimal degradation in the lasers performance.

The IF provides initial wavelength tuning by selecting the desired mode within the cavity and suppressing all others. Figure 3.10 demonstrates how the optical spectrum changes at different parts in the laser and how the filter allow single frequency laser emission far from the maximum amplitude internal diode modes.

The initial temperature and current can be set to steer the internal modes towards the required frequency and output the necessary power but once the IF is placed in the cavity it can tune the output frequency over a range of 10-30 nm depending on the characteristics of the diode used. Figure 3.11 shows a 679 nm laser utilising an AR coated diode operation over a range of 13 nm. This range can be extended by adjusting the half waveplate in the design to increase the amount of light send back to the diode for feedback and by adjusting the current and temperature. This was done here to demonstrate

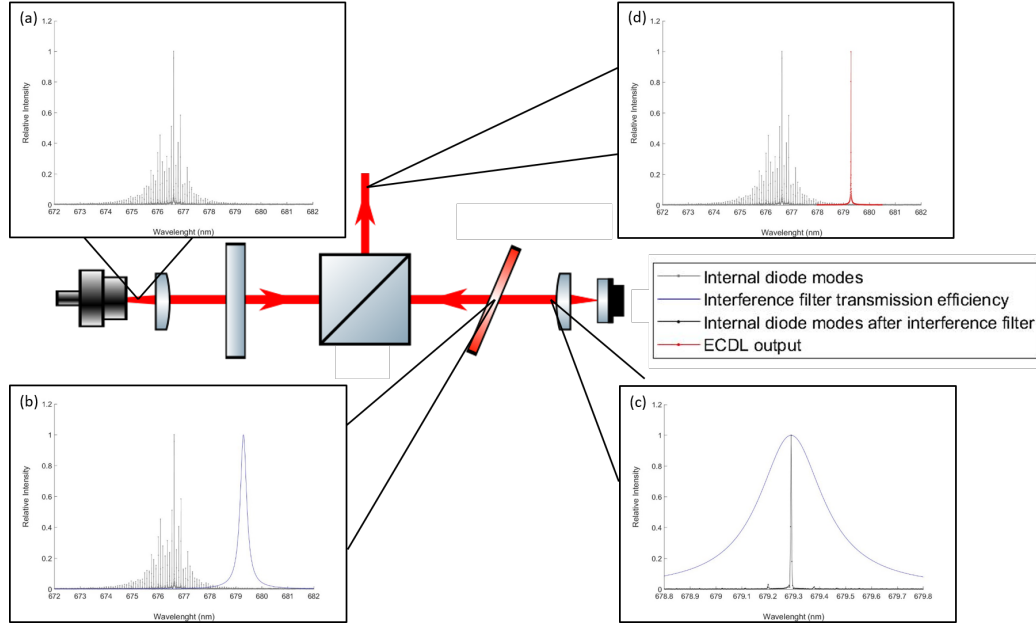


Figure 3.10 This figure shows how the optical spectrum realised from the diode is affected by each component of the ECDL. It should be noted that these graphs were taken in isolation and not within the ECDL and are meant to represent how the diode is stimulated to realise a single frequency which happens almost instantaneously once the diode is switched on. (a) shows the internal modes stimulated in the diode, the spacing of each mode is determined by the FSR within the diode. (b) shows the transmission efficiency for the IF at each frequency and its frequency position in relation to the internal modes. (c) shows the re-normalised transmission of the internal modes after being transmitted through the IF. (d) shows the final output of the laser after the filter has blocked all other internal modes realised from the diode to be suppressed, it also shows the internal modes which will not be present in the final output beam but gives an indication of how the diode has been tuned away from these modes.

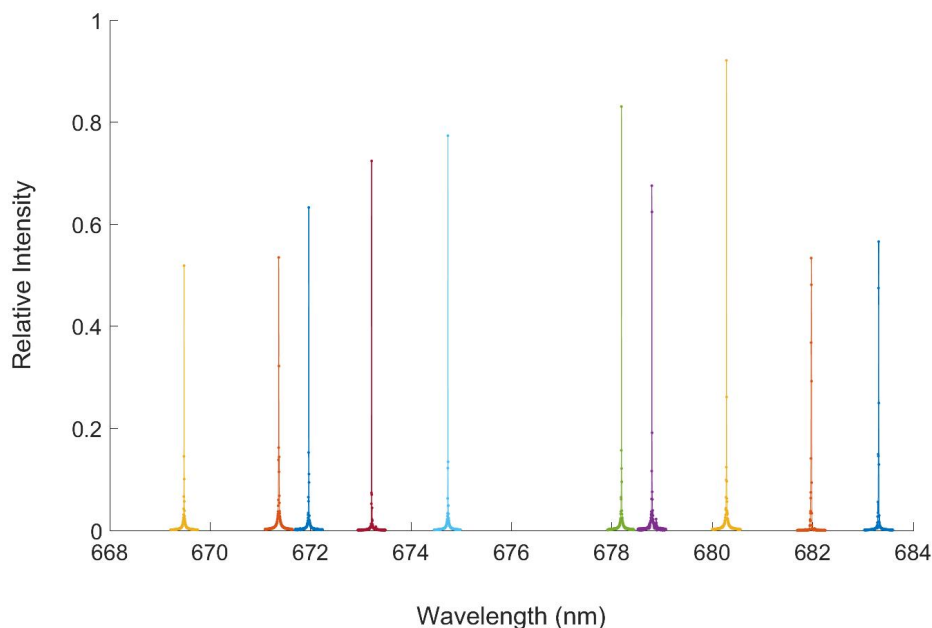


Figure 3.11 A nominally 679 nm laser operating in a wavelength range of 13 nm by adjusting the angle of the filter in the cavity. Each measurement shows the optical spectrum of the laser where the filter has been set at a different angle. This range of wavelengths shows the versatility of the laser, allowing a single diode tuned easily and reliably.

the ease of achieving this wide range of wavelengths by adjusting only a single component.

The frequency of the laser needs to be set to the closest internal mode to the desired frequency. Then tuning is undertaken by adjusting the temperature, current and voltage across the piezoelectric actuator. Examples of how these parameters change the frequency can be seen in figures 3.12, 3.13, 3.14 which were taken using the 679 nm laser. It is usual to only adjust the current and actuator voltage when finding the correct frequency as it can

take a much longer time for the temperature to stabilise in the cavity. The current is initially used to bring the laser close to the correct frequency and adjustments of the voltage allow the most precise frequency tuning. Occasionally the required frequency is not possible to achieve as the frequency lies within the range of a mode hop. A mode hop occurs when a frequency is reached where a different frequency mode is more preferable within the cavity. The likelihood of these occurring can be decreased by simultaneously adjusting both the current and voltage to stay on the same mode in the cavity and increase the range of frequencies that mode can lase at. This is called the mode hop free tuning range (MHFTR). This is set by the FSR of the external cavity when tuning using only the voltage as once the cavity length changes equal to this amount, half a wavelength of distance is added and the standing wave "hops" to lase at preferred wavelength with less or more waves along its length. To increase this, the current is used to adjust the frequency of the internal mode so it is no longer preferable to hop to a different external mode in the cavity. The effect of this can be seen in figure. Figure 3.15, where much longer MHFTR are observed. This can be used in a laser when locking to an external source by adjusting both the voltage and the current simultaneously. This will decrease the likelihood of a mode hop but can also decrease the short-term stability of the laser.

For the laser presented here, the length of the cavity is 50 mm giving a maximum FSR of 3 GHz although the actual FSR will be lower due to the higher refractive index of the optics within the cavity. When tuning only

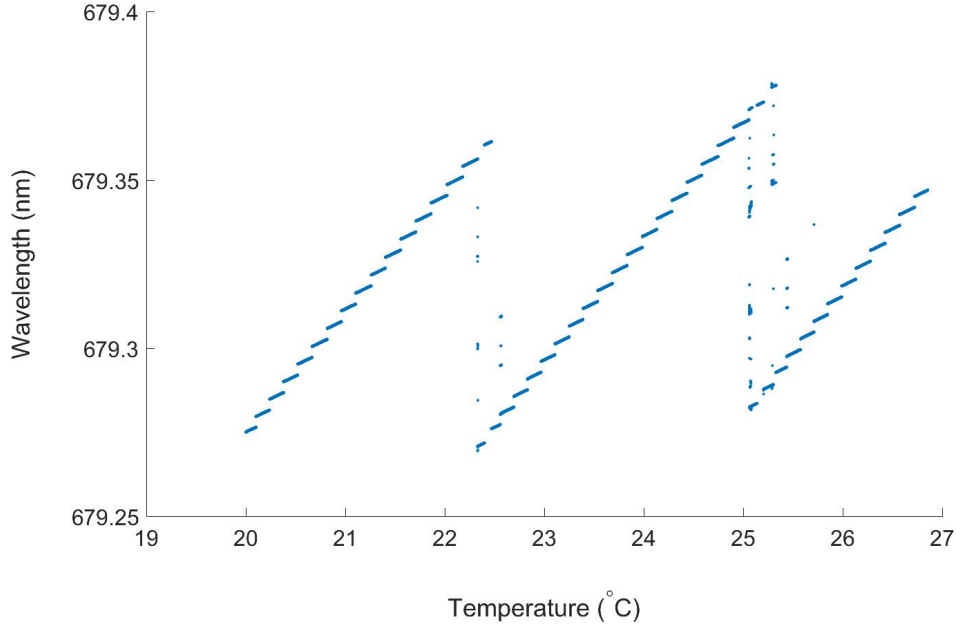


Figure 3.12 An example tuning sweep for the 679 nm laser when adjusting the temperature. The large steps of approximately 1 nm are due to mode hops of the internal modes in the diode. The smaller hops which occur between this large steps are caused when it becomes more energy favourable to laser at a different external mode in the extended cavity.

using the actuator in the 679 nm laser, the wavelength changes by 3.4 pm before a mode hop occurs corresponding to a FSR of 2.2 GHz, at this point the adjacent external mode is preferable. However, by tuning the current we can increase the MHFTR to approximately 14 GHz which acts to adjust the position of the internal diode modes meaning it is no longer preferable to hop to an adjacent external mode. This could be increased further by using an actuator with a longer free stroke.

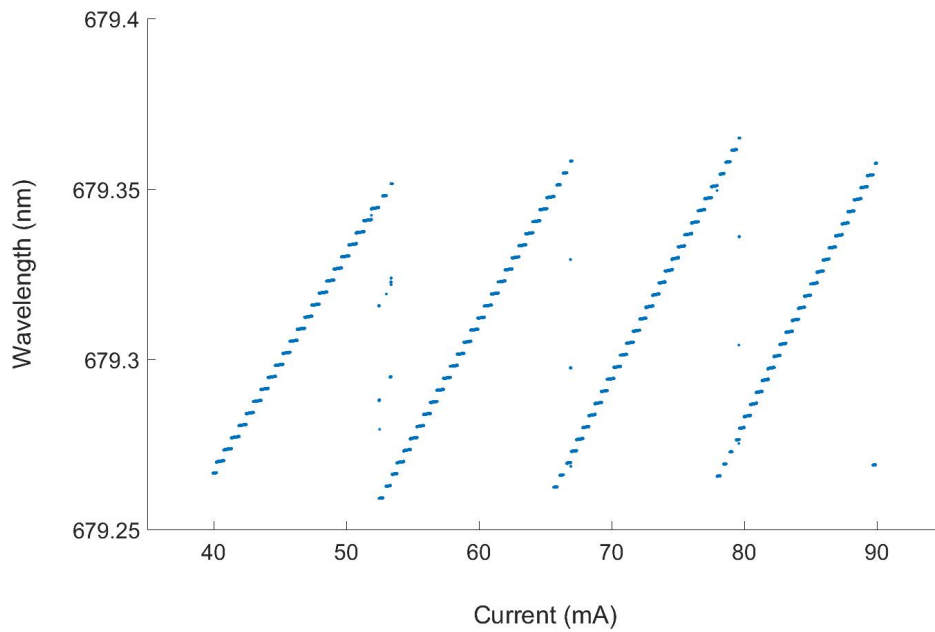


Figure 3.13 An example tuning sweep for the 679 nm laser when adjusting the current. The pattern seen in wavelength mode hops is the same when tuning for tuning the current as was seen for tuning the temperature in figure. 3.12

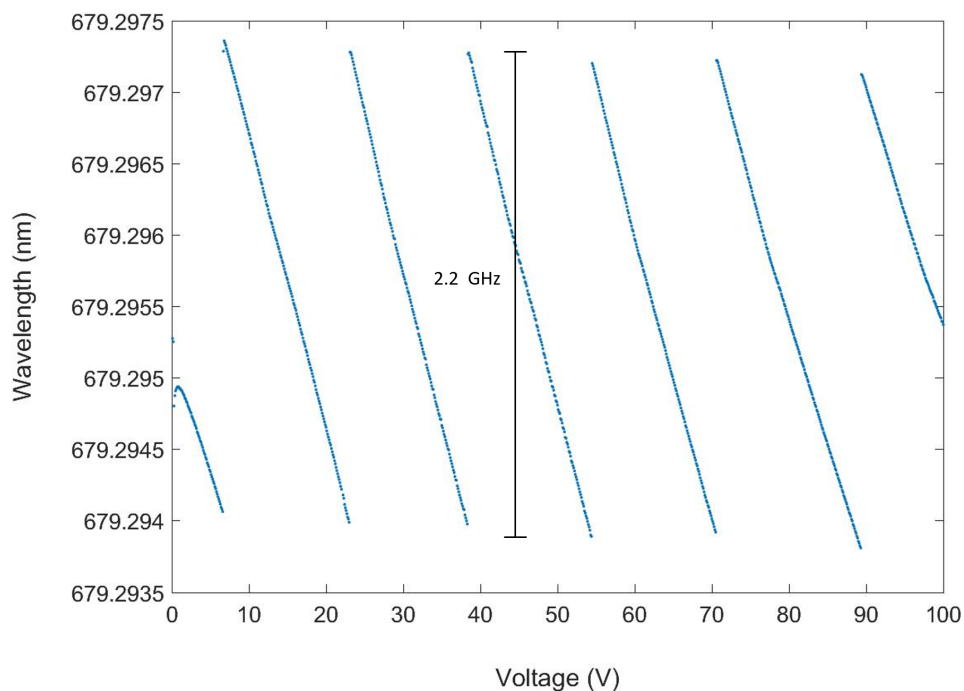


Figure 3.14 An example of how the laser wavelength is affected by sweeping the voltage supplied to the piezoelectric actuator. The voltage is swept through the full range of allowed values from 0 to 100 V and causes the wavelength of the laser to decrease as the voltage increases due to the cavity length of the external cavity reducing. Once the actuator increases by a length equal to half the wavelength this causes the wavelength to “hop” back up to a longer wavelength as this is the preferred mode this the cavity. This gives a MHFTR of 2.2 GHz.

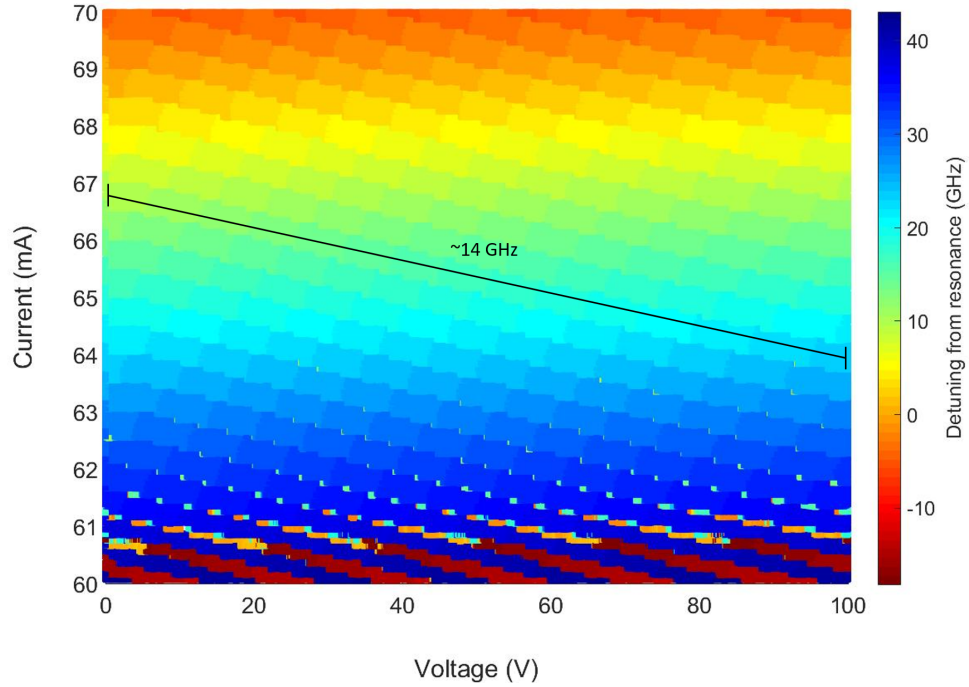


Figure 3.15 An example of how the MHFTR of a laser can be extended by also tuning the laser current and voltage over the piezoelectric actuator at the same time. Here both the diodes internal modes and the external cavity are both being effect so the frequency can be changed without inducing a mode hop. Here the MHFTR is approximately 14 GHz which is limited by the free stroke of the actuator.

3.3 Laser characterisation

Lasers of 5 different wavelengths for use in atomic strontium systems have been produced using iterations of this design. A blue 461 nm laser for the $^1S_0 - ^1P_1$ cooling transition, red 679 and 707 nm lasers used to repump the during this cooling process, and a 813 nm seed laser for tapered amplifier to be used as a lattice laser. This wide range of wavelengths shows the versatility of the design with the main limiting factor being the availability of the interference filters. Off the shelf components are not available at the specifications these filters require. The filter being used have been purchased from MogLabs and LaserOptik who had available stock, however it is likely a custom run is required to produce filters which is quite expensive but many filters are produced meaning the cost of each filter is quite low.

The diodes being used for these lasers are generally the most costly element of the laser. For the 679, 707 and 813 nm, AR coated diodes purchased from Sacher are used and another 707 nm laser is produced used a non-AR coated laser for Thorlabs. These red and near infra-red lasers were the easiest to produce. The 813 nm laser was produced to be later used in the MiniClock system as a seed laser for a tapered amplifier. Here very little power was required to be feed back to the diode in order to reach a stable frequency output and a range of 30 nm of frequency range could be achieved by adjusting the angle of the filter, which was provided by MOGLabs. As with all these lasers, they would require external locking, likely from a high

finesse cavity [36] but the better the passive stability the lower the requirement is on the locking system. The laser undergoing a mode hop could also cause a problem for the locking system if the frequency jump goes outside of the locking capture range. The likelihood of a mode hop can be reduced by incorporating a feed forward system where the current supplied to the laser and voltage across the piezoelectric actuator are adjusted simultaneously but this can often act to decrease the short term stability of the laser. Therefore it is beneficial for the laser not to undergo mode hops while free running, indicating it will remain locked for longer during operation. The stability of the 813 nm laser can be seen in figure 3.16.

The 679 nm and 707 nm lasers using AR coated diodes were also fairly simple to produce and the examples shown in the previous section were taken using the 679 nm laser. Both of these lasers could utilise the same model of filter purchased from LASEROPTIK. This is particularly useful within a strontium system where 4 lasers are required within this frequency range and opens up the possibility of a single filter manufacturing run producing filters which work for many lasers. The 707 nm laser was successfully used for the course of a year while being locked to a high finesse wavemeter without any mechanical re-optimisation of the cavity required. Although these lasers were never tested for their mechanical and thermal stability under stress, this is a good indication that this laser could be suitable for portable applications. It should be noted that the basis of the design has been thoroughly tested for mechanical stability and been presented in reference [37]. The passive

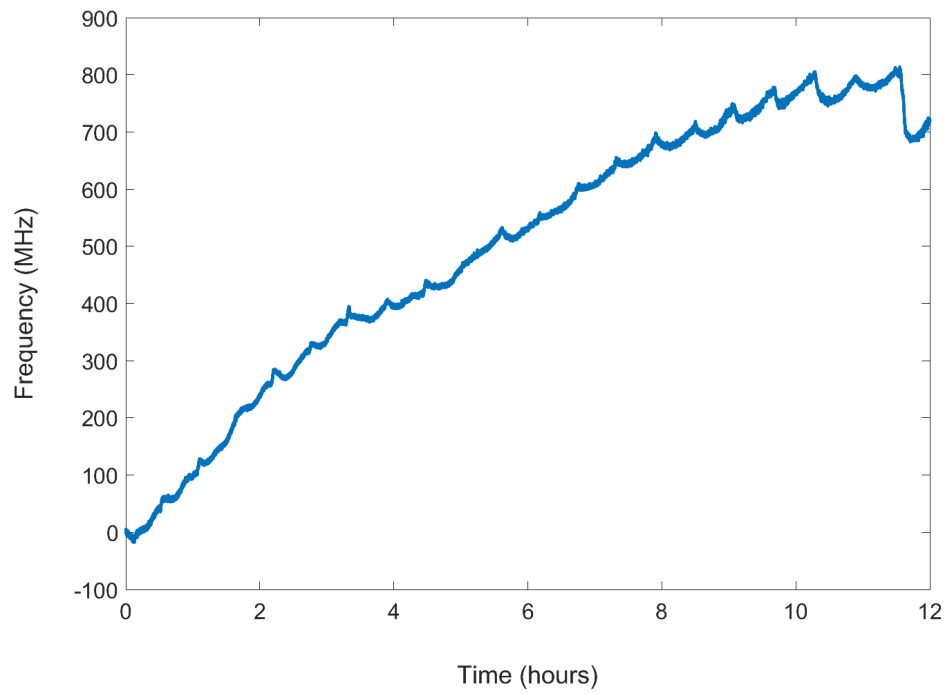


Figure 3.16 The stability of the lattice laser is shown for 12 hours. Over this period there is a slow drift in frequency and the laser did not mode hop.

stability of the 679 nm and 707 nm are shown in figure 3.17 and 3.19.

The 679 nm repump was the most reliable laser and possessed the best passive stability of the IF ECDLs that were built. This was predominately due to the desired frequency for the laser being close to the frequency at which the diode would lase without feedback, in addition to more time being spent to optimise the performance of this laser than for others. For this reason this laser was for the figures shown throughout section 3.2 and will also be used to compare the IF ECDLs to a commercial system. Figure 3.18 shows how the stability compares to a Toptica TA pro laser which operates at 689 nm. This is a much larger, laboratory based system but allows an assessment of the IF ECDL's performance compared to a professionally produced ECDL.

Another 707 nm laser was produced using a diode from Thorlabs which did not have an AR coating. The diode is usually the most expensive part of the laser and for a laser that does not require a narrow linewidth, such as these repump lasers, we wanted to understand the effect of using a lower cost diode within this design. The spectrum of the AR coated diode will look similar to that of the 679 nm diode shown in figure 3.20, but the spectrum for the Thorlabs diode is quite different, see figure. 3.21, as multiple frequency modes are allowed to form within the cavity. Despite this loss of power away from the central mode, there is still sufficient power within this mode to saturate the transition in a strontium MOT. Only a small amount of power, < 1 mW, is required in the 707 nm repump beam so by simply increasing the power in the beam the MOT atom number can reach the same value.

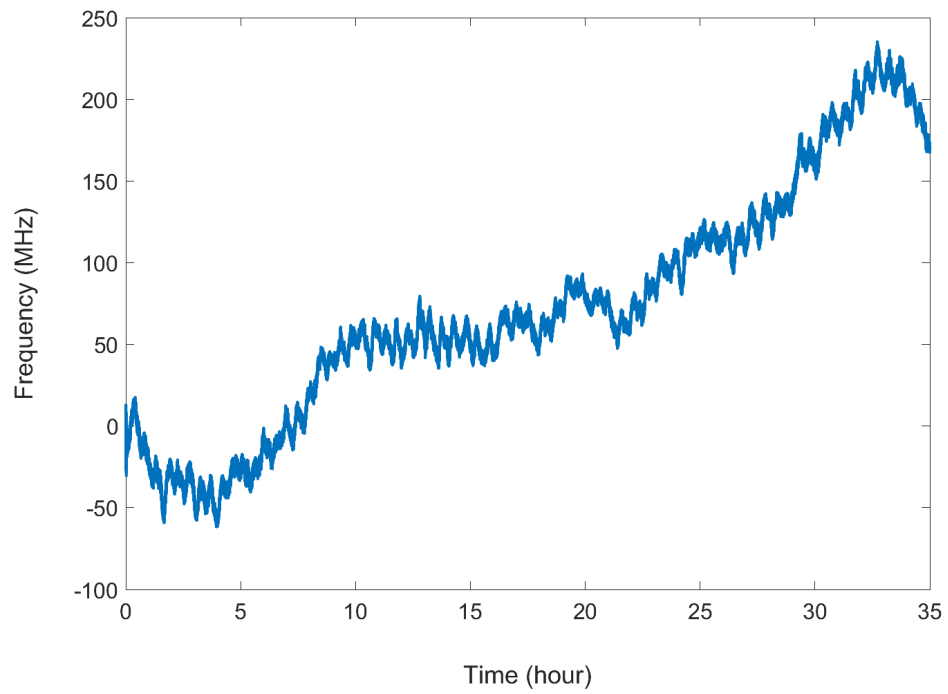


Figure 3.17 The stability of the 679 nm laser over 35 hours. This showed much better stability than the lattice laser in figure 3.16 and there are no mode hops over 35 hours.

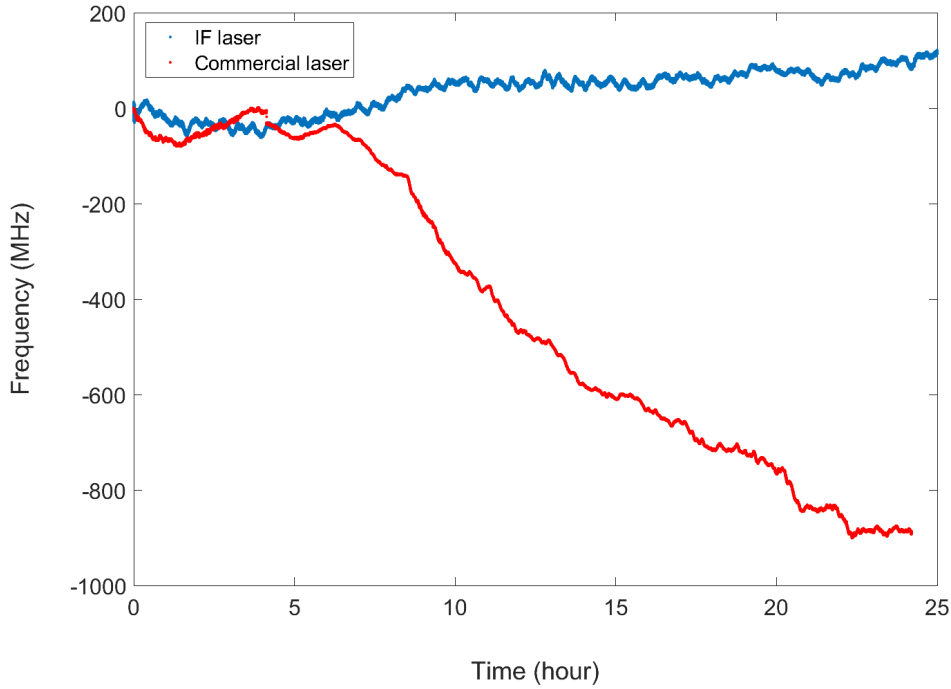


Figure 3.18 The graph shows a comparison of the stability of a IF ECDL and a commercial laser. This shows the lasers that have been built in this project have a comparable passive stability to professionally built systems and in this case much has a better stability, likely due to the thermal stabilisation of the cavity length. This indicates the IF lasers could be used to replace currently existing laboratory based lasers and is initial proof they could be used in portable systems.

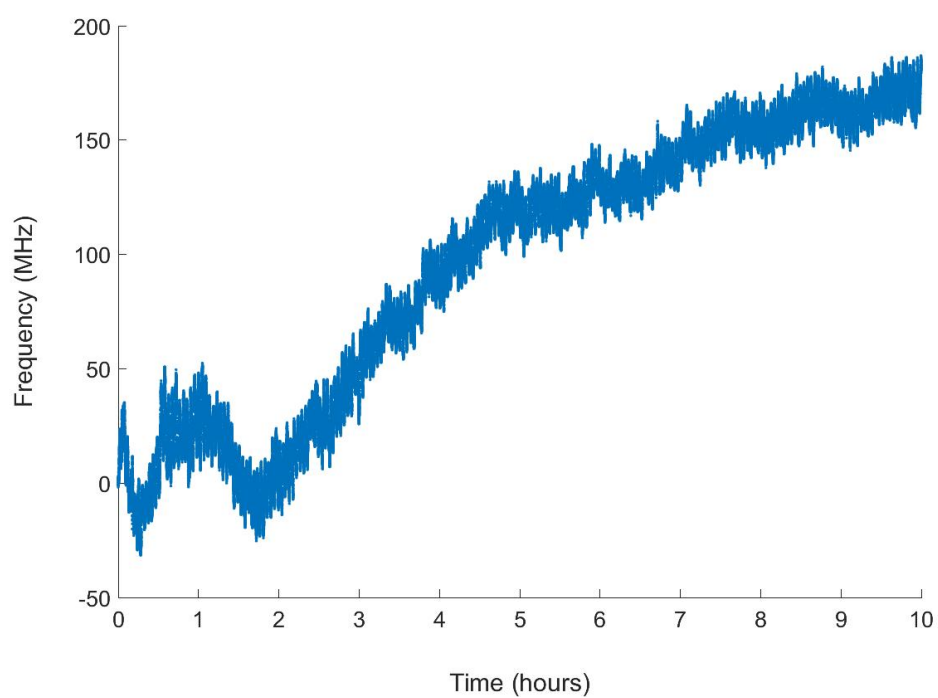


Figure 3.19 The stability of the anti reflection coated 707 nm diode laser over 35 hours. This laser had lower short term stability than the 679 nm laser however still had good long term stability.

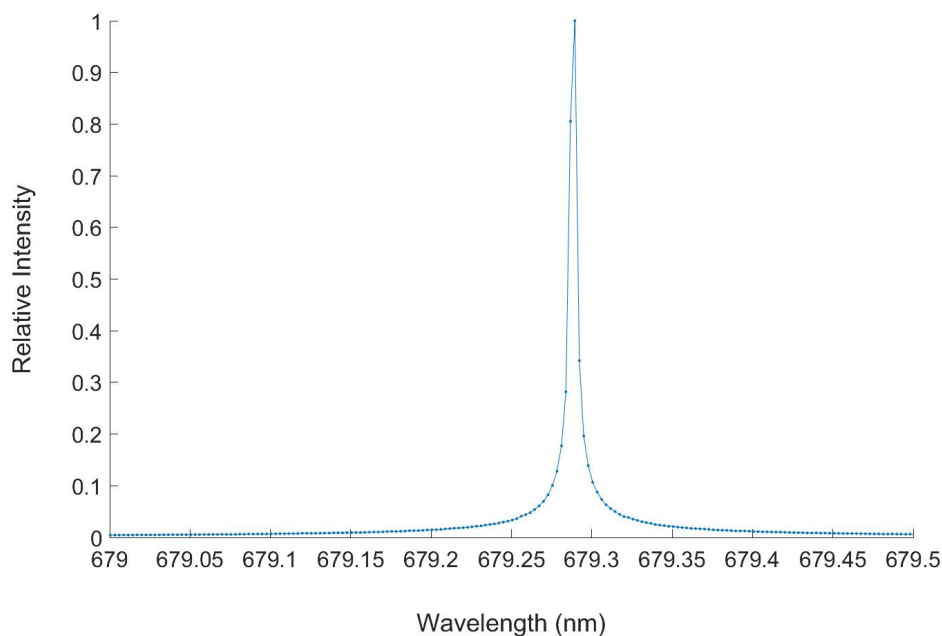


Figure 3.20 The optical spectrum of the 679 nm laser. This shown a clean single frequency peak where all other competing modes in the cavity have been fully suppressed.

5 mW was used within our system which allowed saturation intensity to be reached over a frequency range of 100 MHz which allowed the laser to operate without external locking for the period of hours without manual correction. The stability of this laser is compared to the stability with an AR coated laser and can be seen in figure 3.22

Only in recent years diodes have started to become available at a frequency usable for the strontium $^1S_0 - ^1P_1$ making it possible to produced ECDLs for this frequency instead of using bulk second harmonic generation systems. This new technology using gallium nitrate provide an excellent op-

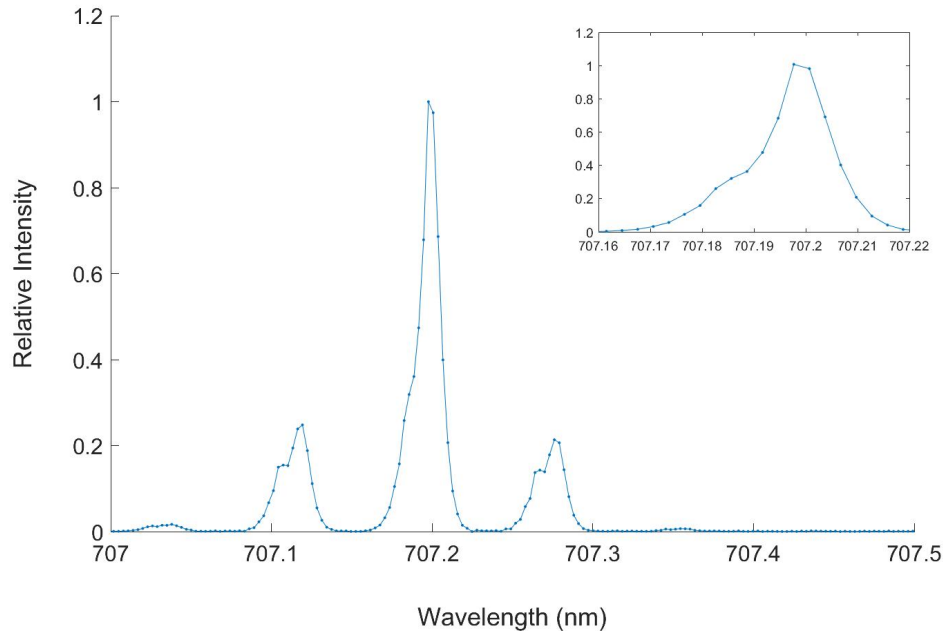


Figure 3.21 The 707 nm laser optical spectrum is shown to have multiple peaks. This is due to the power suppression of adjacent external modes to the desired laser frequency occurring due to the lack of an AR coating on the diode. Normally, a single standing wave of light would form between the back facet of the diode and the mirror in the external cavity, but for diode without an AR coating the presence of a surface where reflection is not suppressed makes it easier for competing modes to also build in the cavity which can be seen here.

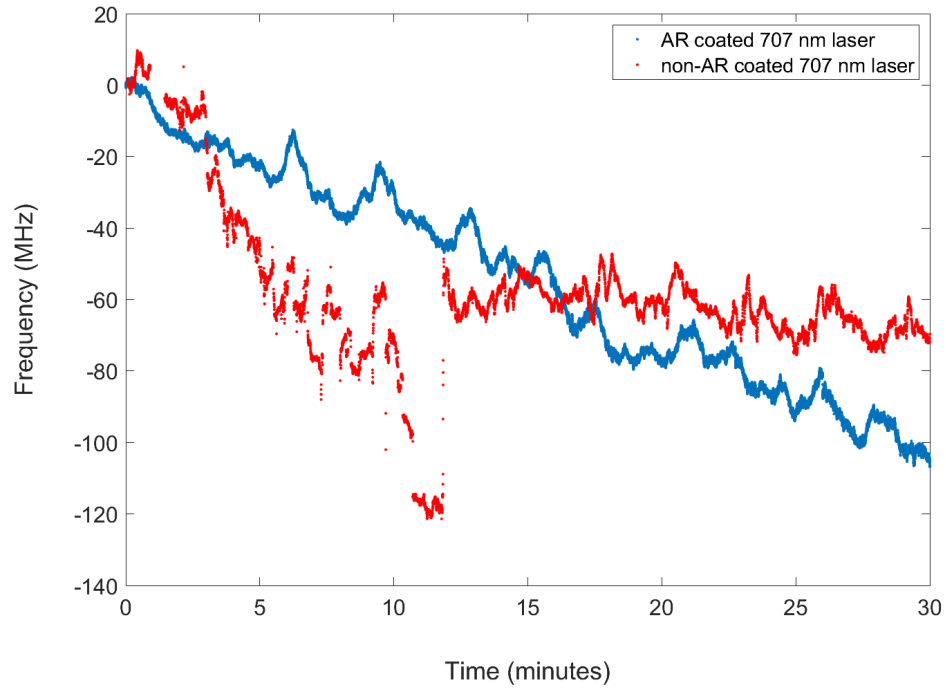


Figure 3.22 The comparative performance of an AR coated and non-AR coated 707 nm laser diode. There are far more jumps in frequency when the diode is not coated, however the stability is similar on this timescale. The mode hops can be seen when there is a large frequency change in a very short period of time, most notably at 12 minutes.

portunity to produce small 461 nm lasers for our system. Likely due to the lack of maturity of this technology, this was the most challenging laser to produce. The diodes being tested produced a lot more heat than diodes used at longer wavelengths so were much harder to keep at a stable cool temperature. Although a stable output at the desired frequency was successfully achieved for each diode tested, the lifetime of the diodes were very short and power output stated to decrease overtime making the lasers unusable as the gain medium starts to degrade. This lose in power output from the diode is a feature of all diodes however this usually happens over the period of years. The longest time a diode produced the specified power output was 8 months before a rapid decrease in power occurred. It is believed this period could be extended by directly cooling the diode. An additional Peltier on the back plate of the diode would have been beneficial to increase the response rate of the temperature feedback loop and preventing the diode from getting too hot which was possibly the main reason for the damage to the diode.

Despite the problems that occurred, the laser produced was used to achieved MOTs within our strontium systems when locked to an external source and used alongside repump lasers. The output of the laser was 42 mW and a free space output was used with a prism MOT system to achieve a blue MOT. The laser was locked to a wavemeter which did not provide a fast enough lock to keep the laser at a stability level where the number of atoms trapped remained stable, however this laser would be locked to a ULE spacer cavity in a portable system which would provide a far superior lock.

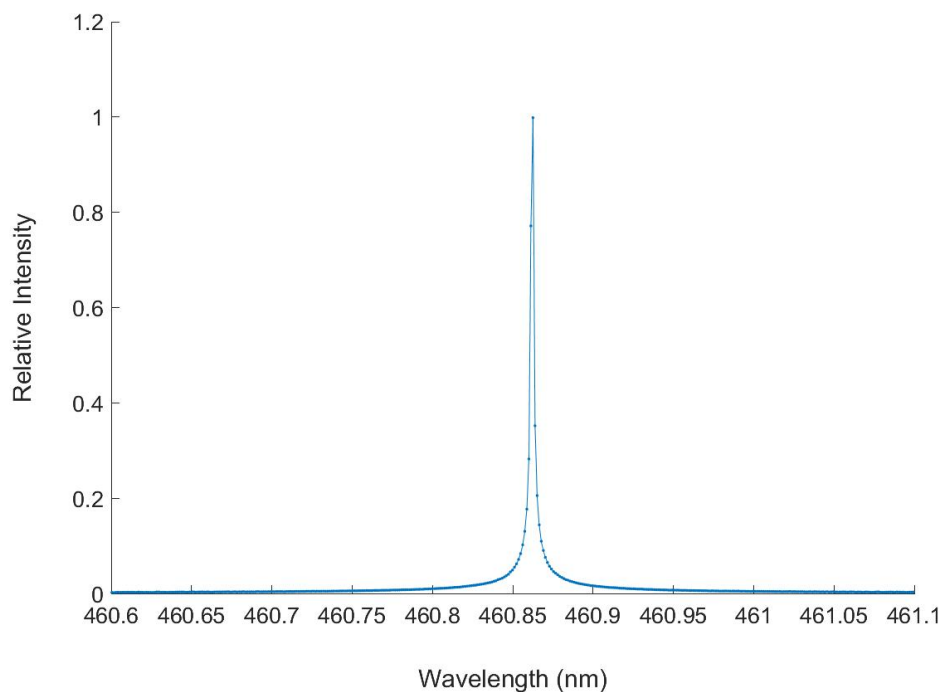


Figure 3.23 The spectrum of a 460 nm AR coated diode lasing at strontium cooling transition within an interference filter ECDL. This is a clean single frequency peak showing this design of laser worse effectively over a wide range of wavelengths.

An example of the spectrum produced and the stability of the unlocked laser can be seen in figure 3.23 and 3.24

Finally a 450 nm diode from the company Osram was used. This diode was not AR coated and was very cheap so many diodes could be tried to find a suitable diode to operate at 461 nm reliably. The diode was operated over the maximum recommended current, however the diodes that were not immediately damaged by going to this high current would produce in excess of 100 mW. The diodes had a wide range of central internal mode frequency,

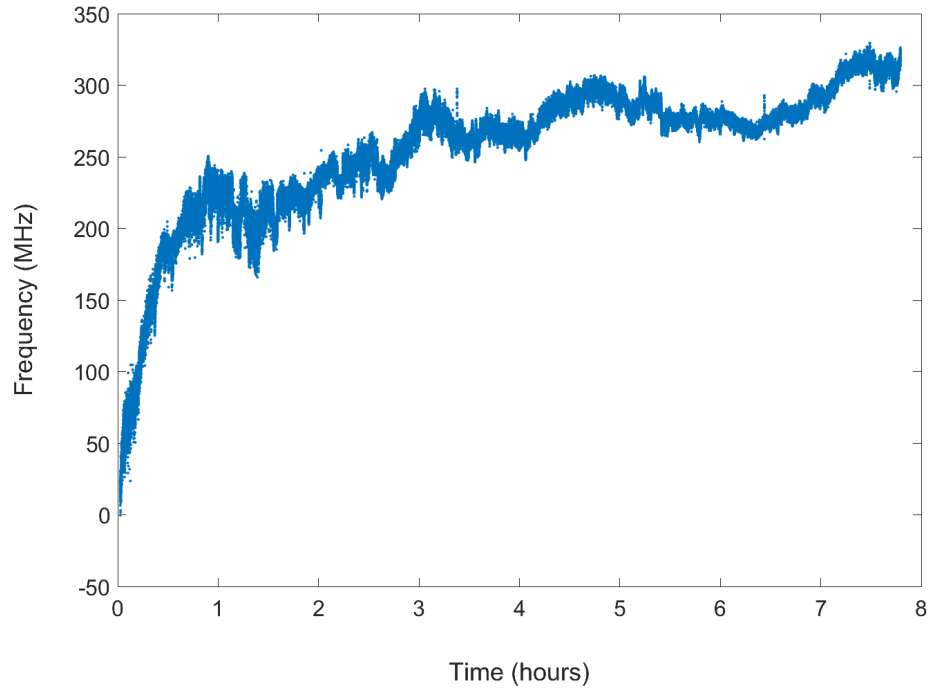


Figure 3.24 The stability of the 460 nm AR coated diode. For this laser an external frequency lock is required to keep the laser stable at the 32 MHz wide blue MOT transition. The short term stability of this laser is poor compared to other lasers that have been produced but the long term stability after the first hour is good.

so each diode was tested to find ones that were closest to 461 nm. These diodes were able to reach the required wavelength, figure 3.25 however, the stability of the output was poor and mode hops were frequent, see figure 3.26. If more diodes were tested from a range of manufacturing runs, it is possible that this diode could provide an ideal option for this laser and with the additional temperature control previously suggested, could have an adequate stability. The lack of need for an AR coating at this shorter wavelength is beneficial as it opens up more options for purchasing diodes. If a diode with the correct central wavelength, high power but without a coating could be sourced this would make an exciting opportunity for a high performance, compact blue cooling laser.

Although only mixed success was achieved for this laser, this still acts as a milestone. A stable blue laser of this size has not been produced in our laboratories before and marks a key achievement in the demonstration that a strontium atomic clock can be made into a portable system. Previously light at this frequency would only be possible with second harmonic generation (SHG), an expensive and bulky procedure. ECDLs are starting to become commercially available however they are still very expensive and large, or have proved to be very unreliable. With improved temperature control, a second generation of this laser could perform with adequate power output for a much longer duration and be suitable for portable strontium quantum technology systems.

For each laser an optical isolator was used with around 35 dB of isolation

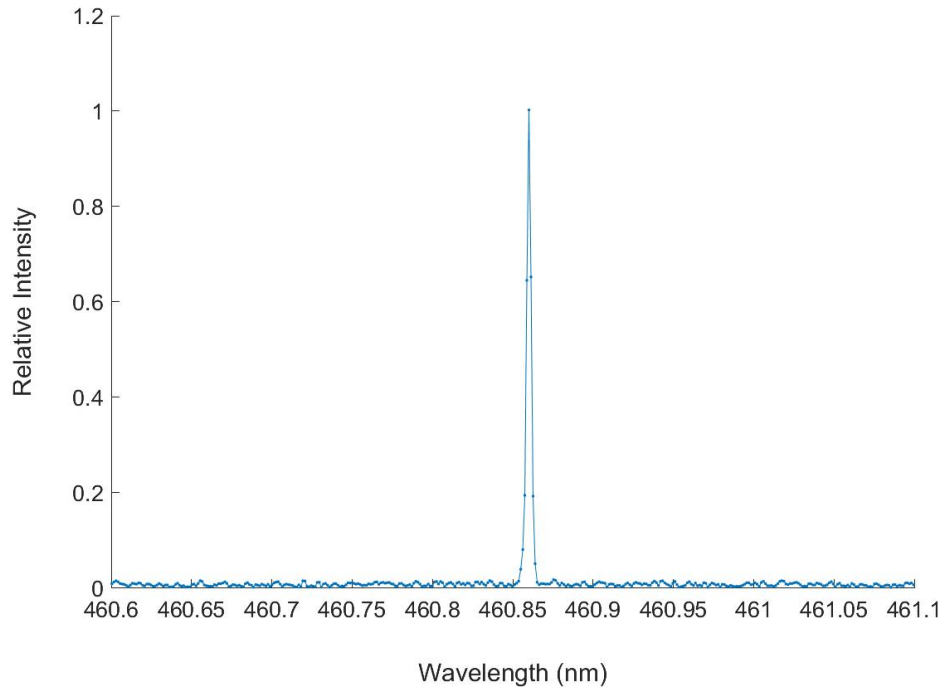


Figure 3.25 A spectrum showing that the 450 nm Osram diode is capable at lasing at the blue MOT transition frequency with a single frequency peak. This would be required for effect cooling of the atoms.

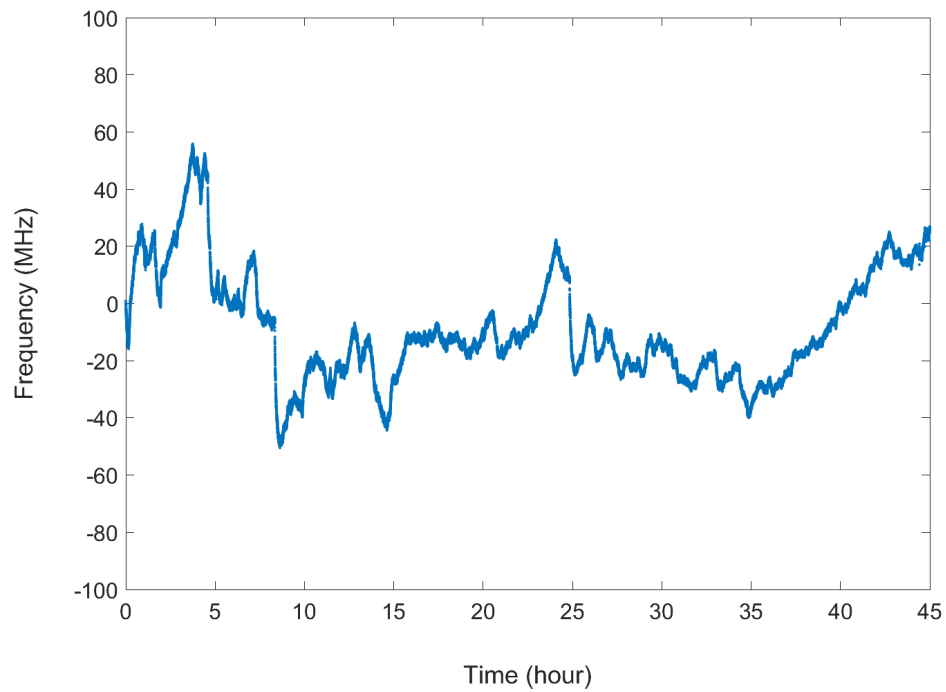


Figure 3.26 The stability using a non-AR coated 450 nm diode. The stability is good compared to the laser over 45 minutes, however after this time a mode hop occurred which would cause the laser to away from the cooling transition.

which was found to be sufficient to stop interference from light reflected back into the cavity. It should be noted that for the case of the 679 nm laser once the output beam was coupled to the 2 fibres which were used to transport the light away from the breadboard that the laser could run without the requirement for any optical isolator and no reduction in frequency stability was observed. Although this is not recommended, it does give some indication that this design does not require optical isolator with high attenuation which can help to reduce the required space in portable optical arrangement.

3.4 Conclusions

This laser design has proved to be very versatile in creating a range of different laser frequencies in a small and cheap package. The laser produced at the 4 frequencies and shown in this thesis were used to cool and trap atoms, proving this technology is suited for portable application. The 461 nm laser producing 42 mW of optical power was a highlight achievement as alternative lasers system are bulky or expensive. Power output is still lower than required but as development of higher power diodes for this wavelength continues, this design would allow these diodes to be used to their full potential.

The inline cavity and cat's eye retro reflector provide a very stable basis for the design of a laser for use in the field and laboratory. The custom lens tube design provides both an easy assembly and controllable cavity length, with a single Peltier stabilising the temperature of the diode and the cavity.

This design offers increased versatility in comparison to other ECDLs which utilise interference filters; allowing quick and easy adjustment of the percentage of light remaining in the cavity. Easy optimisation of the power output of the laser can be achieved by adjusting the waveplate to precisely select the correct power returning to the diode. When using the half waveplate configuration, excess power is not lost by transmitted all the light through the filter making this ideal to use when laser power is the limiting factor to the experiment. This is the case for the 461 nm laser where an increase in blue laser power will lead to a faster loading time and larger atom number for the MOT. The waveplate and PBS also allows for an easy extension in the range of frequencies that can be achieved by increasing the amount of light feeding back to the diode to tune the light further away from the unperturbed modes from the diode, although this could act to reduce the lifetime of the diode.

The lasers produced have worked effectively in a laboratory on a strontium clock system and are ready to be incorporated in to a portable system for operation in the field. One 707 nm laser operated for over a year without any maintenance demonstrating the robust nature of the laser. The range of frequencies produced show this design could be used for a wide range of applications if the filters can be sourced. In addition to the high performance and small size, the cost of the laser is relatively low compared to commercial options. This is very desirable for quantum technology where cost of the demonstrators produced is a limiting factor in the scalability of the products for commercialisation. The size of these lasers is small even in comparison

with a simple Litrow design laser and many lasers could be placed within a small footprint which is very desirable specifically for a strontium clocks where many frequencies are required. If required it is possible this design could be further reduced in size by using smaller optics however this would make the initial assembly and tuning much harder.

Chapter Four

Optically activated atomic strontium source for portable systems

As the prospect of strontium optical clocks leaving the laboratory and becoming truly portable increases, there is a push to decrease the size of the clock while maintaining the high accuracy that is possible in optical atomic clocks [38]. Although there is great benefit to using strontium in atomic clocks [25][31][39][40][41] and other quantum technology devices [42][43][44], working with strontium comes with some issues which set a limit on the design and size of the vacuum chamber. Strontium is commonly used in its bulk metallic form and placed within a dispenser or oven, and electrical heating is used to bring the material to a temperature where the atoms sublime from the surface of the source [45]. This is also standard practice for other atomic

sources such as caesium and rubidium; however strontium has a much lower vapour pressure leading to some adverse effects. Firstly, strontium needs to be heated to a much higher temperature in order to release a high enough atomic flux to be usable; above 500 K at the ultra high vacuum (UHV) pressures used in atomic experiments, causing the average velocity of atoms of this element to be higher and a low proportion of those atoms to be under the capture velocity of the MOT. This leads to longer load times for the trap, a big concern for clock systems as it increases the down time of the clock when there is no interrogation of the atoms in the lattice with the clock laser. Thus, the stability of the measurement decreases as the laser has a longer period to drift frequency without correction to the atomic transition. Secondly, once the atoms are released from the atomic source if they come into contact with any surface within the system they will adsorb to that source, “sticking” to the wall and thus are not able to be trapped within the MOT. This is not the case with, for example, rubidium which once released will ricochet within the chamber many times before being adsorbed. For an atomic species with low adsorption rates to the chamber wall the MOT can be loaded from vapour pressure, but for strontium line of sight from the source to trapping region is required to prevent contact between the strontium atomic beam and the chamber walls. This puts constraints on the geometry of the system making it more difficult to miniaturise the system.

Commonly we overcome the difficulties found when using strontium through a number of methods: using an oven to release a high flux of strontium; dif-

ferential pumping to select only atoms that will pass through the trapping region and blocking all other atoms (including atoms from impurities in the source); and ensuring the pressure remains low in the science chamber. Also, using a Zeeman slower to increase the proportion of atoms in the atomic beam that are at a velocity which can be captured by the MOT [46]. These steps keep the loading rate and atom number of the MOT high but also make the system very large in size. Decreasing the size is possible by sacrificing performance such as the removal of the Zeeman slower and using a dispenser, as was done in the MiniClock system detailed in chapter 2. This increases the time between measurements in the clock as the load time to reach sufficient atoms in the blue MOT is greatly increased but allows the atomic package to be a lot shorter in length. The dispenser still requires a large amount of space and needs to hold enough strontium to run continuously for a long period of time. Ideally, fast switching of the atomic source would also be possible to help to reduce the amount of strontium required in the system. Atomic switching would also help keep the pressure inside the science chamber low after the blue MOT phase, reducing collisions with atoms trapped in the lattice. This can be achieved with an atomic shutter in the path of the beam but again adds complexity and size to the system with moving mechanical parts that are unlikely to be suited for portable applications. If a smaller atomic source can be used then there is more flexibility where it can be placed within the system, ideally requiring no additional vacuum parts and keeping the system compact.

4.1 Previous work

To address these desires, the University of Birmingham has undertaken experiments to use a strontium oxide powder as an atomic source placed within the science chamber and use laser light to induce the release of atoms from the surface of the source. This has some very exciting advantages for optical clocks and for portable quantum technology as the reduction in system size, amount of strontium required, and fast switching of the atomic source are great benefits to such systems. This method was first discovered and published by Birmingham in 2016 [47], with more details on the discovery of this method found in W. He's thesis [25]. This paper not only showed the proof of principle that this type of loading could be done using a strontium oxide powder, but also indicated that this method could have advantages over using strontium emitted using traditional methods. Both a fast loading time of under 200 ms from when strontium was first released until one million atoms are trapped (a commonly used blue MOT atom number in strontium clocks), and a fast output decay time for the atomic flux once the emission laser is switched off, under 10 ms. These findings and the possibility of the unique, compact design this source would allow are of great interest however, there were still further questions to be answered before this technique could be implemented within an atomic system.

The main issue found with this method was the unreliability and the difficulty in observing a strontium output from the source, additionally there

was trouble in both initially stimulating an output and then maintaining it for long periods of time. This was corroborated by M. Yasuda (et al.) at the National Institute of Japan [48] who replicated these results with Ytterbium which has a similar atomic structure to strontium. They found similar issues with source, however their discovery opens up this technology to portable Ytterbium experiments [49]. These difficulties need to be overcome before this source type could replace classically used methods in quantum technology as failure to load a MOT successfully each experimental cycle will lead to more downtime in experiment, which for clocks would decrease the stability of the measurement. To achieve this a better understanding is needed of the required characteristics and methodology required to release the atoms in order to achieve a predictable output. This includes: initial conditions for strontium emission and how to locate suitable sites on the targets surface, how long it takes strontium to release from the source once the laser interacts with the target, the duration of atomic output from a single point, and the process required to stimulate new emission once a region is depleted. A more detailed understanding of the experimental parameters and additional, possibly adverse, effects from this technique are required to better understand where this loading technique would be most appropriate. For example, increased knowledge of the emission laser parameters is needed, including information on the frequency, power and size of the emission laser at the target; how the pressure in the chamber changes over time due to the atomic emission and how this and any other parameters may effect the

trapped atoms; the way the position and mounting of the source effects the efficiency and reliability of the loading; and how the sample composition and preparation could be used to provide the performance. Finally we wish to know more about the physical process the sample undergoes to cause the release of strontium from the oxide powder; as this may help us to optimise the use of the source and understand how the source might be used within a strontium clock. It is expected that heating of the source with the laser is the dominant mechanic for the release of atoms from the target surface, but as of yet there has been no evidence to support this.

This chapter will discuss the possible mechanics of the laser emission, outline the chamber that was built to further test the validity of this source and experiments that were undertaken to answer the questions outlined above. A majority of the data focuses on strontium oxide using a 405 nm laser as this proved to be the most effective combination in previous work undertaken. The findings presented help to identify how this type of source could be used in the future and the feasibility of it's use in a strontium lattice clock.

4.2 Background and theory

Using light to stimulate the release of atoms is not a new concept. The laser ablation technique uses fast pulses of laser light to cause the release of atoms and is a very large field of study [50] which has been used to load ion trapping systems [51][52]. However this requires large and expensive pulsed

laser systems and the particles released can be groups of atoms, molecules or single atoms, of which only single atoms are required for MOTs. This may make laser ablation useful for ion traps but less so for neutral atom systems, especially when aiming for portable applications. Light induced atomic desorption (LIAD) is another common technique where a much lower intensity flash of light, compared to laser ablation, causes the desorption of atoms stuck to the walls of a vapour cell or vacuum chamber. This acts to increase the vapour pressure of the atom species in the system for the duration of the trap loading, increasing the capture rate of the trap and allow the pressure to decrease once sufficient atoms are trapped. This technique has been used for rubidium [53], caesium [54], sodium [55] and lithium [56] effectively, however it is not appropriate for strontium due to the low vapour pressure at room temperature. To induce LIAD of strontium a much higher power light source is required to release the strontium from the chamber wall which upon release would then adsorb back to the chamber wall on next contact. Another method is direct heating of an atomic source using a continuous wave (CW) laser which can be periodically blocked to cause a pulsed atomic output. This has been demonstrated for rubidium where a CW laser was used to heat and release the surface layer of atoms held in a dispenser [57]. Here between 0.5 and 4 W of laser light was focused down to 35 μm in order to stimulate the pulsed release of rubidium. This system would not be ideal for a strontium system yet again due to the low vapour pressure of strontium making the process more difficult. A much more powerful laser

would be required; well over the 40 mW available in this experiment, to rapidly heat the strontium and create a usable atomic flux. Once the energy is absorbed from the laser onto the material it starts to dissipate from the point of incident via conduction. A very intense light source is required to cause local rapid heating to reach the sublimation temperature and induce the release of strontium, if the input of heat energy is lower than the flow of heat away the required temperature cannot be reached. As this is not ideal for a portable system we alternatively work towards reducing heat flow away from the point of incident by using a strontium oxide powder.

4.2.1 Strontium and strontium oxide atomic structure

Strontium is in group II of the periodic table, alkaline earth metals. As an alkaline earth metal strontium has two valence electrons, and in the bulk structure forms metallic bonds between the atoms in the crystal. This bonding structure is weak compared to transition metals and strontium rapidly oxidises when in contact with oxygen as stronger ionic bonds can be formed. Pure strontium is a good thermal conductor, with a conductivity of $35 \text{ Wm}^{-1}\text{K}^{-1}$, an order of magnitude lower than the best conductors. This means when heating pure strontium the heat energy moves quickly away from the point of injection. This is partly due to the valence electrons in metallic bonding which are not localised to a single atom and can easily conduct heat through the structure, this presents difficulties when trying to heat only a small area with a laser. Instead of using very intense lasers or fast

pulsed laser, an alternative is to reduce the thermal conduction by physically limiting the areas where conduction can occur. This is observed when using with dendritic strontium which can be release atoms when by CW light emitted from a laser diode. Dendrites are small pillars that form on the surface of strontium when it is produced, these parts are more isolated and can thus be heated quick enough to sublime into a gas within a vacuum systems. Unfortunately, these only release a small amount of strontium and are limited in number so do not act as a sustainable source of atoms.

In laser ablation physics, the process of heating a substance with a laser to cause emission is called a photo-thermal process [50]. Although this is usually undertaken with laser pulses of duration in the order of microseconds or less, the mechanics can still be applied here. The main other process in laser ablation is a photo-chemical process where the absorbed photons cause direct bond breaking in the material, thus no energy is transferred to heat in the material. These two processes can happen alone or in combination to remove surface atoms from the material. For strontium a photo-thermal process is not easily achieved due to the rate of heat dissipation from the point of contact. A photo-chemical process is unlikely for either strontium or strontium oxide due to the energy of photons being in the visible part of the spectrum being too long to break the bonds in these chemicals.

An initial look at the characteristics of strontium oxide may make it seem unlikely to be a better candidate for low energy laser stimulated atomic source. Strontium forms much stronger bonds with oxygen than with itself,

454(15) kJ mol⁻¹ for a single strontium oxygen pair and 592.0 kJ mol⁻¹ when it forms a crystalline structure based on its enthalpy of formation. At 1 atm pressure, the boiling point for strontium oxide is over twice than of strontium, 3470 K vs 1650 K. An exact value for the boiling point of strontium oxide at the pressures in our vacuum system was not able to be found, however, if the compound follows the common vapour pressure curve we see if pure elements (which the author understands is unlikely and this number should only used for reference) the oxide would sublime at approximately 1000 K. The ionic bonds that form mean thermal conduction is no longer as high. The electrons are now localised, however thermal conduction still undergoes in the lattice structure meaning the thermal conduction for strontium oxide at 0°C and under vacuum is 18 Wm⁻¹K⁻¹, as found in a study by H. Szelagowki et al. reference. [58]. This paper offers more insight into the thermal conductivity of strontium oxide powder as they undertake in-depth measurements and theoretical modelling of porous strontium oxide at different porosity temperatures. They quantify this with a measurement of porosity, p , which is the ratio of the void volume to the total volume ranging from 0 for a completely solid object to 1 for empty space. The definition of porous here corresponds to gaps between or within the strontium oxide which can also be applied to strontium oxide powder as a hole and the gaps between each piece of the powder. Here they prove that an increase in porosity leads to a decrease in thermal conduction due to the increase in physical gaps limiting the path heat can flow. These gaps would allow heat flow via

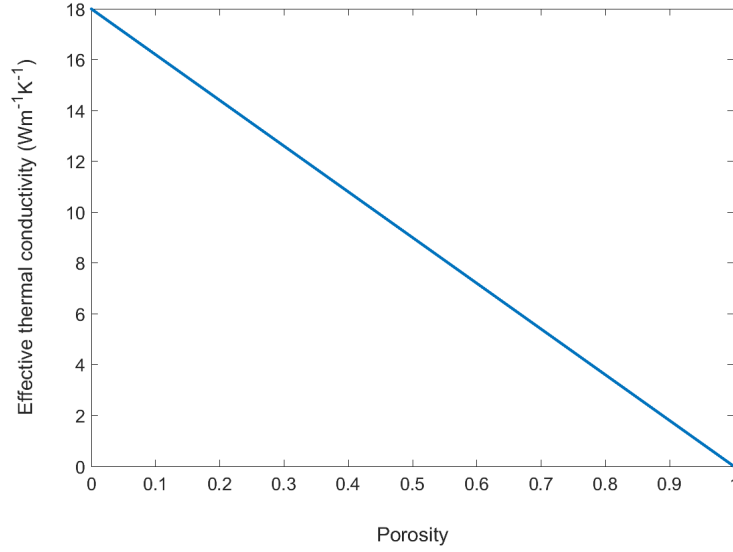


Figure 4.1 The change of effective thermal conductivity in strontium oxide with varying porosity at 0°C.

convection and radiation which are both considered in their final value for effective thermal conduction, λ_{eff} for the porous substance. They present the following equation which is valid at 0°C and is plotted in figure. 4.1,

$$\lambda_{\text{eff}} = \lambda_0(1 - p)_0. \quad (4.1)$$

This allows the ability to tune the thermal conductivity if porosity can be controlled. Although with perfectly spherical identical sized pieces of powder in perfect hexagonal packing the porosity would remain constant when changing grain size, in practice this will be extremely difficult to achieve and the sample preparation will affect on the porosity. For results presented in this thesis the powder was not altered once removed from its container

so a range of grain sizes are present in the sample. At this time it has not attempted to measure the porosity in our experiment and there is likely a range of porosities over different areas in the powder sample. It also needs to be considered that individual large grain of the powder will have a porosity close to or equal to zero compared to an equal weight of powder comprised of many small grains which will have a much higher porosity. If the grain size is too small the light may strike multiple pieces of the powder at once.

The paper by H. Szelagowk also discusses the change in thermal conductivity at different temperatures. This is a very common phenomenon and for all metals the change is only a few percent over a wide range of temperatures. For porous strontium oxide the change is much more drastic, reducing by a factor of 2 in under a 700 K increase, see figure 4.2. This effect could play a significant role in our system, helping to rapidly increase the temperature with little heat dissipation once above a threshold temperature. At 600 K where strontium would normally sublime in UHV the thermal conductivity could be less than a fifth than that of pure strontium allowing the oxide to reach the higher temperature required to reach a temperature required to sublime.

4.2.2 Photon absorption causing bond breaking

For the energy to be transferred from the photon to the atoms an electron needs to absorb the energy, increasing its energy level. This energy will allow the bond between the atoms to break either by directly breaking the bond

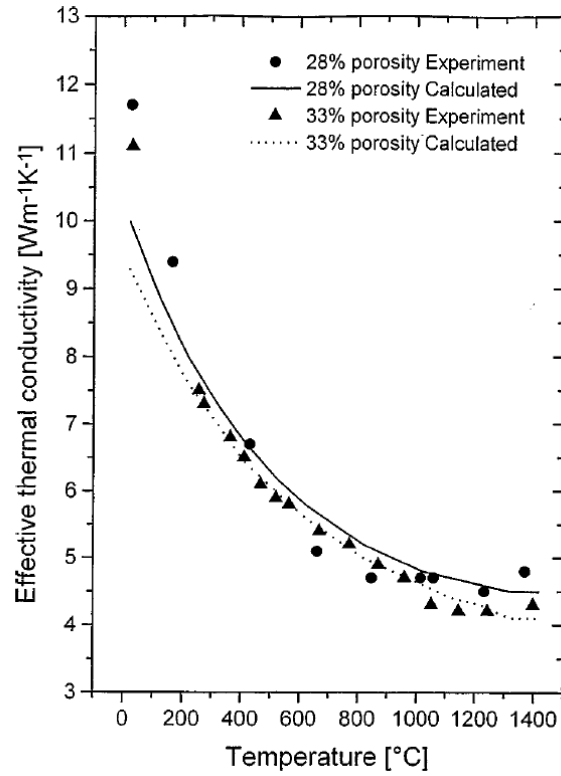


Figure 4.2 This graph taken from Journal of Applied Physics 85, 193 (1999), H. Szelagowk [58] and shows the change of effective thermal conductivity with increasing temperature taken under vacuum.

or by transferring to heat within the substance and allowing evaporation or sublimation to occur. In strontium oxide the valence electrons are localised to a single unit cell thus the electrons do not carry the energy away from the point on contact. The energy in the excited electron can transfer the energy into lattice vibrations or phonons via radiation-less transitions, the vibrations in the atoms can then transmit the heat rapidly throughout a material as demonstrated in diamond which has a higher thermal conductivity than silver, copper, and gold. Like electron transitions, the phonons occur at discrete energy levels determined by the lattice structure and elements in the material. If the energy difference matches that of the excited electron, radiation-less transfer would readily occur and the electron would fall back to a lower ground state and adsorb another photon. A potential wavelength dependence could lead to a higher efficiency of energy transfer into the compound and lead to the output of strontium gas.

The discussion presented in this section helps to understand the properties for strontium oxide and provides possible reasons for why this proves to be a more efficient source for laser induced emission versus pure strontium. Experiment investigation in section 4.4 will show that the strontium oxide is indeed heating during this process and it is likely that the efficiency of the method is due to the low thermal conductivity keeping the heat in a localised area.

4.2.3 The release of strontium oxide into a gas

The next question that needs to be tackled is: what is the form that it will take when sublimating from the powder? It is stated that strontium oxide decomposes when reaching its boiling point at 1 AU, however this is from the liquid phase that it does not pass through at UHV pressures, as at these pressures the oxide sublimates straight from the solid to gaseous phase. The amount of strontium vs strontium oxide gas was measured in reference [59] by heating from oxide on a platinum heater which allows us to infer the state of the gas in our system. Although the purpose of their study was to find the dissociation energy of strontium oxide, the equations they produce allow a better understanding of our system. They measure the partial pressure of strontium gas, $\text{Sr}_{(g)}$, and strontium oxide gas, $\text{SrO}_{(g)}$, over strontium oxide heated on platinum and produce the following equations which are valid within their respective ranges.

$$P_{Sr} = 1013.25 \times 10^{\left(6.633 - \frac{2.536 \times 10^4}{T}\right)}, \quad (4.2)$$

in the temperature range of 1643 - 1851 K.

$$P_{SrO} = 1013.25 \times 10^{\left(6.707 - \frac{2.793 \times 10^4}{T}\right)}, \quad (4.3)$$

in the temperature range of 1747 - 1850 K.

These results are plotted within the temperature range where they are both valid, see figure 4.3. We extend these equations outside of their tem-

perature range to make an estimate of the sublimation temperature at the vacuum pressure being used within this experiment, 2.67×10^{-8} mBar, which is similar to the pressure of 1×10^{-9} mbar used in our experiment. This estimate value assumes the equation above holds valid over a wider temperature range and that the sublimation temperature remains similar at our lower pressure and thus is only used as a rough guide to infer the temperature range that would have to be reached to release strontium from the oxide if this was a purely thermal process. A temperature of 1360 K is acquired and is shown in figure 4.4.

The information researched and presented here will be further investigated in section 4.4 with the aim to apply this knowledge to create an efficient and effect strontium source.

4.3 Description of test setup

A new experimental setup was designed and built to further the testing of the feasibility of using this type of source in an atomic strontium clock. This was predominately done so a prism MOT arrangement could be used, as this is the current design we use within our portable systems. This allowed us to build a very flexible setup that would allow many different tests to occur without breaking vacuum to replace components, and meant the vacuum chamber did not have to be optimised for the latter stages of the clock, as at this point we only are testing the effect with the blue MOT stage and can

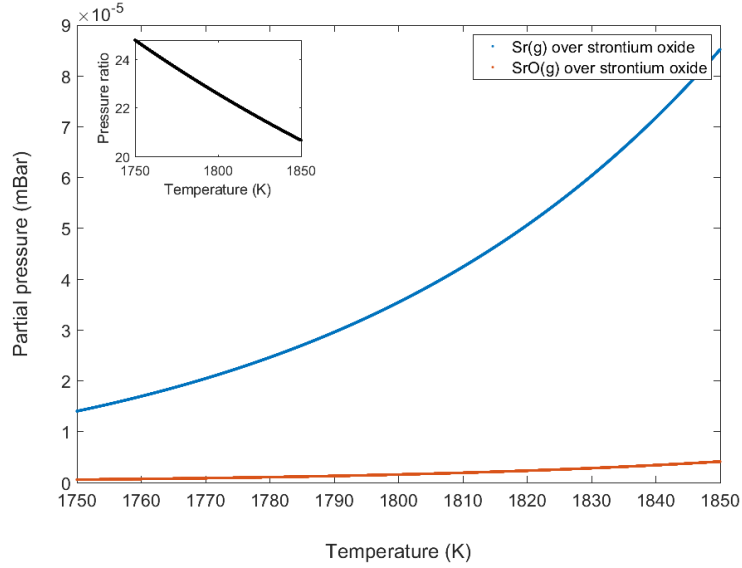


Figure 4.3 The partial pressure of strontium gas, $\text{Sr}_{(g)}$, and strontium oxide gas, $\text{SrO}_{(g)}$ over strontium oxide heated on a platinum filament. Results are plotted from equation presented in reference [59] which are both valid within the temperature range shown here. The inset graph shows the ratio of the two gas species ($\text{Sr}_{(g)}/\text{SrO}_{(g)}$) in the chamber over the same temperature range which indicates a large majority of the emission is pure strontium gas although this proportion drops with an increase in temperature.

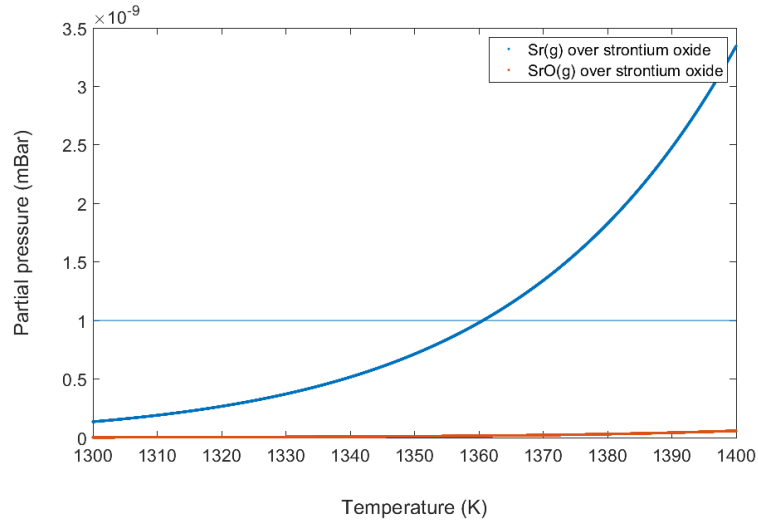


Figure 4.4 Extending the equations presented in reference [59] into to a pressure comparable to the background pressure in the experiment. This allows s the rough prediction of the sublimation temperature for strontium oxide. At a temperature of 1360 K the vapour pressure of strontium oxide reaches that of the background pressure which defines the sublimation temperature at this pressure.

infer the effect in the latter stages of the clock measurement cycle.

A full characterisation of the source needs to be acquired before it can be used within an atomic system and the most pressing concerns are: the reliability of the source, the lifetime of the source, the substances released in addition to the strontium, and the physical process of how the strontium is released and the possible impact this may have on the measured clock transition. To complete these measurements the system needs to be designed with lots of optical access, multiple mounting points where atomic sample holders can be attached, a way to measure the pressure inside the science chamber with good conductance, and a process to measure the molecules released during operation.

The chamber was an octagon purchased from Kimball physics with 2 CF35 and 8 CF16 mounting points. This allowed the science chamber to be built and changed rapidly between measurements and allowed a high conductance into the science chamber from one of the CF35 holes and an a viewport attached to the other with a wide enough clear aperture for the MOT light to enter the system. To the other ports a range of viewports, sample holders, ion pumps, and a strontium dispenser could added to complete a range of tests and comparison measurements. A render of the experimental setup can be seen in figure 4.5.

The science chamber contains a prism MOT arrangement similar to that of the MiniClock but considered some of the improvements outlined at the end of chapter 2. The right angle prisms that are used are smaller with a

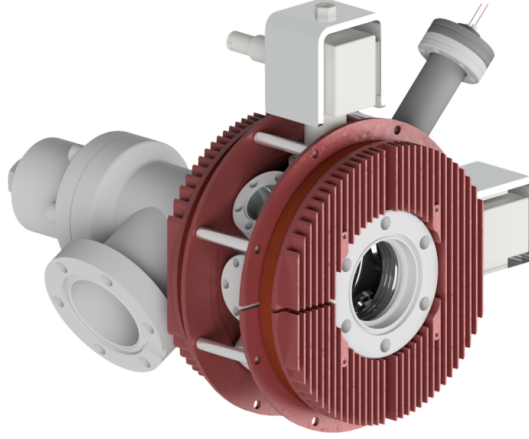


Figure 4.5 A rendered image of the chamber and coils that were built and designed to test the optically activated source.

size of 10×10 mm on their square surfaces compared to 12.5×12.5 mm. As discussed in chapter 2, reducing the beam size in the MiniClock prism setup helped to increase the number of atoms due to the limited amount of power that was available. Setting the prisms to be a smaller size will help achieve a higher atom number setup, and opens up the possibility of making the beam smaller while still having light strike the atoms from all sides. Additionally the quarter wave plate and mirror were placed within the vacuum chamber and relying on the process of mounting the optics to provide adequate alignment to produce a MOT. This allows a vacuum pump to be attached from the underside of the prism achieving far superior vacuum capacitance to the science chamber for increased speed in initial pumping of the chamber and removal of waste gases removed during the sublimation of the source. Prisms were glued to a custom aluminium mount and a quarter

wave plate and mirror were attached to the underside. This mount had two mounting points that allowed sample holders to be placed very close to the MOT centre to allow a range of points to test where the source can be placed in the chamber. A diagram of this can be seen in figure 4.6.

The magnetic coils were designed and built from copper which has superior heat dissipation compared to aluminium. Although these coils are not required to be used in a atomic clock and thus do not require a fast switching time, a slit in the copper was added with a plastic support place in the gap to reduce Eddy currents. The chamber being used was wider than that in the MiniClock so the coils had to be much larger and have more turns to provide the required magnetic field gradients so heat sinks were incorporated into the design to help dissipate heat away. Unfortunately during continuous operation of the coils caused an increase in temperature to over 70°C despite the heat sinks. As this temperature was reached and showed no indication of the increase reaching a plateau , an external fan was installed to keep the coils at a lower, stable and safe temperature.

The lasers being used for this experiment were a Titanium-sapphire Lasers from M2 for the 461 nm light which was locked to a High Finesse wavemeter, two free running home built interference filter ECDLs in the design described in chapter 3, and the activation laser was a 405 nm laser diode with no external tuning but this would be could be varied to test the wavelength dependence of the release of strontium. Light is provided to the system via a telescope utilising a tophat diffuser and a lens as we have used

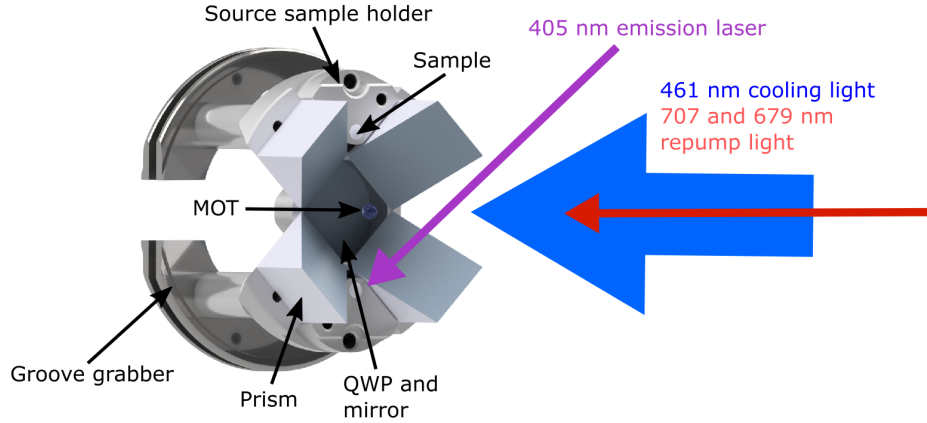


Figure 4.6 A rendered image of the prism mount and prism mirrors, with strontium sample holders place in the gaps between the prisms. This allowed strontium samples to be placed very close to the trapping region on the science chamber and would lead to a higher flux of strontium atoms. The other two cutouts allow for a increased pumping speed in the area around the MOT to help increase the lifetime. The number of sample holders and gaps could be adjusted once and optimised arrangement is found to either increase the amount of strontium held in the system or increase the pumping speed at the trap as proves necessary. For this experiment, TorrSeal was used to hold the prisms in place, this would normally not be advisable due to the high out gassing for TorrSeal and a UHV glue should be used. However, TorrSeal was use as it was the easiest to work with and chamber was only required to achieve the first stage of cooling strontium. The prism mount was attached to spacers and “groove grabbers” to attach it to the inside of the chamber.

in the MiniClock experiment, and we use both the circle and square diffuser within our measurements. Repump light at 679 and 707 nm is provided by a single fibre and is either injected on the front face of the diffuser at an angle, which has been show to still saturate the transitions, or directly into the chamber through a viewport.

Finally, the activation laser to stimulate the release of strontium was also brought to the breadboard by fibre and was placed on a fine adjustment kinematic mount to adjust the angle of the beam. The light is directed at the source from the opposite side of the chamber from where the source is held without propagating through the area where the MOT will form. The laser diode is placed in a temperature controlled diode mount and the output light collimated and then coupled to an optical fibre. This allows for beam space correction and also allows easy adjustment of the focus and position out the light entering the science chamber. The fibre would provide a Gaussian beam output and we could easily change the lens in front of the fibre or the lens position to change the focus of the light at the source.

The optical spectrum of the light emitted was measured, see figure 4.7, and the fibre is mounted on a fine adjustment optic mount with an aspheric lens which can be adjusted to change the focal point of the beam.

Lastly, the vacuum chamber was be tested. Once the effect of the atomic source was understood, section 4.4.1, both the prisms and source were placed within the science chamber and a base pressure of 1×10^{-9} mbar was achieved. A strontium dispenser was used to achieve a blue MOT and ensure the optics

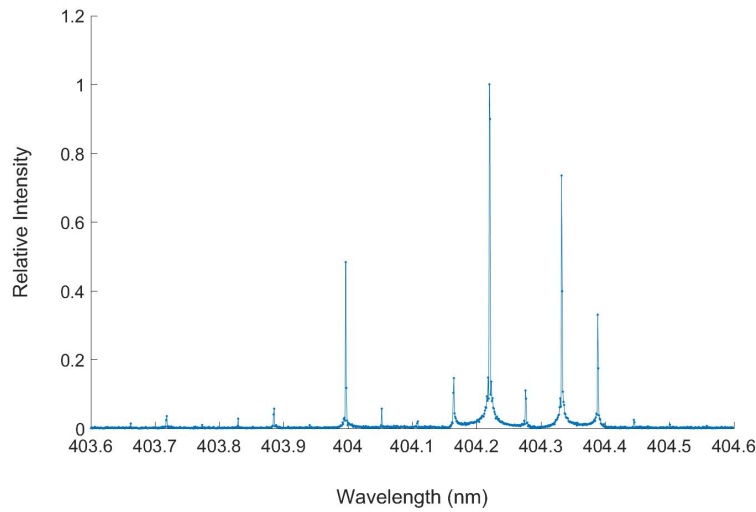


Figure 4.7 The spectrum of the emission laser used to stimulate the release of strontium. The diode is not placed in an extended cavity so lases at multiple frequencies with a peak frequency at 404.2 nm. The spectrum was taken at a current value of 75 mA and a temperature of 22 °C, the temperature is kept the same throughout the experiment, however the current is changed regularly. It is expected that this could cause the spectrum to change but not by a significant amount.

were aligned with the chamber and the MOT was optimised. A current of 5.8 A was applied to the dispenser and a MOT was achieved showing atom trapping was possible within the system. This would also allow a comparison to the MOT that could be achieved with the strontium oxide source.

To observe either fluorescence or the magneto optical trap in the science chamber a Chameleon 3 camera from FLIR was used. A band pass filter was placed in front of the camera lens which was centred at 461 nm with 80% transmission and blocked the 405 nm emission laser. This acted to block the scattered light from the emission laser striking the source which caused noise on the signal which could not be removed when processing the images. The output signal was achieved by selecting a region of interest (ROI) around the feature of interest and removing the background from the image. A sum of all the counts on pixels was taken which would give a “brightness” value in counts.

4.4 Experiments taken and results

4.4.1 Testing vacuum compatibility

The initial step taken was to prove the each source was vacuum compatible and would not affect my chamber if placed inside the test chamber. Pure strontium is known to have a low partial pressure and thus will not affect the pressure in the science chamber at the pressures required. An initial test of vacuum compatibility needs to be undertaken to insure that

UHV can be reached and that the outgassing from, or sublimation of, the source do not damage other components within the chamber. Strontium oxide (SrO), strontium carbonate (SrCO_3), strontium hydroxide ($\text{Sr}(\text{OH})_2$), and strontium tetramethylheptanedionate ($\text{SrC}_{22}\text{H}_{38}\text{O}_4$) are all tested under vacuum. These compounds offer a range of potential advantages if used within a strontium clock. Strontium oxide is the main focus of this work, the other compounds listed above will release more waste atoms into the chamber to produce a single strontium atom. Strontium carbonate can be purchased which is enriched with strontium 87, which is the preferred isotope to use in laboratory based strontium clocks as it offers a higher potential stability in the measurement. Purchasing pure strontium 87 is very costly, and natural strontium is commonly used as the atom sources which only contains 7% of the desired ^{87}Sr isotope. An enriched source could enable faster loading of the blue MOT while reducing waste atoms into the system. Strontium hydroxide has a much lower boiling temperature to strontium oxide at 1 AU, this could prove more energy efficient to release strontium atoms into the system. Strontium tetramethylheptanedionate also presents an option for a low energy source as this compound has a boiling point of 250 °C at 1 AU. This has the additional possibility of being used with an electron ionising source.

A 4 way cross was connected to a turbo pump to bring down the pressure of the chamber from atmosphere and the fall of the pressure is compared to an empty vacuum chamber. After each measurement, the source was

removed and the chamber was pumped down from atmosphere again to check there was no contamination from the source. The results from these tests can be seen in figures 4.8 and 4.9. It is clear to see that the strontium tetramethylheptanedionate is not suitable for the vacuum levels that are required as it appears to be separating within the system releasing pollutants into the system. This could have been useful due to the possibility that it would require less energy to release strontium, however it would also release a lot of other elements into the system, increasing the vacuum pressure, for this reason no further tests on this compound was undertaken. The rest of the sources appeared to be good enough to place in the vacuum system where ion pumps would pull the pressure down to the required level where we could see the affects of the source at this lower pressure.

4.4.2 Stimulating emission

The 405 nm was focused to a beam size of $0.116(6) \text{ mm}^2$ and directed at the strontium oxide which was initially being tested in the system. As was previously found there was some difficulty finding an initial spot which would emit strontium. When scanning the laser across the surface of the sample the pressure would slowly increase, and if the laser was kept in the same place the pressure would raise and then remain at a constant level as shown in figure 4.10. Once a spot was found which would release strontium, the pressure would very rapidly increase and fluorescence could be observed using a 461 nm probe beam tuned to resonance and the camera observing the chamber

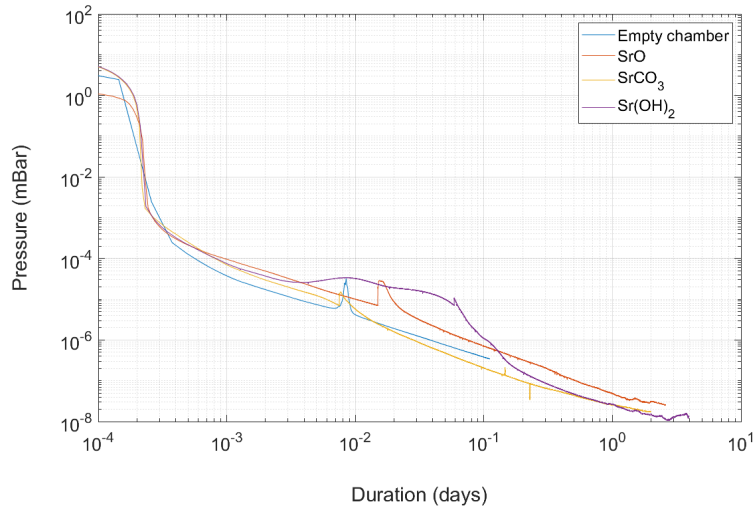


Figure 4.8 The graph shows the vacuum compatibility of the different sources. It is possible to see that all components have a trend similar to the empty chamber showing they likely could be used in a science chamber and have no negative effects. There is some deviation from the common trend for the $\text{Sr}(\text{OH})_2$, this could be due to gas or moisture being harder to remove from the powder, however the same pressure was reached after a day of pumping.

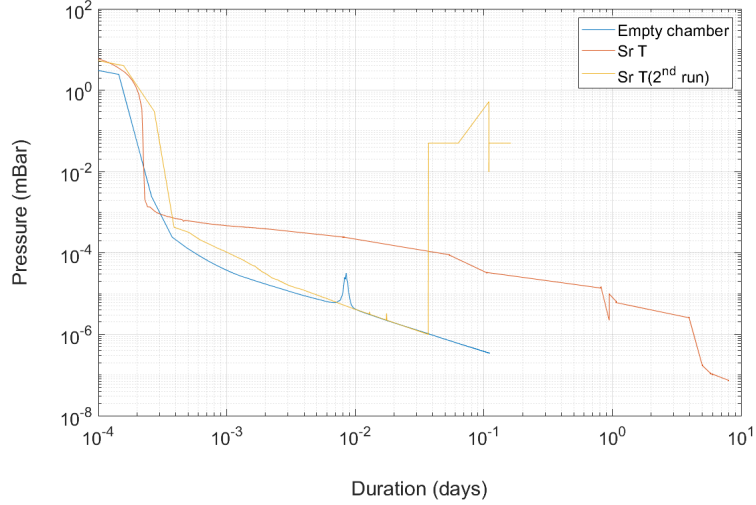


Figure 4.9 A graph showing the vacuum compatibility of $\text{SrC}_{22}\text{H}_{38}\text{O}_4$ or Sr T. Two experiments were done with the second run causing damage to the pressure gauge during testing which is shown by the sudden increase in pressure during this run.

via a cf16 viewport. An unprocessed image can be seen in fig 4.11 with an example of the initial output from the source shown in fig. 4.12 where the brightness and pressure in the chamber are measured during the initiation of the output. It must be noted that the response detected on the camera and by the ion pump controller are unlikely to be temporally synchronised, as the delay between these signals has not and could not be corrected. It was found that at the set beam size, a power of 16 mW in the emission laser would stimulate sustainable emission when scanning the laser over the source. Lower power would not cause emission and high power would often cause an extremely fast rise in emission and pressure and risked damaging the ion pumps or depleting the source too quickly.

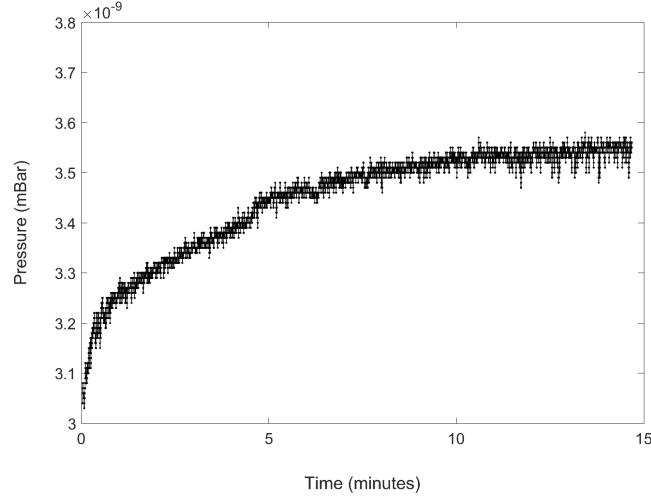


Figure 4.10 The increase in pressure in the chamber when the emission laser is turned on but the position is not scanned. It was hoped that sublimation output would occur after an extended period but this was not the case.

If 16 mW is used the pressure can increase upwards of 10^{-5} mbar at which point the laser was turned off to risk damaging the ion pumps that were attached to the system. A beam of on resonance blue light at a intensity of above I_{sat} was directed at the centre of the chamber where the trapping centre is and retro reflected from the mirror. To keep a continuous output while maintaining a safe pressure, the power of the laser could be decreased once strontium output was observed which would lead to a decrease in measured fluorescence. Scanning with a laser below 16 mW at this beam size produced no strontium output, this could indicate a threshold intensity is needed to initiate the strontium output, however it is possible that with more perseverance, emission could be initiated at a lower power.

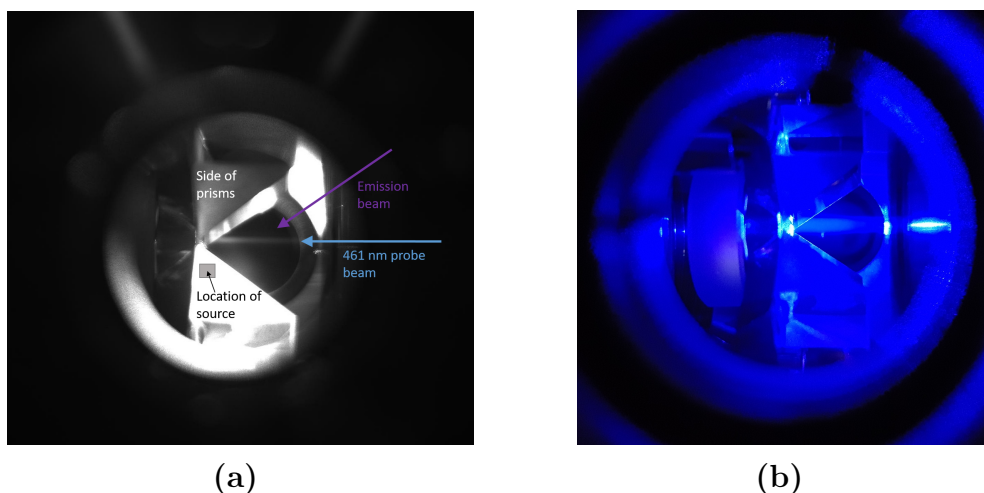


Figure 4.11 The captured images from (a) a phone camera and (b) the Chameleon camera, of fluorescence emitted from atoms realised from a strontium oxide powder. The view looks into the chamber via a cf16 viewport, the circle seen in the foreground and looks at the side of the prisms. The source in this image behind the prism at the bottom. A clear line of fluorescence can be see where the on resonance 461 nm probe beam interacts with the emitted atoms.

It was possible that an area on the source could be found where a sustainable constant output could be found with continuous emission from the activation laser. In this situation the fluorescence would slowly drop over time while the pressure increased, as shown in figure 4.13. It is uncertain why this relationship was observed as it was expected both would drop over time. However it is clear that continuous output within this system where only a maximum of 6 ls^{-1} vacuum pumping was provided from the 2 ion pumps is not sustainable, and pulsing the output would be more appropriate to prevent the pressure from rising too high.

Pulsing the atomic flux into the chamber would be the ideal way to oper-

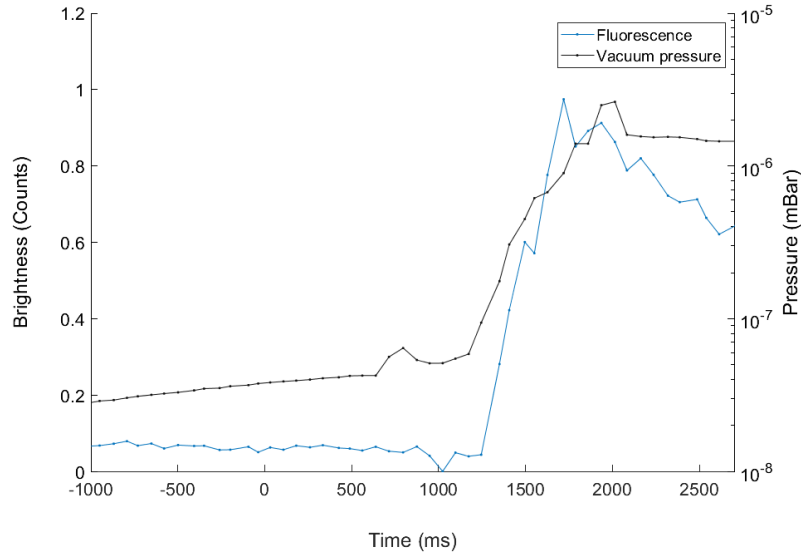


Figure 4.12 The characteristic trend of measured brightness and pressure when atoms start to be emitted from the SrO powder. During the measurement the emission laser is on throughout. The pressure slowly increases once a spot is found that can release strontium followed by a rapid increase in pressure and detection of fluorescence. The fluorescence signal reaches a peak and starts to fall whereas the pressure remains high.

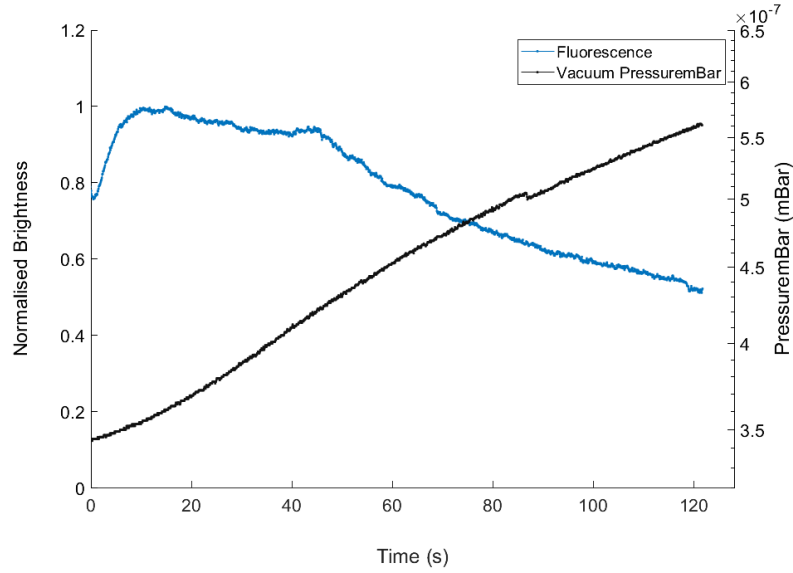


Figure 4.13 An example of the change in measured fluorescence brightness and pressure during constant exposure from the emission laser. The characteristic trend of decrease in brightness while the pressure increases can be seen; however, here the pressure does not increase rapidly to a value where there is risk of damaging the ion pumps which often happens in these measurements. This shows it is possible to have a constant output of strontium if the correct laser power and powder structure can be achieved but it is uncertainty what these exact parameter are. It is likely to achieve this while with a constant UHV pressure a larger vacuum will be required.

ate an optical atomic clock as this would reduce the background pressure and flux of strontium atoms through the trapping region after the MOT has been loaded. This reduces the number of collisions with the trapped atoms during clock spectroscopy. These collisions would increase the chance atoms are removed from the trap and thus negatively effect the clock signal obtained so a reduction in this is ideal. The emission laser is pulsed, as shown in figure 4.14, and this allows a high flux during loading of the atoms but also allows the pressure to fall within the system once loading has been achieved.

4.4.3 Characterisation of the source

The effect of pulsing the emission laser was then tested to simulate a clock experiment cycle where emission would only be required while loading the blue MOT. This proved effective at emitting strontium over many cycles and helped to keep the pressure lower as it dropped while strontium was not being released. This also showed there was a delay between the emission laser striking the target and the release of strontium which had a strong dependence on how long the laser was covered after the previous emission, as shown in figure 4.15. The delay between the laser interacting with the source and the emission of the source was further investigated. Reduction in the delay or precise knowledge of this parameter would be crucial for designing an experimental cycle so a flux of atoms was available at the correct time to be captured in the MOT and have a quick load. Figure 4.16 shows how the amount of time the laser was off for affects how quickly strontium is

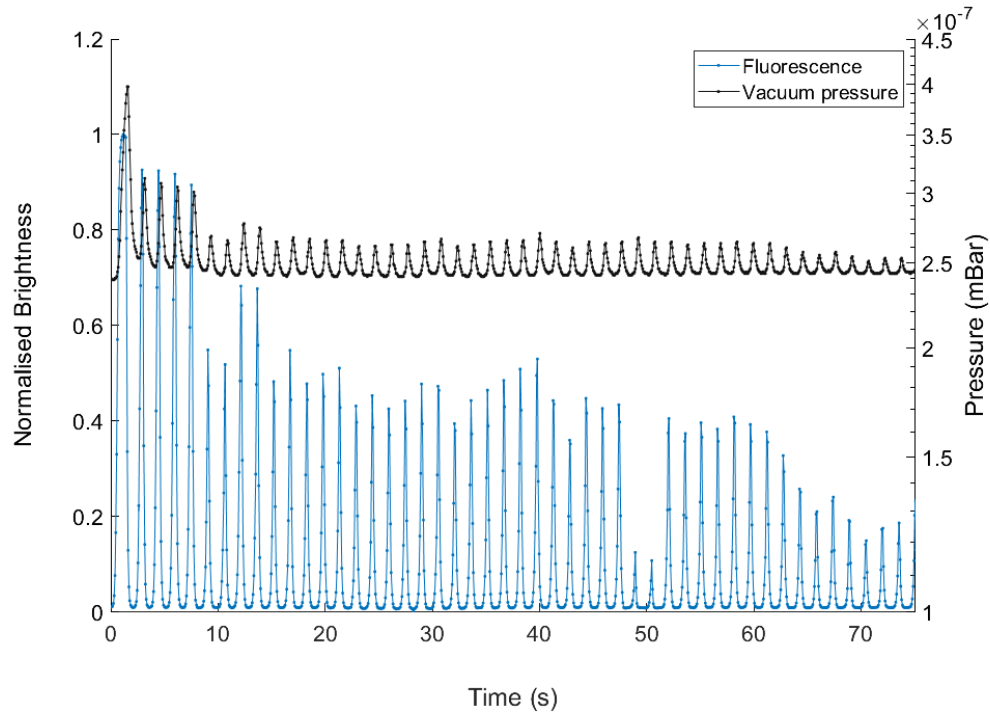


Figure 4.14 A graph showing the change of brightness and pressure when stimulating atoms to release in a pulses. The laser power of each pulse remained the same and the measured brightness well over the measure. The pressure fell between pulses but the minimum pressure remained roughly at the same level.

observed. This effect was also seen if the emission laser was turned off for too long, after a certain length of time with no laser stimulation, usually 3 or more seconds, the source would no longer release strontium. However, this was not always the case, and it was possible in some instances where the initial conditions that allowed the output to start were not destroyed during output stimulation that output could be seen after a prolonged time without the emission laser interacting with the source. This can be seen in figure 4.17 where the emission laser is blocked for over 5 minutes and emission is stimulated once the laser turns back on.

This indicates that residual heat energy is left in the source after strontium has stopped being released which then dissipates over time. When observing the source directly with a camera, it is clear that the source gets very hot during the measurement as the brightness of the source increases after the initial switch on of the 405 nm laser and continues to glow after the emission laser is blocked. This is confirmed by placing a high pass filter in front of the camera to confirm the light emitted is not from reflection of either laser or a fluorescence effect. This is plotted below, figure 4.18.

This is not ideal for a clock experiment as for visible light to be emitted, the temperature of the source must be in excess of 700 K and the black-body radiation emitted will cause AC Stark shifts on the clock frequency. This would not necessarily be a problem if the amount of AC Stark shift is measured; however, as the source cools the frequency shift will be changing over time making it more difficult to model the effect it has on the clock

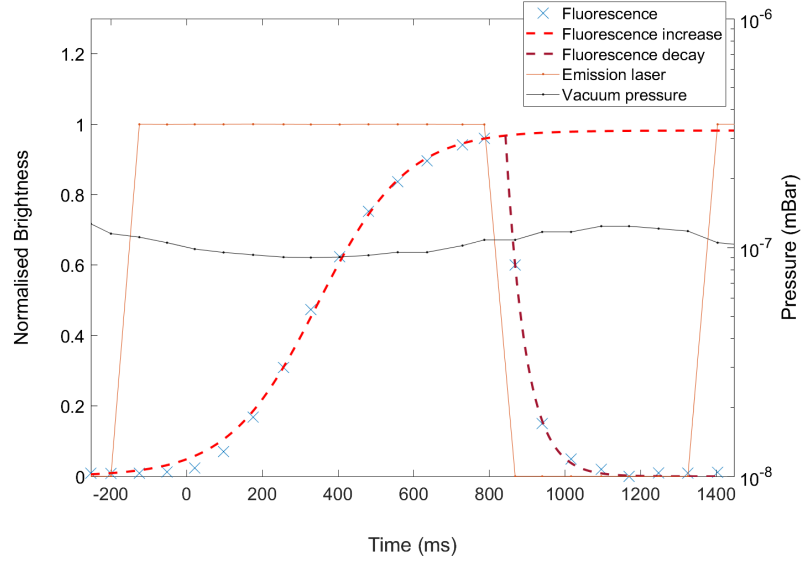


Figure 4.15 The graph shows how the measured brightness from the atoms and pressure changes during each pulse. The increase in fluorescence has been fitted to an exponential increase reaching a maximum output. Maximum output is reached after 1100 ms of the laser being turning on and 970 ms after emission can be detected. The decay of the output once the emission laser is turned off is also plotted which has a decay time of 53 ms and takes approximately 250 ms to become undetectable. There is also a delayed response in the change of pressure but it can not be determined if this data is acquired at the exact same time as the laser emission and change in brightness. There was no way to check if measured pressure value was temporally synchronised with the other data received at the same time thus no time correction was added to this data.

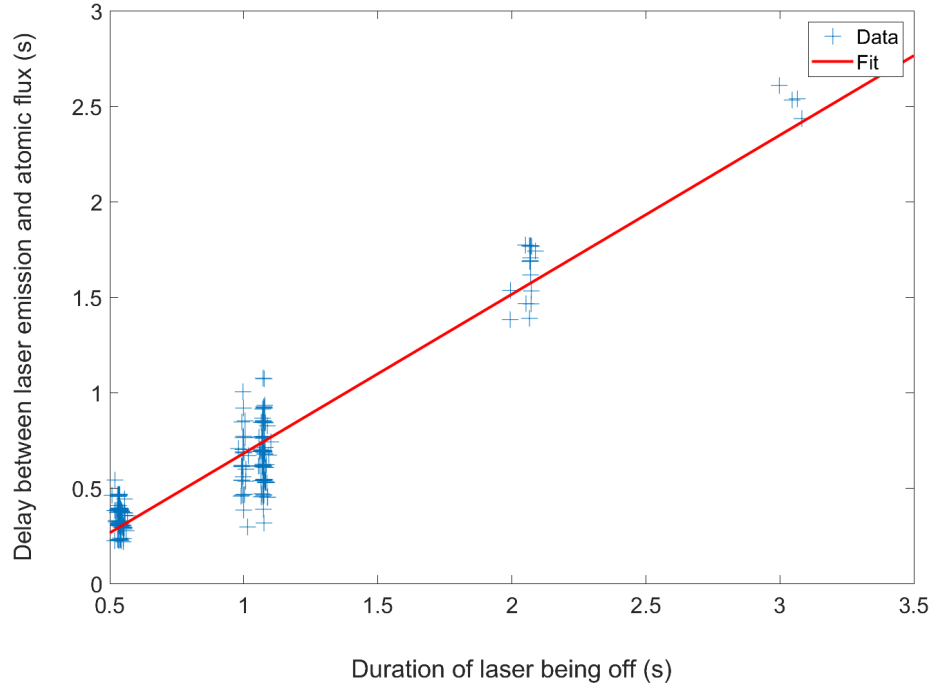


Figure 4.16 The graph shows the relationship between the time the laser is off for and the time it takes for strontium to release from the source. The longest time the emission laser can be covered and an output is reliably achieved is 3 s. Within the range shown the data fits reasonably well to a linear relationship with a gradient of 0.83. For clock experiments, once the blue MOT is loaded the rest of the experimental cycle occurs in under 1 seconds so this loading is well suited for this reason. However, other types of experiments the ability to have longer periods between loading the MOT may be crucial.

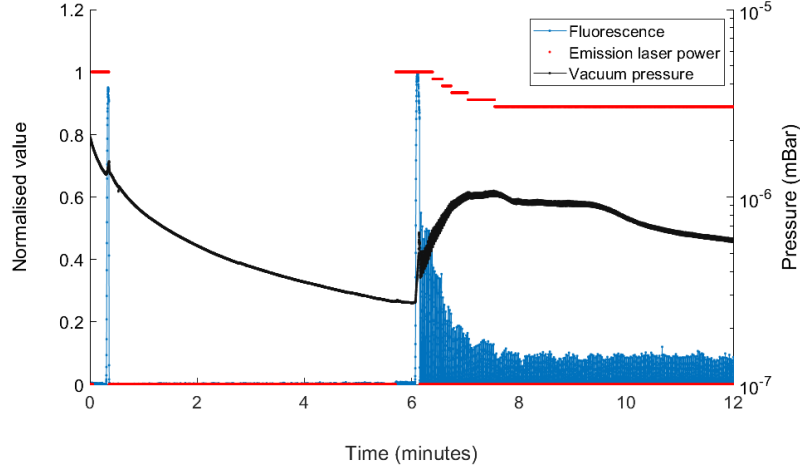


Figure 4.17 An example of how the emission can be stimulated again in the same position when the emission laser is blocked for over 5 minutes. This event is rare and likely occurs only when the initial conditions that allowed emission to start have not been destroyed by the process of sublimating the atoms.

transition. This issue will be further discussed in section 4.5 where possible mitigation will be presented. This results also gives some indication that the atoms are hot upon release and thus a characterisation of the temperature of the atoms was undertaken using a 461 nm probe beam.

4.4.4 Measuring the temperature of the atoms.

Measurements of the atomic velocity were taken in 2 orthogonal directions, along the x and y axis as indicated in figure 4.19. The images taken with the camera observing either the xy or yz plane but images in the yz plane allowed an accurate emission spot to be determined within the area the powder is contained. A probe laser stimulating the 461 nm transition was used to

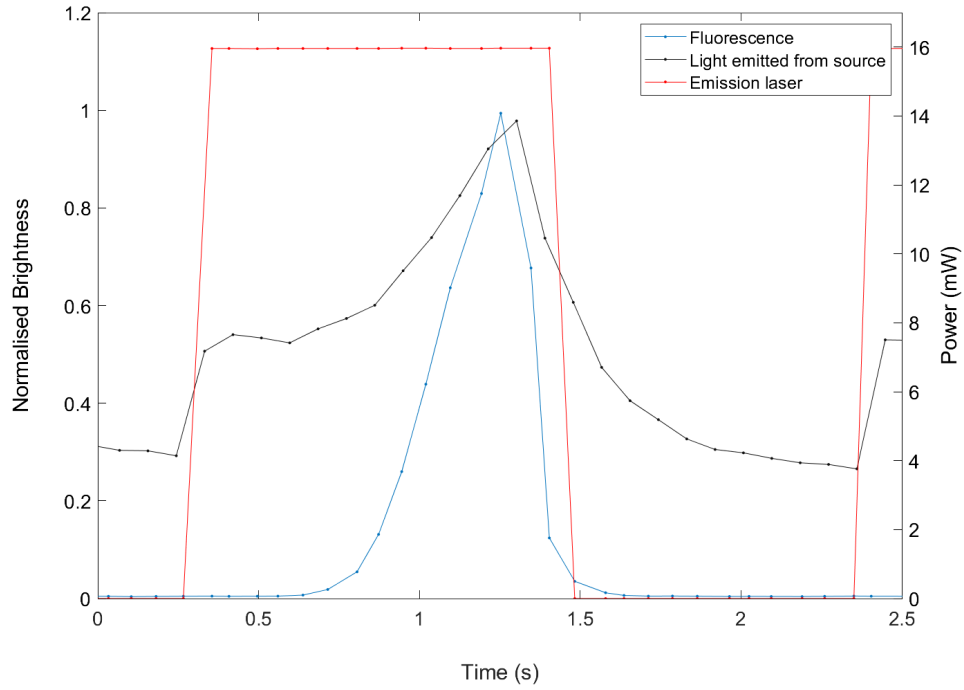


Figure 4.18 The graph shows how the light emitted or reflected from the source changes over a atom sublimation cycle. When the emission laser switches on there is an increase in brightness measured from the region of the atomic source due to reflection. Although a filter is used to block the 405 and 461 nm light there is still some leakage through from the emission laser as a lot of light is reflected from the source which is a white powder. After a short delay the measured brightness increases to a maximum where the emission laser is turned off. This increase in brightness must be due to the source heating and radiating at a wavelength that can be detected by the camera. The brightness drops significantly when the emission laser is turned off, due to the no longer being reflection, and then decays over the period of one second as the source cools.

measure the fluorescence emitted from the atoms at different detuning from resonance: which will allow the velocity distribution of the atoms to be measured due to the Doppler shift of the light caused by the atoms motion. The temperature of the released atoms is calculated by fitting the Maxwell-Boltzmann distribution equation to the measured data. When the probe is placed along the x-axis the light is retro reflected from the mirror, thus when sweeping over the detuning we see peaks either side of zero detuning as shown in figure 4.20. As the sweep occurred over 9.6 minutes we see the 4 maxima in the graph decrease over time due to the depleting of the source. This will cause a slight asymmetry in the data but does not affect the peak velocities as seen in figure 4.22, where the Doppler equation has been used to convert the detuning, Δ , to velocity, v ,

$$v = c(1 - \frac{f_0 - \Delta}{f_0}), \quad (4.4)$$

where c is the speed of light in the vacuum and f_0 is the resonance frequency of the transition.

For each measurement cycle the laser stimulated emission for 1 s and was blocked for 0.5 s. The maximum brightness value for each cycle was extracted and is plotted in figure 4.22. Upon release the atoms move in a straight line away from the point of sublimation, thus are not travelling parallel to the probe beam. Using the knowledge of the location of emission and a CAD model of the system, the angle between the atomic trajectory

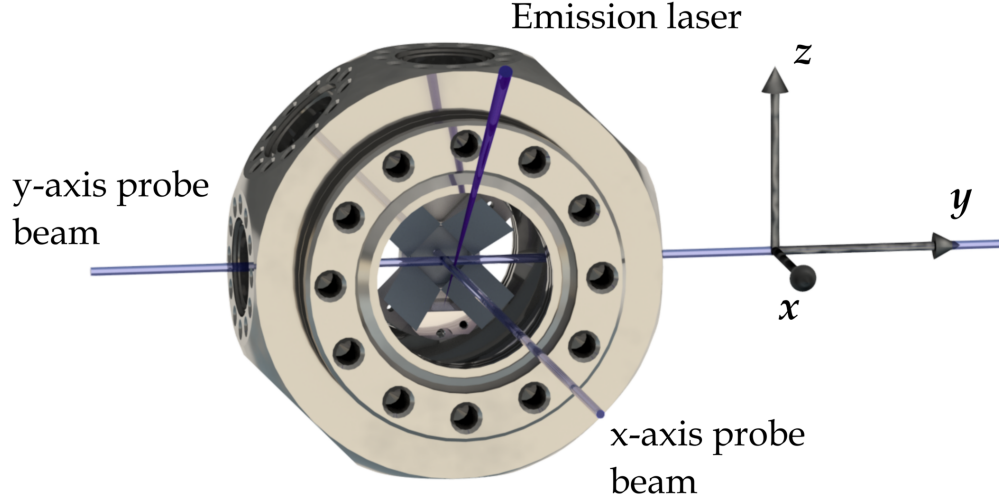


Figure 4.19 A rendered image of the chamber with the direction of the beams used to measure the temperature of the atoms.

and the probe beam at the MOT trapping region can be determine. Over the length of the probe beam atoms will have different trajectories, thus will experience a different Doppler shift, thus have maximum fluorescence at different frequencies so to overcome this issue a small segment of the detected image is extracted where the atoms will all be travelling in the same direction as seen in figure 4.21. This allows measurements to be taken on a beam of atoms instead of an expanding comb, allowing a simpler model for the Maxwell-Boltzmann distribution to be used.

The measurement is set up such that the atoms all travel in the same direction in the region of interest so the Maxwell-Boltzmann distribution for molecular speed to be used to find the temperature T of the atoms. This

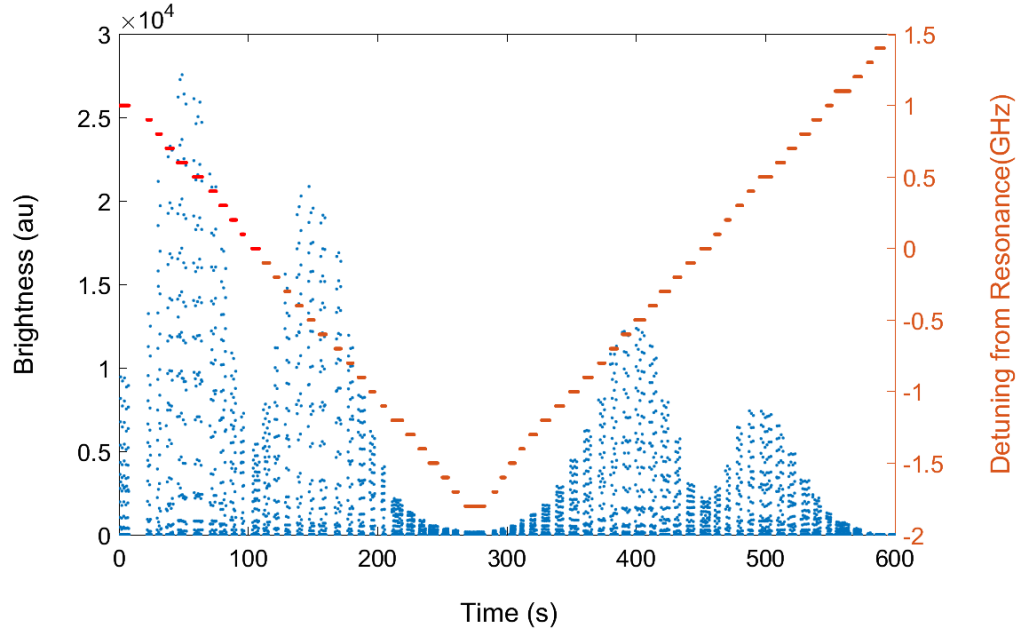


Figure 4.20 The graph shows the data collected during the measurement to acquire the temperature of the atoms. The data was taken with the probe beam along the x-axis of the chamber, thus it reflects from the in vacuum mirror and there is 2 frequencies were the detuning and Doppler shift cancel out giving a maxima in the fluorescence measurement. 4 peaks appear in this graph as the frequency was swept over resonances twice. Each peak decreases in amplitude as the amount of strontium being released each pulse decreases. The maximum value of each pulse can be extracted and used to find the temperature of the atoms.

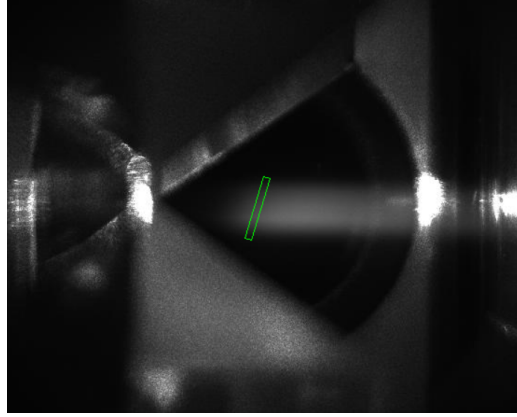


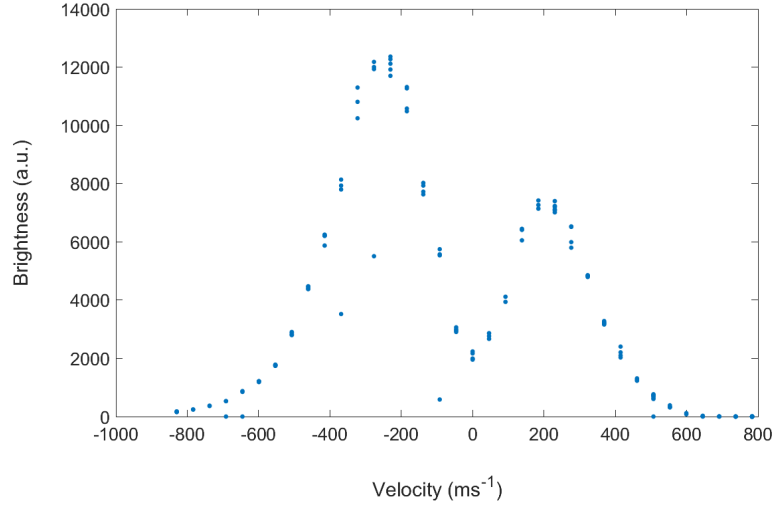
Figure 4.21 An example of the ROI that has been used to measure the brightness for the atoms with the same velocity. The ROI is angled towards the location the atoms are emitted from. The width of the ROI was adjusted until the width of the velocity distribution did not decrease further if the width of the ROI was made smaller. This proved that the atoms in the region had the same velocity and would allow a temperature distribution to be fitted.

equation is as follows,

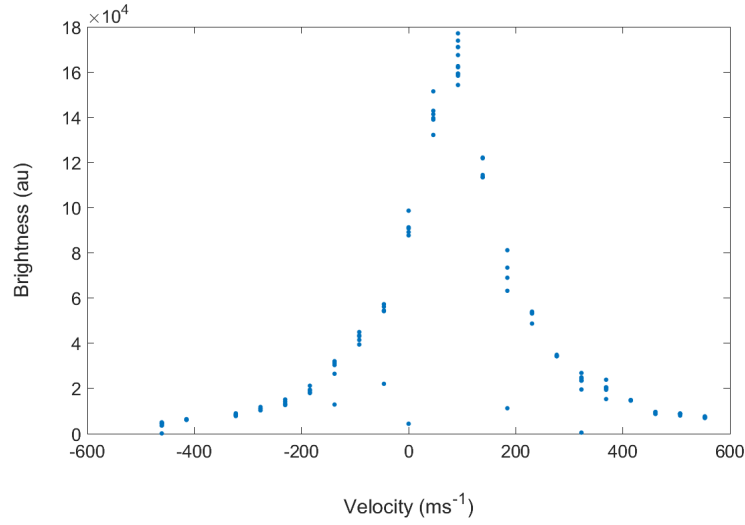
$$f_v = 4\pi \left(\frac{m}{2\pi k_B T} \right)^{\frac{3}{2}} v^2 \exp \left[-\frac{mv^2}{2k_B T} \right], \quad (4.5)$$

where v is the atomic speed, m is the mass of a strontium 88 atom and k_B is the Boltzmann constant.

This equation is fitted to the data extracted to allow a value of T to be found by using a multiplication factor, A , to scale the measured brightness to the distribution of the atoms. For the case where the measurement is along the x-axis there are two distributions either side of zero which are separated for fitting.



(a)



(b)

Figure 4.22 The graphs show the velocity distribution of the atoms at the trapping region of the science chamber along the x-axis in (a), and y-axis in (b).

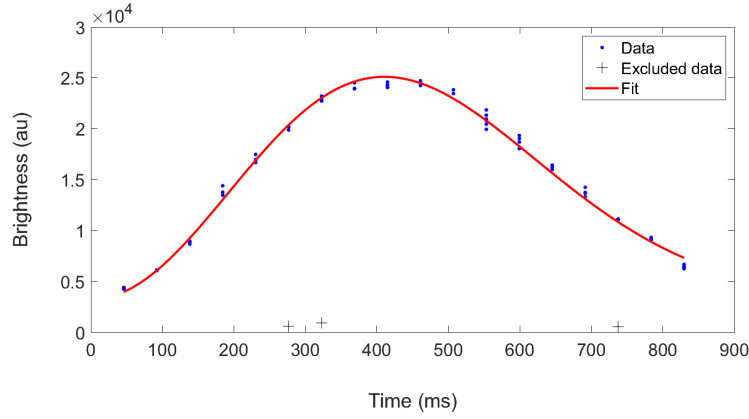
As the speed of the atoms is desired to be used there needs to be compensation for the angle between the atomic flux trajectory and the laser beam as this angle will effect the Doppler shift and thus the measured resonance frequency of each atom. To achieve an accurate temperature measurement the angle between the atoms trajectory and the laser, θ , is used so that v becomes $v \cos \theta$. This leads to a strong dependency on the knowledge of θ especially when the angle is close to 90° . Due to the uncertainty on the exact location the atoms emit from the source it is difficult to precisely know the angle between the source trajectory and the probe laser. This uncertainty leads to a very large error when measuring the temperature at the trapping region (approximately 1000 K for a $\pm 1^\circ$ error). To reduce this effect, the fluorescence is measured at a point where the angle between the atomic trajectory and the probe laser is much less by selecting a region of interest close to the side of the chamber, thus reducing the uncertainty by a factor of 20. The fits to these extracted curves can be seen in figure 4.23 with the output temperatures from the fitting curve being 1762(27) K and 1690(74) K when the probe is located in the x or y axis respectfully. An estimated 4° error on angle correction for the x axis and 2° error on the y axis gives a range of temperatures 1671 - 1871 K and 1629 - 1803 K, thus an estimated temperature of approximately 1700 K proves a estimate of the temperature of the release atoms. A more accurate temperature measurement requiring a specialised set up to measured directly against the trajectory of the atoms. This ball park number is slightly higher than predicted in the discussion in

section 4.2.3 however is consistent with the observation of visible light being emitted from the source.

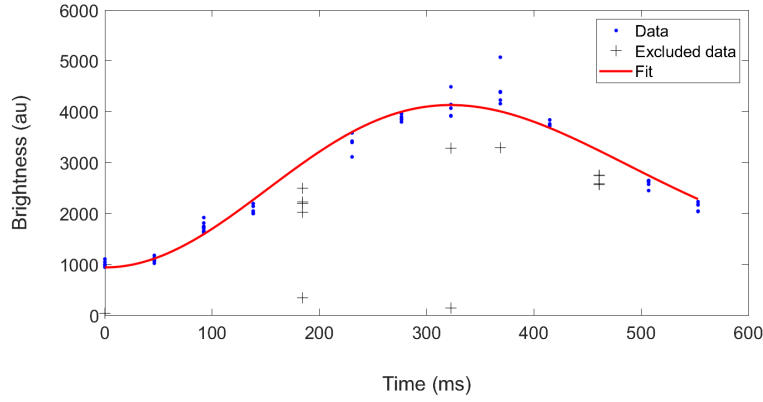
4.4.5 Pressure

Investigating how the pressure of the system affected the strontium emission from the powder proved to be very difficult throughout the project. It is expected that at high pressure higher laser power or longer sample illumination time is required to cause the release of atoms, however testing this was not performed successfully. Although the pressure increased between 1 and 4 orders of magnitude above the background pressure of 1×10^{-9} mbar due to oxygen released into the system, there was no clear evidence it affected emission. The primary objective in regards to pressure was to ensure that there was a sufficient decrease between emission pulses so that the pressure would fall or remain stable over time. The pressures observed during experimentation were low enough to achieve a MOT, as shown in section 4.4.8, but would not be suitable for atomic clock experiments. Additional pumping to the chamber would allow comparison measurements to be made to determine how the pressure affects the performance of the source, how low the pressure could be kept during operation, and what type of experiments the source could be suitable for.

The majority of the pressure increase occurs during initial stimulation of a strontium output flux, both while scanning the emission laser position for a point where the conditions for starting sublimation are met, and in



(a) x axis velocity distribution



(b) y axis velocity distribution

Figure 4.23 The graphs show the velocity distribution measured along the x and y axis of the chamber. The fitted Maxwell-Boltzmann distribution allows a temperature to be extracted for each plot. Some data points have been excluded from the either when either emission flux was unexpectedly low or the code used to extract the data failed.

the first output before the timed sequence of the beam is turned on. Both of these areas have room for improvement in order to better control the pressure levels in the system. Figure 4.17 shows how the pressure can be allowed to fall for a longer period when an area where sublimation first occurs and if those conditions have not been destroyed by the emission occurring. This was also performed with a delay of 20 minutes and 1 hours indicating it is likely possible to let the pressure drop to background levels before an experiment is undertaken. To keep the pressure low during the first emission of strontium, improved experimental control would allow the power in the laser to be adjusted and turned off in real time once a suitable output is reached, limiting the emission of unnecessary atoms.

4.4.6 Improving the consistency of trapping from a laser emission source

Now the source has been characterised and better understood the aim is to improve the reliability of the source for use in a cold atom system. As discussed at the beginning of this chapter the main difficulties with this source were the initial stimulation of strontium output, keeping the output working for a prolonged length of time, and consistently capturing atoms in a MOT.

For this loading method to be usable in quantum technologies an output that is longer than what has been attained and shown so far needs to be

achieved. It is as yet uncertain how to create the properties in the powder so that atom emission can be reliably achieved, thus a different method needs to be found. As has been demonstrated, atomic flux is much more likely from a point that is already glowing hot. This is the case at the point of emission, as well as the areas adjacent to this point. This was utilised by moving the emission laser slightly to focus light close to the previous point of atomic release and where the source is still warm enough to allow sublimation to occur. The output of strontium would then still occur but in an area that has a higher accessible reserve of strontium and thus allowed the atomic flux to increase. This effect can be seen in figure 4.24 where the emission laser is operated in pulses and after multiple cycles the measured brightness starts to decrease as the surface atoms become depleted. It is therefor assumed that only the surface atoms can be heated sufficiently to produce the required atomic flux for the experiment. This is shown as the output of atoms decreases despite a new, lower layer of atoms being exposed to the emission laser. Moving the laser allows this reduction in output to be compensated for and maintain a useful atomic flux for the experiment.

Once it was determined that the flux output could be increased, it is then necessary to determined how long operation could continue using this method. This was undertaken by hand, monitoring the output and adjusting the position of the emission laser until a increase in the measured fluorescence was observed, this can be see in figure 4.25. It would be later desirable to set up automatic feedback where a piezoelectric actuator mount would control

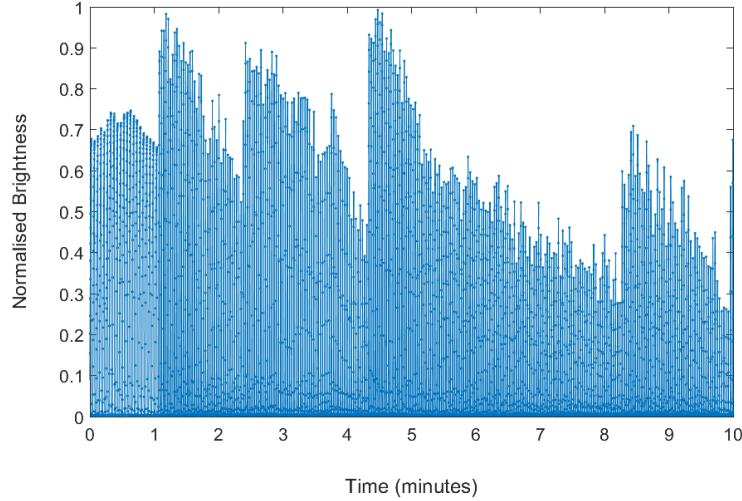


Figure 4.24 This graphs shows that an increase in atomic flux is possible by moving the position of the emission laser. An increase in brightness can be seen at around minute 1, 2.5, 4.3 and 8.2.

the laser position in responses to a decrease in measured value. One hour of continuous output however, is a good indication that this method could prove robust in an automatic system.

As the source had to remain “warm” between pulses to ensure that emission could continue, it was investigated whether decreasing the laser power instead of blocking the laser would allow the time between loading phases to be longer, and the output of atoms to occur quicker after the pulse. This will be referred to as the “high/low” method, where blocking the laser will be called “on/off” method. After some experimentation it was found that adjusting the laser between 18 mW and 8 mW in a pulsed fashion allowed there to be consistent output while allowing the pressure to fall between “high” pulses.

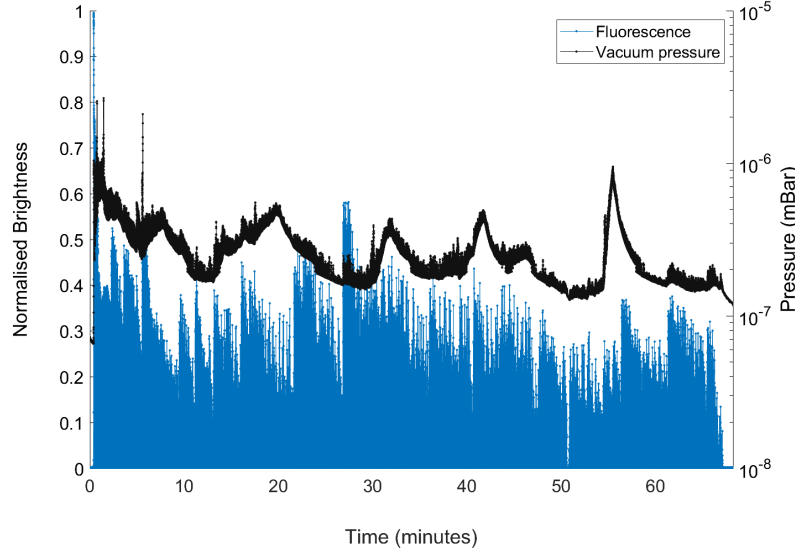


Figure 4.25 The figure shows how strontium can be output from the source for over an hour duration when pulsing the output and adjusting the emission laser position to increase the emission.

This experimentation can be seen in figure 4.26 with figure 4.27 showing a few cycles at the above values. The duration between the laser power being high and the duration until atomic emission is extracted from the data and plotted in figure 4.28. This shows that the release of strontium occurs much sooner after the emission laser is set to the high/low method than it was observed in the on/off method, figure 4.15, and can still regain output after a far longer period of no emission of atoms. However, if the duration the laser is off for is too short, this will lead to a increase in pressure as seen in figure 4.29, likely due to the long decay time for this loading technique which was 317 ms for the example high/low method shown in figure 4.27 and 53 ms for the on/off method example in figure 4.15. Previously it has been

observed that the pressure falls during the measurement unless the laser is moved to stimulate higher output, but it is clear in this graph that a short duration between emission pulses with the high/low power being used here is not suitable. For a strontium clock it is usual to have a short loading period into the blue MOT and the rest of the experimental cycle occurs in under one second, thus the high/low method does not seem suitable for an atomic clock, unless the increase in pressure can be compensated for with a larger ion pump and the long decay time is shown to have no negative effects later in the experiment cycle. It is also possible that a lower optical power in the “low” part of the emission laser cycle would be a good compromise to stimulate quick strontium output and allow the pressure to fall between emission pulses. The change in power in this experiment was driven by changing the supply current to the diode and a wider range of powers was not attempted to avoid damaging the diode. Other methods of adjusting the laser power are possible and would need to be used to investigate this method further.

4.4.7 Optimising the sample holder for the atomic source

To investigate the uncertainty around the trajectory the atoms would take when emitted from the powder, and how the angle between the laser and surface of the sample would effect this, two sample holders were designed which would hold the sample in different angles in relation to the trapping region. The sample holders were secured next to the prisms so they were as close as possible to the trapping region in the chamber. This would act

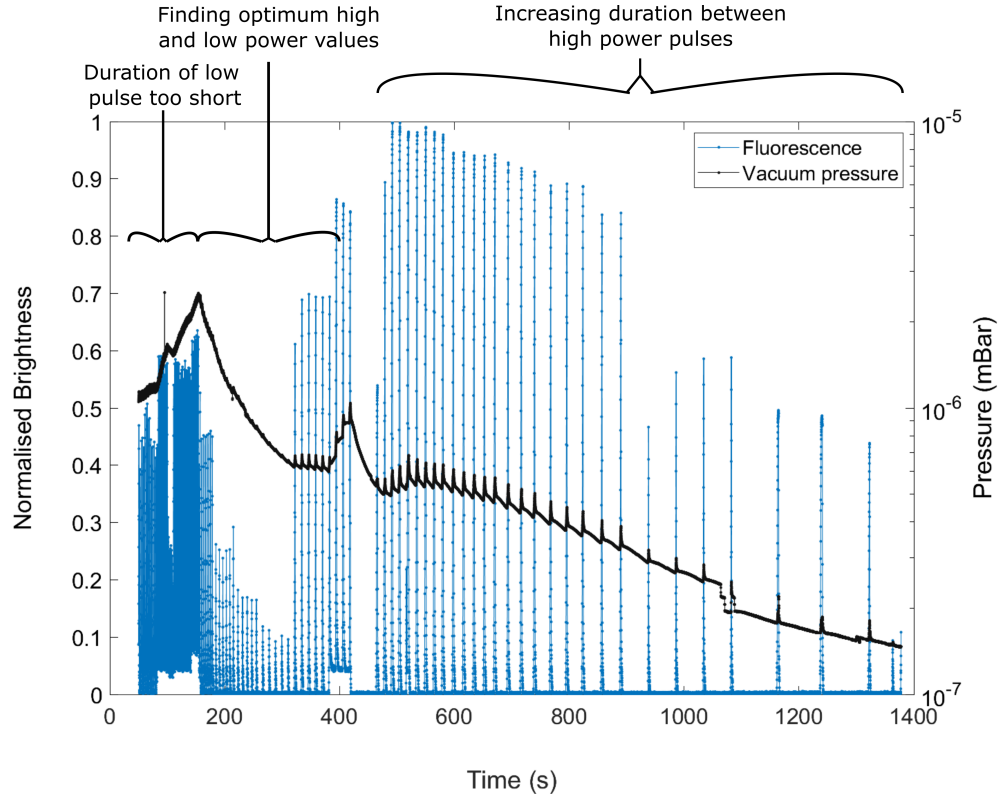


Figure 4.26 The graph shows the experiment that was undertaken to investigate the high/low method. The investigation aimed to find a timing sequence and power where emission would occur every laser pulse and the pressure would remain the same or decrease over time. It is possible to see that before 200 s the pressure was increasing due to the short duration the laser remained at low power. Between 200 and 400 s both the high and low power values were adjusted until a high atomic flux output was observed for each pulse, the emission would stop between each pulse and the pressure would remain stable or decrease. Finally the duration between high pulses was investigated for the rest of the measurement shown.

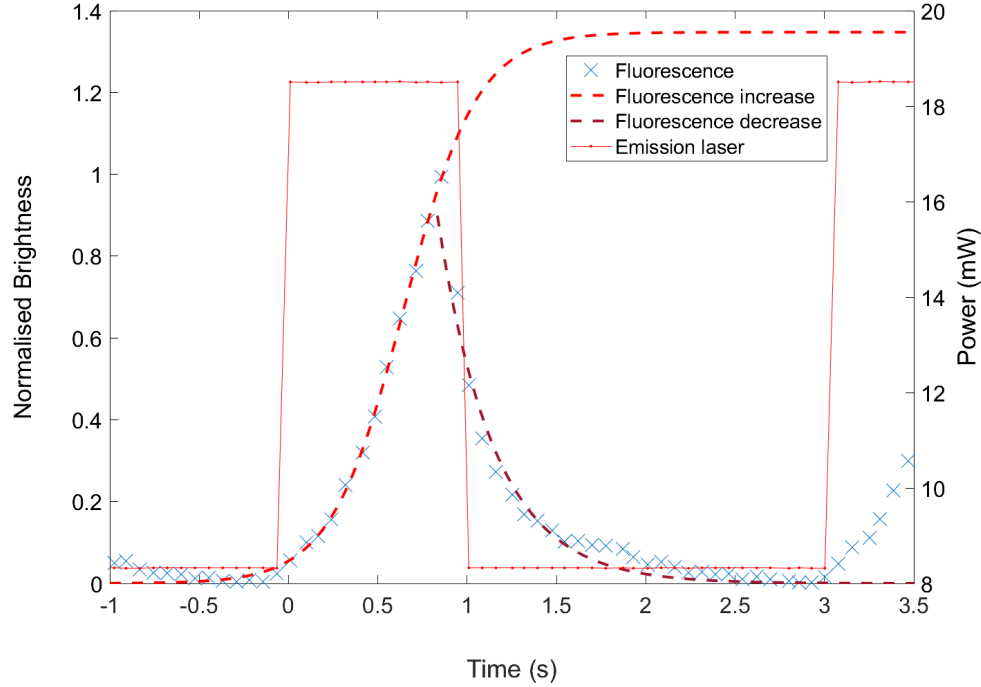


Figure 4.27 The graph shows how the measured atomic flux changes during emission laser pulses using the high/low method. With a high power of 18 mW for 1 s and low power of 8 mW for 2 s, it was possible to observe the atom sublimation drops below a detectable limit between periods of emission. This indicates that emission stops during this time, allowing experimentation on the atoms without a local source of high pressure affecting results. Emission then reoccurs very rapidly after the emission laser is set back above threshold. This is an improvement on the on/off method where if the emission laser was off for 2 s it would take approximately 1.5 s for emission to start. Although the emission is quicker to start, it takes longer to reach each maximum output, 1800 ms instead of 1100 ms for the period method, this is likely due to a higher flux of strontium being emitted in this method which is evident from the steeper gradient of the slow and the fact the pressure reading was higher for this method. The decay is also plotted which is much slower with a decay time of 317 ms and taking approximately 1.5 s for the output to become undetectable.

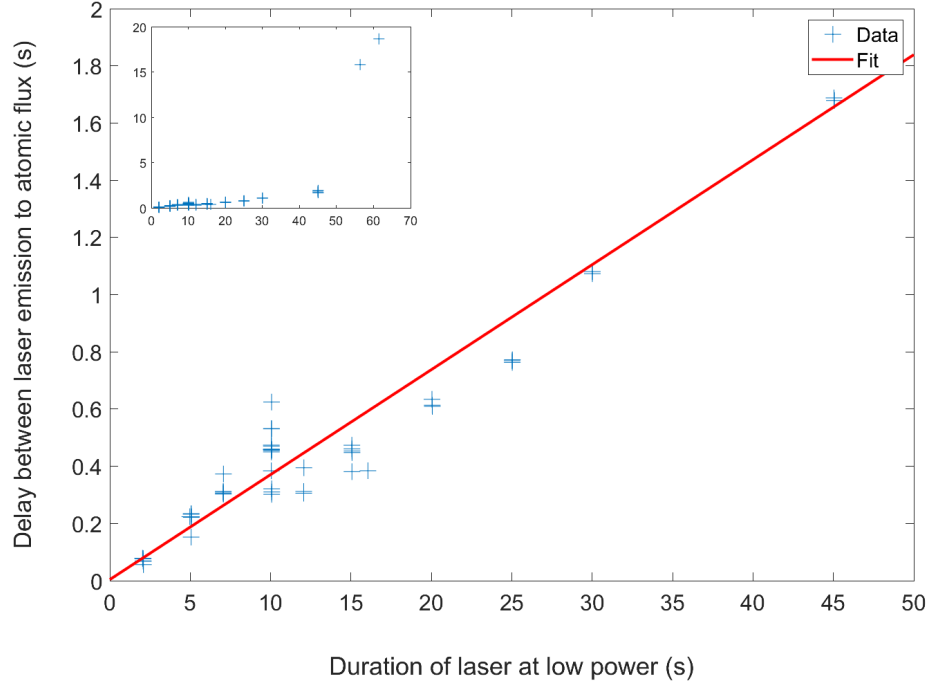


Figure 4.28 The graph shows the delay until emission is observed from when the laser is set to high power in the high/low method with varying low power duration. This shows that emission starts 5 time faster at 1 s low duration compared to the laser being blocked for the same duration. The gradient of the linear fit is 0.037 for the range between 0 and 45 s, compared to a gradient of 0.83 for the on/off method. It is clear that reducing the laser power below threshold for atomic flux output allows for atoms to be released much quicker, especially when it is necessary to have long periods being atomic flux output. An additional benefit is the duration between emission can be extended over a far greater range. For the on/off method, 3 s between emission pulses was the maximum reliable duration that could be allowed before the powder cooled too far and emission could not be regained. The inset graph shows that this duration could be extended to at least 60 s however the linear relationship no longer holds.

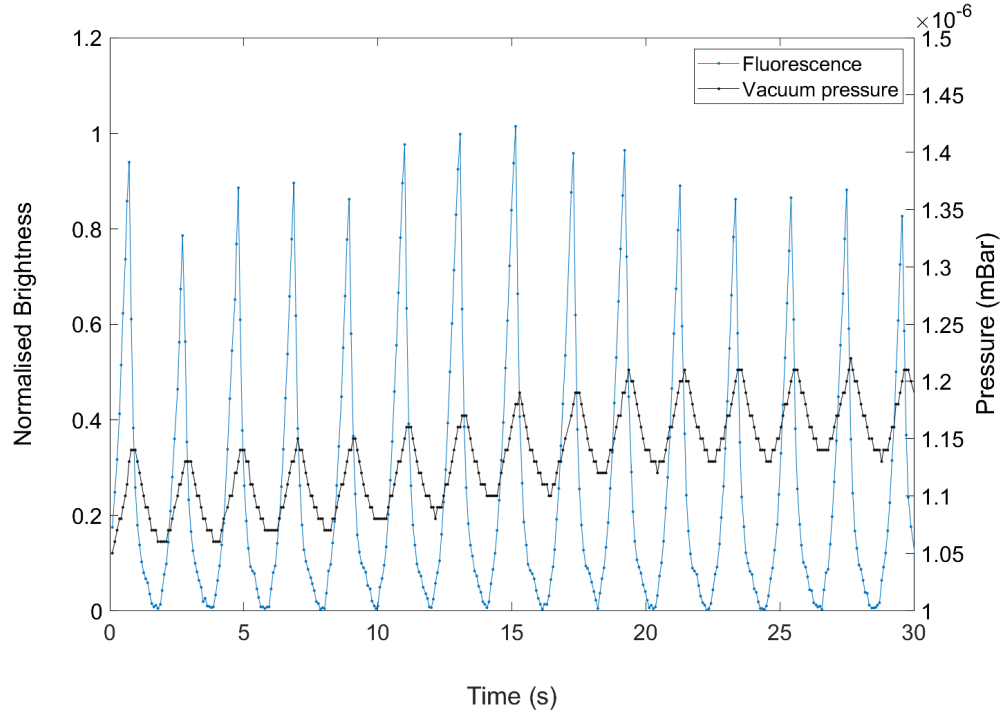


Figure 4.29 The graph shows how the pressure inside the chamber slowly increases when the emission laser is pulsed using the high/low power method. The pulse is high for 1 s and low for 1s, a cycle that proved very effective with the on/off method, however here the pressure does not fall as quickly between pulses meaning it gradually increases over time. It is possible this effect could be compensated for with a large vacuum pump but this was not tested in this project.



(a) flat sample holder



(b) angled sample holder

Figure 4.30 The two sample holders tested within the experiment. Holder (a) when mounted points towards the cf35 viewport of the chamber, whereas holder (b) points directly at the trapping region of the chamber.

to increase the flux of atoms through the trapping region and improve the reliability that the atoms released from the source would pass through an area where they can be trapped. The holders were made of aluminium, with the flat holder having a hole 2 mm in diameter and 2 mm deep where the powder was held. The angled holder allowed for a larger hole that was also 2 mm deep, see figure 4.30. The flat holder held so sample surface would be perpendicular to the cooling light, whereas the angled holder would directly face the area the MOT would form. A consistent laser trajectory was used for the emission beam, emitted from a point on the other side of the trapping region to the sample holder being tested, without passing through the point where MOT would form, see figure 4.31.

Initial tests measured the flux of atoms at the trapping region using a narrow beam of light on resonant with the 461 nm transition for strontium 88. This would give a strong indication on what locations strontium was

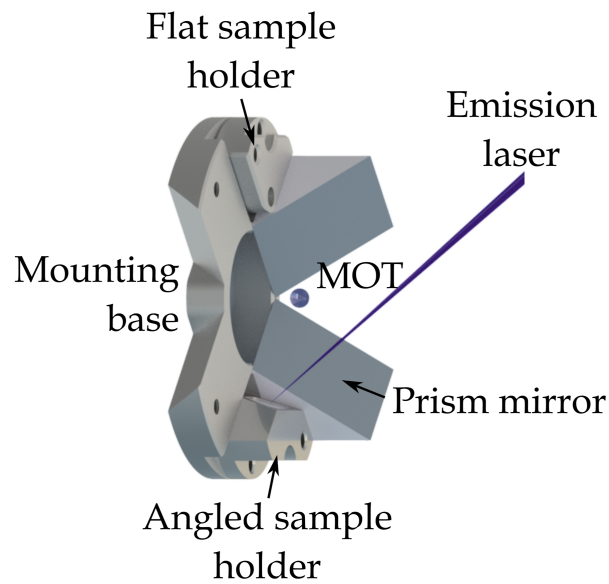
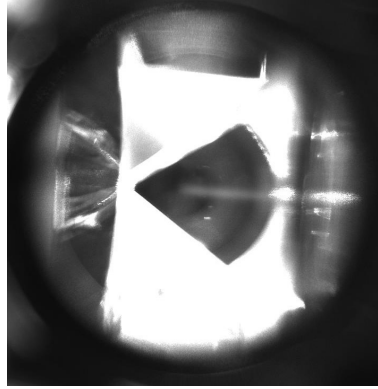
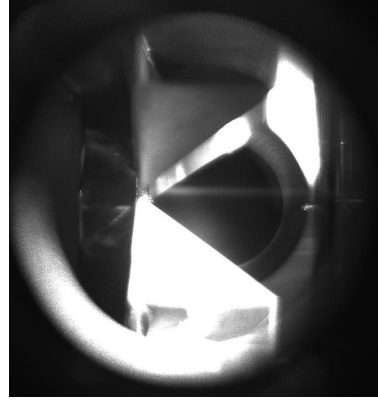


Figure 4.31 The sample holders are secured next to the prism to minimise the distance between the source and the trapping region. One holder points towards the front of the science chamber (top) while the other points directly towards the trapping region (bottom). The emission laser is shown for one of these sample holders and is directed at the target from the other side of where the MOT would form without passing through this area to avoid effecting the trap.

emitted to and that would be able to be trapped in the MOT. Figure 4.32a shows a problem for the flat holder as no strontium is detected in the area closest to the mirror and waveplate. There is a cut off where no strontium is observed which could set the limit on the biggest angle the strontium is released at. However, it is possible that the powder is recessed into the hole made to hold the sample, preventing it from having a line of sight to the area closest to waveplate and mirror. This is not a problem for the angled holder which shows a much more even distribution over the region that MOT would be formed, figure 4.32b. Adjusting the angle of the laser incident on the source made no observable difference of the angle the strontium atoms travelled once emitted so the angle of the release can not be corrected for in this way. Additionally, it was observed that for different points of emission on the source surface the range of emission angles could be drastically different as seen in figure 4.33. It is assumed this is due to small angle changes along the source surface as the topography of the powder changes between areas. It is observed that a small change in the area of emission will effect the angle and range of angles the atoms are released at, thus it is crucial that the source be held close to the trapping region with the surface angled towards this point. In this experiment the distance between the powder surface and the trapping region was 11 mm which allowed a consistent flux to be detected at the trapping region. For a majority of the results shown in this thesis so far, the angled sample holder was used to obtain the graphs and images.

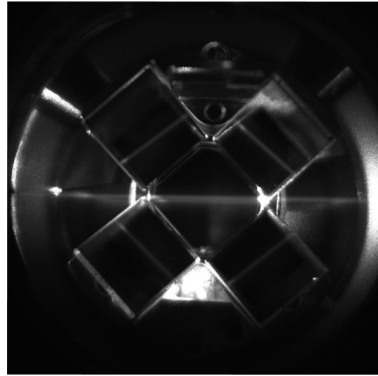


(a) flat sample holder

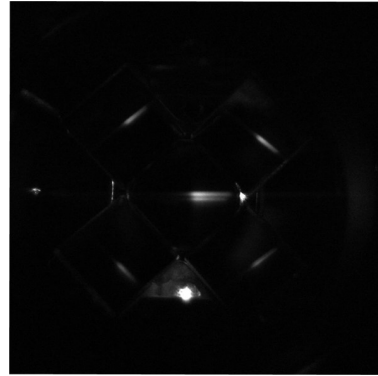


(b) angled sample holder

Figure 4.32 The atomic distribution released from the flat and angled sample holders. A detection beam at resonance frequency is used to probe the location of the emitted strontium for the two different design of holders.



(a)



(b)

Figure 4.33 The two images show how a small different in location of emission can make an extreme difference to the range of trajectories with which the atoms can leave the source. The exposure of the camera is different between the images but both used an on resonance detection laser. Fortunately in both images atoms are detected at the trapping region of the science chamber and were taken using the angled sample holder.

4.4.8 Obtaining a MOT with the optically activated source

The angled sample holder was established to achieve a better atomic flux through the centre of the chamber and thus will give the best chance of capturing atoms in a MOT. Initially alignment of the trap was established using an atomic dispenser to allow the cooling and repump beams to be aligned. An atomic output from the source was achieved using the on/off method and a MOT was detectable at the trap centre as shown in figure 4.34. This was a great success and it was clear that MOT could be loaded consistency due to atoms always passing the trap centre. Improving the reliability of the source was one of the main objectives of the project and it was clear that moving the source close, and angling it towards, the trapping region was a big step forward to achieving this goal.

The consistency of the MOT loading over time was tested and this proved to be good, with the brightness of each MOT measured to be the same. An example of this can be seen in figure 4.35 which additionally shows the brightness of the MOT and hence the number of atoms captured, can be controlled with the laser power. This proves the laser power allows some control over the flux of atoms release and the loading rate of the MOT. A single MOT load is plotted and analysed in figure 4.36 this shows the values for the loading and decay of the MOT compared to the times for the release of atoms from the source.

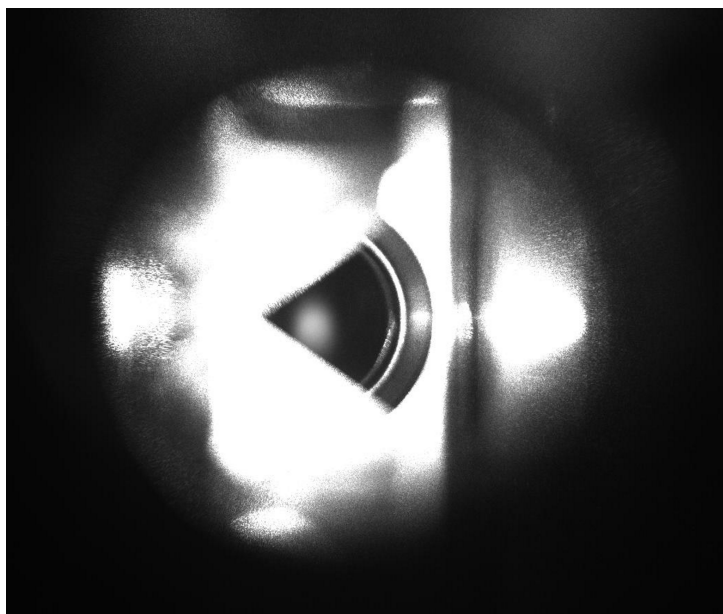


Figure 4.34 An image of a MOT trapped in the test chamber using an optically activated source.

The dispenser that was attached to the system allows a comparison of the MOT that can be achieved in this system using the optically activated source to a more common atomic source. The dispenser is attached to a feedthrough and held in a nipple attached to a CF16 viewport on the chamber. There is no aperture or differential pumping between the dispenser and science chamber, meaning the pressure will be higher in the science than it would normally be experience in a system designed to use a dispenser. Despite this, a comparison between the two source types can still be made. Figure 4.37 shows this comparison within this chamber taken with the same parameters.

The effective and reliable loading from the optically activated source into a MOT has been shown to work for many experimental cycles. The knowl-

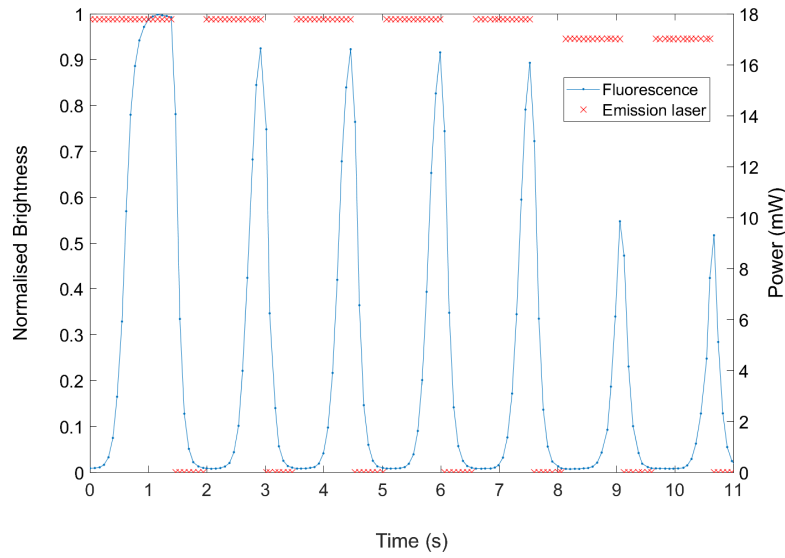


Figure 4.35 The graph shows the capture and decay of atoms from a MOT when the optically activated source is switched on and off. It is also possible to see the MOT brightness decrease by 40% when the emission laser power is decreased by 1 mW while the pulse duration is kept the same. This is a clear example that the emission laser power can be used as a control for the loading rate of the atoms into the MOT.

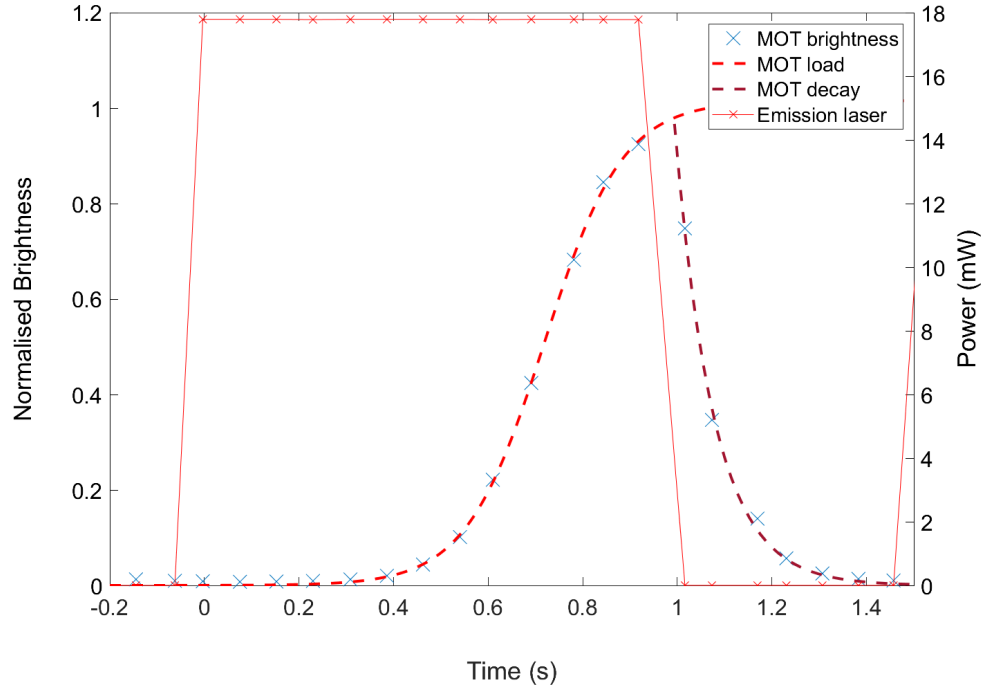
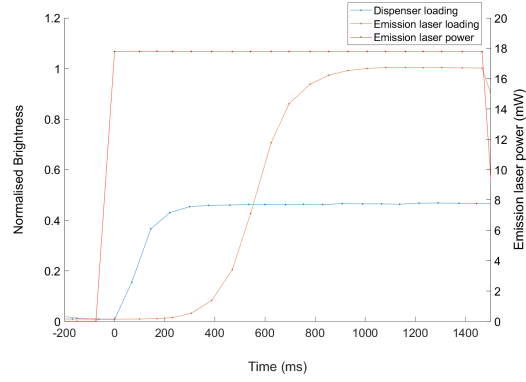
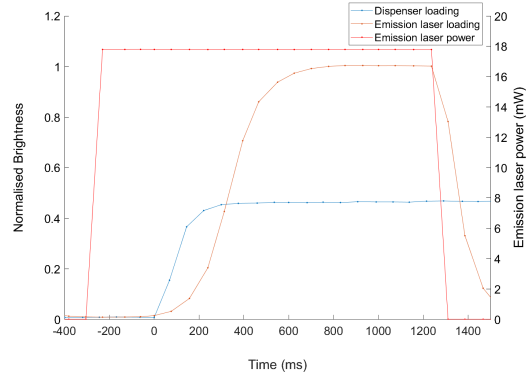


Figure 4.36 The graph shows a single load into a MOT using the optically activated source and the load and decay have been plotted. Here the on/off method was used so there is a 0.3 s delay between the emission laser turning on a the MOT being detected. The MOT reaches a steady state after 1.2 s. The decay of the MOT has a decay time of 82 ms and takes 470 ms to reach a background reading. Both the decay time and time till zero reading are longer than is seen for the decay in strontium emission from figure 4.15 where these numbers were 53 ms and 250 ms respectfully. This is longer period is due to the atoms being trapped within the MOT.



(a)



(b)

Figure 4.37 A comparison of the MOT achieved with a dispenser vs an optically activated source, showing the atom number that can be achieved with these two sources and switching of the emission laser. (a) shows these two sources loading with zero seconds occurring at the switching on of the magnetic field for the dispenser source and the switching on of the emission laser for the optically activated source. Although the dispenser MOT loads much faster it reaches saturation at a lower atom number. The measured pressure during these measurements was approximately the same at 3×10^{-7} mBar. However for approximately the first 200 ms of the emission laser being switched on no MOT is detected and there is little to no atomic flux. Thus the emission laser could be switched on before the end of the previous experimental cycle to ensure quick loading of the MOT if the emission laser has no effect on the measurement taking place. An example of this is shown in (b).

edge gain when investigating measuring the fluorescence can be applied to create fast and efficient loading of the trap. The loading of the trap reaches saturation after 1200 ms with the 50 mW blue trapping beam used in this experiment. This will allow the a experimental cycle of MOT loading for approximately 1 s, and further cooling and measurement for up to 1 s. This has proven to work reliably throughout the study of this type of source. Despite the higher average atomic velocity, the optical activated source can trap more atoms than using a dispenser and allows the rapid switch off of the source to reduce collisions between thermal and trapped atoms. It is likely that the oxygen released into the chamber will negatively effect the lifetime of the trap, however without a comparative measurement and significantly lower vacuum pressure it is not possible to characterise this effect.

4.5 Conclusion

It has been shown that the optically activated strontium oxide powder can be successfully used as a source of atomic strontium for a MOT. The key achievement has been demonstrating how the source can be used for a period of at least an hour, which has previously not been possible, and indicates that the source could be a promising option for a portable quantum system. The information presented will allow for an informed decision by the reader, if the benefits and limitations of the source are suitable for the goals they wish to achieve. More experimentation however, will be required to operate in each

specific use case.

This investigation was made possible by the construction of a test chamber to allow the characterisation of the source. This was built and characterised to allow a range of measurements to be undertaken, such as the pressure increase during emission, the delay till emission occurs, and the temperature of the released atoms. A lot of work was also done to understand how to capture the atoms in a trap more reliably, as previously this was a big issue. It was shown by placing the powder close to the trapping centre (11 mm for this experiment) and angling the holder towards the point the MOT would form allowed for a high flux of atoms for each experiment cycle and allowed reliable atomic loading.

A significant issue that has been observed is the heating and cooling of the sample of strontium oxide powder during the pulses of the emission laser. The changing black-body radiation after the blue MOT has been loaded will effect clock spectroscopy and may have a large contribution to the uncertainty of the frequency, see section 1.3.2. At this time, the magnitude of this effect is unknown and thus the severity of this issue for an optical clock is uncertain. Although the powder is very hot and close to the the trapped atoms, heating only occurs over an area of $0.116(6) \text{ mm}^2$; thus the total heat energy change will not be as significant of a change compared to the total heat of the vacuum chamber, which is at a similar distance away from the atoms. Whether the effect is significant also depends on the desired stability and uncertainty of the clock. This source is aimed at a portable application, such as the

MiniClock detailed in chapter 2 where a desired stability of 1×10^{-15} per $\sqrt{\tau}$ at 100 s is the aim [24]. This aim is over an order of magnitude lower than what is possible in a laboratory setting [60] and thus it is more likely the optically activated source will be appropriate for this application. Without modelling it is impossible to say if this source is useful for a clock. A possible mitigation of the effect would be to implement the high/low method detailed in this chapter. As the temperature of the source will not drop as much between pulses the change in black-body radiation induced frequency shift over the clock measurement will be reduced, although the magnitude of the effect will be increased and the pressure in the chamber will also be higher.

For implementation of this loading method into an atomic system, the next step would be to create autonomous control for the loading of the MOT, allowing measurements for much longer periods to be undertaken. Within this experiment, observation of the fall in atomic output was done by monitoring the results obtained by a camera, and adjustments were made by hand to increase the flux when required. The use of a feedback mechanism from the camera to a piezoelectric actuator controlled mount would allow other potential limitations to be investigated. It is not yet known if the method to increase the atomic flux output would work for hours or days, or if after some time a new area of the powder would be required to be found. It is possible that it may keep emitting strontium until the source is depleted completely, another factor that would be required to be understood before implementation into a system.

The source is targeted towards portable quantum technology so the question needs to be answered about how a powder could be successfully held in a sample holder and remain there whilst being transported. It is proposed that an extremely fine mesh with gap sizes on the micron scale could be used to contain the powder but allow the gas to be emitted. This will require more optical energy to heat the powder to the required temperature due to light being reflected from the mesh, but it is not expected that this will limit operation. As the strontium gas will cool and adsorb when contacting the mesh, it is possible an appropriately high flux will not be achievable with mesh reducing the output in this way.

Finally, an investigation into ^{87}Sr enriched strontium carbonate would prove very exciting as the clock transition of ^{87}Sr provides the best reference for a strontium clock. Pure enriched strontium 87 is extremely expensive to purchase so it is used with its natural abundances. To achieve a trap of ^{87}Sr , 93% of the emitted strontium atoms are of the wrong isotope, thus a majority of the flux of atoms reaching the trapping region are not captured. Increasing the flux of the desirable isotope with an enriched source would decrease the load time of the first stage cooling, allowing shorter periods between spectroscopy of the clock transition.

Chapter Five

Conclusions

This thesis has focused on the developments in the miniaturisation of strontium technology with the aim of improving strontium optical lattice clocks. This has both looked at present development and potential future techniques to reduce the size and weight required for a portable system. Detailed conclusions can be found at the end of each chapter but the initial work presented on the “MiniClock” project showed the confirmation and characterisation of the red MOT in the vacuum chamber, see chapter 2. Limitations in the technology were identified during this project which led to further work being done on the laser system and atomic source. The laser systems being used at the time proved to be bulky or unreliable and an alternative was required. A design using an interference filter within an extended cavity diode is presented and multiple lasers at 4 different frequencies are produced, chapter 3. The typical technique to produce an atomic source in strontium systems is to use a dispenser or an oven which releases atoms at a temperature above 600

K. Ideally these atoms would be slowed to increase the capture rate of the trap but this is not done in the MiniClock system to save power and volume. Omitting a slowing process leads to a long loading time for the blue MOT. An alternative atom source was discovered by the University of Birmingham in 2016 [47] but further work was required before it could be used. The highlight of this thesis is the improvements in reliability and understanding of this strontium oxide source in chapter 4. A 405 nm activation laser is used to heat the surface of the sample causing emission of strontium. The source was shown to capture twice as many atoms compared to a dispenser within the same chamber also without pre-slowng of the atoms. The benefit of the reduction in size will be crucial in portable applications. My work has identified the limitations when using this source for a strontium clock and will allow future users to make an informed decision before attempting to use such a source in an cold atomic system. Although more work is required to fully understand and optimise the source, this presents a potential source for other strontium technology applications where black-body radiation (BBR) induced AC Stark shifts are not as impacting to performance.

5.1 Future work

5.1.1 Portable strontium optical lattice clock - Mini-Clock

After initial characterisation of the broadband red MOT, laboratory work continued by others on the MiniClock experiment. A single frequency red MOT with a temperature of a few micro Kelvin has been measured and an optical lattice has been achieved. The system has been reassembled from a bulky laboratory experiment into a compact and robust portable package. The control module, consisting of: the computer control, control electronics, laser systems, laser frequency stabilisation and control, and distribution interfaces, has also been complete and is ready for operation with the atomic module. The clock module has been designed and built by project partners at the National Physics Laboratory (NPL). This module produces extremely stable and narrow linewidth light for probing of the clock transition.

Work will continue to integrate the three modules together by Defence Science and Technology Laboratory (dstl), the third partner and funder for the project. Although this project has not reached completion as of yet, many lessons have been learnt during this attempt which will be used to guide all three partners in future endeavours.

5.1.2 Portable lasers utilising an interference filter in an ECDL

The compact extended cavity diode laser (ECDL) utilising an interference filter (IF) presents an additional option for users when building either a portable or laboratory based system. These laser are light in weight, small in size and relatively cheap to build. The performance in the laboratory was reliable over long periods of time, requiring little human adjustment once built, and do not requiring frequency locking when low laser stability is required such as the repump laser for strontium.

Future work on the characterisation of the performance of the lasers when subject to external thermal, mechanical and acoustic modulation is required before a laser of this design could be used in a portable system. This will inform the user of any additional shielding or control that is required to mitigate these effects. Additionally, this design has the possibility to be reduced in size further which may also increase portability.

5.1.3 Optically activated atomic strontium source for portable systems

A better understanding of the characteristic of the optically activated source has been established but for the atomic source to be used, it is now required that trap loading be optimised for a desired application and system, using the information that has been presented in this thesis. For use in a clock

system, further understanding of the magnitude of the effect of the blackbody radiation is required to determine exactly how this would affect the clock frequency. Improved measurement of the temperature of the released atoms and the source are needed to model the frequency shifts this source would cause in operation.

An investigation into the initial conditions to cause the release of strontium from the powder will mean the powder can be prepared in such a way that the source is no longer required to remain hot between laser pulses and still allow a fast switching atomic flux to be generated. As was discussed in section 4.2.1, the porosity of the powder could be controlled and varied to find optimum conditions to initiate sublimation. Additionally, the effect of increasing the pumping speed in the science chamber will help to decrease the pressure in the chamber, allowing the magnitude of the affect of the released oxygen has on the loading rate of the strontium atoms being trapped to characterised. This knowledge will improve the understanding of where this source might be applied and enable the user to select an appropriate vacuum pump based on their use case.

References

- [1] T. Akatsuka et al. “30-km-long optical fiber link at 1397 nm for frequency comparison between distant strontium optical lattice clocks”. In: *Jpn. J. Appl. Phys.* 53.032801 (Feb. 2014). DOI: [10.7567/JJAP.53.032801](https://doi.org/10.7567/JJAP.53.032801). URL: <https://iopscience.iop.org/article/10.7567/JJAP.53.032801>.
- [2] M. Takamoto et al. “Test of general relativity by a pair of transportable optical lattice clocks”. In: *Nature Photonics* 14.411-415 (Apr. 2020). DOI: [10.1038/s41566-020-0619-8](https://doi.org/10.1038/s41566-020-0619-8). URL: <https://www.nature.com/articles/s41566-020-0619-8>.
- [3] B. Dowden. *Time*. Mar. 2021. URL: <https://iep.utm.edu/time/#H19>.
- [4] N. Poli et al. “Optical atomic clocks”. In: *La Rivista del Nuovo Cimento* 36.555-624 (2013). DOI: [10.1393/ncr/i2013-10095-x](https://doi.org/10.1393/ncr/i2013-10095-x). URL: <https://link.springer.com/article/10.1393/ncr/i2013-10095-x>.
- [5] P. Gill. “When should we change the definition of the second?” In: *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 369.1953 (Oct. 2011), pp. 4109–4130. DOI: [10.1098/rsta.2011.0237](https://doi.org/10.1098/rsta.2011.0237). URL: <https://royalsocietypublishing.org/doi/10.1098/rsta.2011.0237>.
- [6] F. Riehle. “Towards a redefinition of the second based on optical atomic clocks”. In: *Comptes Rendus Physique* 6.5 (June 2015), pp. 506–515. DOI: [10.1016/j.crhy.2015.03.012](https://doi.org/10.1016/j.crhy.2015.03.012). URL: <https://www.sciencedirect.com/science/article/pii/S1631070515000638>.
- [7] P. Gill. “Is it the time right for a redefinition of the second by optical atomic clocks?” In: *Journal of Physics: Conference Series* 273.012053

- (Oct. 2015). DOI: [10.1088/1742-6596/723/1/012053](https://doi.org/10.1088/1742-6596/723/1/012053). URL: <https://iopscience.iop.org/article/10.1088/1742-6596/723/1/012053/meta>.
- [8] BIPM and F. Riehle. “CCTF Strategic plan”. In: *BIPM Strategy documents* (Apr. 2016). URL: <https://www.bipm.org/en/committees/cc/cctf/strategy.html>.
- [9] F. Riehle. “Optical clock networks”. In: *Nature Photonics* 11.25-31 (Jan. 2017). DOI: [10.1038/nphoton.2016.235](https://doi.org/10.1038/nphoton.2016.235). URL: <https://www.nature.com/articles/nphoton.2016.235?foxtrotcallback=true>.
- [10] C. J. Foot. “Laser cooling and trapping”. In: *Atomic Physics*. Great Clarendon Street, Oxford OX2 6DP, UK: Oxford University Press, 2005, pp. 178–213.
- [11] R. Grimm, M. Weidemüller, and Y. B. Ovchinnikov. “Optical Dipole Traps for Neutral Atom”. In: *Advances In Atomic, Molecular, and Optical Physics* 42 (2000), pp. 95–170. DOI: [10.1016/S1049-250X\(08\)60186-X](https://doi.org/10.1016/S1049-250X(08)60186-X). URL: <https://www.sciencedirect.com/science/article/pii/S1049250X0860186X>.
- [12] NIST. *Atomic Spectra Database*. DOI: [10.18434/T4W30F](https://doi.org/10.18434/T4W30F). URL: <https://www.nist.gov/pml/atomic-spectra-database>. (accessed: 14/06/2021).
- [13] A. Ludlow. “The Strontium Optical Lattice Clock: Optical Spectroscopy with Sub-Hertz Accuracy”. PhD thesis. University of Colorado, 2008. URL: https://jila.colorado.edu/sites/default/files/2020-11/theses_2008_AndrewLudlow.pdf.
- [14] J. Sanjuan et al. “Long-term stable optical cavity for special relativity tests in space”. In: *Optics Express* 27.25 (Nov. 2019), pp. 36206–36220. DOI: [10.1364/OE.27.036206](https://doi.org/10.1364/OE.27.036206). URL: <https://www.osapublishing.org/oe/fulltext.cfm?uri=oe-27-25-36206&id=423632>.
- [15] J. M. Robinson et al. “Crystalline optical cavity at 4 K with thermal-noise-limited instability and ultralow drift”. In: *Optica* 6.2 (2019), pp. 240–243. DOI: [10.1364/OPTICA.6.000240](https://doi.org/10.1364/OPTICA.6.000240). URL: <https://www.osapublishing.org/optica/fulltext.cfm?uri=optica-6-2-240&id=405188>.

-
- [16] C. J. Kwong et al. “Characterization of the long-term dimensional stability of a NEXCERA block using the optical resonator technique”. In: *Meas. Sci. Technol.* 29.075011 (June 20158). DOI: [10.1088/1361-6501/aac3b0](https://doi.org/10.1088/1361-6501/aac3b0). URL: <https://iopscience.iop.org/article/10.1088/1361-6501/aac3b0/meta>.
- [17] R. Hobson et al. “A strontium optical lattice clock with 1×10^{-17} uncertainty and measurement of its absolute frequency”. In: *Metrologia* 57.065026 (Oct. 2020). DOI: [10.1088/1681-7575/abb530](https://doi.org/10.1088/1681-7575/abb530). URL: <https://iopscience.iop.org/article/10.1088/1681-7575/abb530>.
- [18] K. Gibble. “Systematic Effects in Atomic Fountain Clocks”. In: *J. Phys.: Conference Series* 723.012002 (2016). DOI: [10.1088/1742-6596/723/1/012002](https://doi.org/10.1088/1742-6596/723/1/012002). URL: <https://iopscience.iop.org/article/10.1088/1742-6596/723/1/012002>.
- [19] K. Gibble. “Scattering of Cold-Atom Coherences by Hot Atoms: Frequency Shifts from Background-Gas Collisions”. In: *Phys. Rev. Lett.* 110.180802 (2013). DOI: [PhysRevLett.110.180802](https://doi.org/10.1103/PhysRevLett.110.180802). URL: <https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.110.180802>.
- [20] M. Pizzocaro et al. “Intercontinental comparison of optical atomic clocks through very long baseline interferometr”. In: *Nat. Phys.* 17 (Oct. 2020), p. 223. DOI: [10.1038/s41567-020-01038-6](https://doi.org/10.1038/s41567-020-01038-6). URL: <https://www.nature.com/articles/s41567-020-01038-6>.
- [21] Takuma Nakamura et al. “Coherent optical clock down-conversion for microwave frequencies with 10^{-18} instability”. In: *Science* 368.6493 (May 2020), pp. 889–892. DOI: [10.1126/science.abb2473](https://doi.org/10.1126/science.abb2473). URL: <https://science.sciencemag.org/content/368/6493/889>.
- [22] M. Gellesch J. Jones R. Barron A. Singh Q. Sun K. Bongs et al. “Transportable optical atomic clocks for use in out-of-the-lab environments”. In: *Advanced Optical Technologies* 9.5 (Sept. 2020), pp. 313–325. DOI: [10.1515/aot-2020-0023](https://doi.org/10.1515/aot-2020-0023). URL: <https://www.degruyter.com/view/journals/aot/9/5/article-p313.xml>.
- [23] S. Origlia et al. “Towards an optical clock for space: Compact, high-performance optical lattice clock based on bosonic atoms”. In: *Phys. Rev. A* 98.053443 (Nov. 2018). DOI: [10.1103/PhysRevA.98.053443](https://doi.org/10.1103/PhysRevA.98.053443).

- URL: <https://journals.aps.org/pra/abstract/10.1103/PhysRevA.98.053443>.
- [24] D. Morris et al. “Development of a Portable Optical Clock”. In: *2019 Joint Conference of the IEEE International Frequency Control Symposium and European Frequency and Time Forum (EFTF/IFC)*. IEEE, Oct. 2019. DOI: [10.1109/FCS.2019.8856051](https://doi.org/10.1109/FCS.2019.8856051). URL: <https://ieeexplore.ieee.org/document/8856051>.
 - [25] W. He. “Towards Miniaturized Strontium Optical Lattice Clock”. PhD thesis. University of Birmingham, United Kingdom, 2017. URL: <https://etheses.bham.ac.uk/id/eprint/7460/>.
 - [26] S. Viswam. “Advanced laser frequency stabilisation systems for mobile strontium optical lattice clocks”. PhD thesis. University of Birmingham, United Kingdom, 2020. URL: <https://etheses.bham.ac.uk/id/eprint/10058/>.
 - [27] M. Menchetti. “Experimental set-up for realising long-range interaction using strontium atoms in an optical lattice”. PhD thesis. University of Birmingham, United Kingdom, 2019. URL: <https://etheses.bham.ac.uk/id/eprint/9064/>.
 - [28] M. Haw et al. “Magneto-optical trap loading rate dependence on trap depth and vapor density”. In: *Journal of the Optical Society of America B* 29.3 (Mar. 2012), pp. 475–483. DOI: [10.1364/JOSAB.29.000475](https://doi.org/10.1364/JOSAB.29.000475). URL: <https://opg.optica.org/josab/fulltext.cfm?uri=josab-29-3-475&id=229570>.
 - [29] A. M. Steane, M. Chowdhury, and C. J. Foot. “Radiation force in the magneto-optical trap”. In: *J. Opt. Soc. Am. B* 9.12 (Dec. 1992), pp. 2142–2158. DOI: [10.1364/JOSAB.9.002142](https://doi.org/10.1364/JOSAB.9.002142). URL: <http://opg.optica.org/josab/abstract.cfm?URI=josab-9-12-2142>.
 - [30] D. A. Steck. *Rubidium 87 D Line Data*. URL: <https://steck.us/alkalidata/rubidium87numbers.pdf>. (revision 2.2.2, accessed: 08/02/2022).
 - [31] K. Bongs and et al. “Development of a strontium optical lattice clock for the SOC mission on the ISS”. In: *Science Direct* 16.5 (June 2015),

- pp. 553–564. DOI: [10.1016/j.crhy.2015.03.009](https://doi.org/10.1016/j.crhy.2015.03.009). URL: <https://www.sciencedirect.com/science/article/pii/S1631070515000602>.
- [32] X. Baillard et al. “Interference-filter-stabilized external-cavity diode lasers”. In: *Optics Communications* 266.2 (2006), pp. 609–613. DOI: [10.1016/j.optcom.2006.05.011](https://doi.org/10.1016/j.optcom.2006.05.011). URL: <https://doi.org/10.1016/j.optcom.2006.05.011>.
- [33] R. Wyatt and W. J. Devlin. “10 kHz linewidth 1.5 μm InGaAsP external cavity laser with 55 nm tuning range”. In: *Electronics Letters* 19.3 (Feb. 1983), pp. 110–112. DOI: [10.1049/el:19830079](https://doi.org/10.1049/el:19830079). URL: <https://ieeexplore.ieee.org/document/4247284?arnumber=4247284>.
- [34] D. J. Thompson and R. E. Scholten. “Narrow linewidth tunable external cavity diode laser using wide bandwidth filter”. In: *Review of Scientific Instruments* 83.023107 (Feb. 2012). DOI: [10.1063/1.3687441](https://doi.org/10.1063/1.3687441). URL: <https://aip.scitation.org/doi/full/10.1063/1.3687441>.
- [35] A. Martin, P. Baus, and G. Birkel. “External cavity diode laser setup with two interference filters”. In: *Applied Physics B* 122.298 (Dec. 2016). DOI: [10.1007/s00340-016-6575-9](https://doi.org/10.1007/s00340-016-6575-9). URL: <https://link.springer.com/article/10.1007/s00340-016-6575-9#citeas>.
- [36] Gianmaria Milani et al. “Multiple wavelength stabilization on a single optical cavity using the offset sideband locking technique”. In: *Optics Letters* 42.10 (2017), pp. 1970–1973. DOI: [10.1364/OL.42.001970](https://doi.org/10.1364/OL.42.001970). URL: <https://www.osapublishing.org/ol/fulltext.cfm?uri=ol-42-10-1970&id=366493>.
- [37] Eryn C. Cook et al. “High passive-stability diode-laser design for use in atomic-physics experiments”. In: *Review of Scientific Instruments* 83.043101 (2012). DOI: [10.1063/1.3698003](https://doi.org/10.1063/1.3698003). URL: <https://aip.scitation.org/doi/full/10.1063/1.3698003>.
- [38] W. Bowden et al. “A pyramid MOT with integrated optical cavities as a cold atom platform for an optical lattice clock”. In: *Sci Rep* 9 (Aug. 2019), p. 11704. DOI: [10.1038/s41598-019-48168-3](https://doi.org/10.1038/s41598-019-48168-3). URL: <https://doi.org/10.1038/s41598-019-48168-3>.

-
- [39] A. D. Ludlow. “An optical clock to go”. In: *Nature Physics* 14.431-432 (2018). DOI: [10.1038/s41567-018-0047-6](https://doi.org/10.1038/s41567-018-0047-6). URL: <https://www.nature.com/articles/s41567-018-0047-6>.
- [40] Hobson et al. “Midinfrared magneto-optical trap of metastable strontium for an optical lattice clock”. In: *Phys. Rev. A* 101.1 (Jan. 2020), p. 013420. DOI: [10.1103/PhysRevA.101.013420](https://doi.org/10.1103/PhysRevA.101.013420). URL: <https://link.aps.org/doi/10.1103/PhysRevA.101.013420>.
- [41] J. Grotti et al. “Geodesy and metrology with a transportable optical clock”. In: *Nature Phys* 14 (May 2018), pp. 437–441. DOI: [10.1038/s41567-017-0042-3](https://doi.org/10.1038/s41567-017-0042-3). URL: <https://doi.org/10.1038/s41567-017-0042-3>.
- [42] I.S. Madjarov et al. “High-fidelity entanglement and detection of alkaline-earth Rydberg atoms”. In: *Nature Physics* 16.857-861 (Apr. 2020). DOI: [10.1038/s41567-020-0903-z](https://doi.org/10.1038/s41567-020-0903-z). URL: <https://www.nature.com/articles/s41567-020-0903-z#citeas>.
- [43] L. Hu et al. “Atom Interferometry with the Sr Optical Clock Transition”. In: *Phys. Rev. Lett.* 119.263601 (2017). DOI: [10.1103/PhysRevLett.119.263601](https://doi.org/10.1103/PhysRevLett.119.263601). URL: <https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.119.263601>.
- [44] L. Hu et al. “Sr atom interferometry with the optical clock transition as a gravimeter and a gravity gradiometer”. In: *Class. Quantum Grav.* 37.014001 (2019). DOI: [10.1088/1361-6382/ab4d18](https://doi.org/10.1088/1361-6382/ab4d18). URL: <https://iopscience.iop.org/article/10.1088/1361-6382/ab4d18>.
- [45] M. Schioppo et al. “A compact and efficient strontium oven for laser-cooling experiments”. In: *Review of Scientific Instruments* 83.103101 (2012). DOI: [10.1063/1.4756936](https://doi.org/10.1063/1.4756936). URL: <https://aip.scitation.org/doi/full/10.1063/1.4756936?ver=pdfcov>.
- [46] I. R. Hill et al. “Zeeman slowers for strontium based on permanent magnets”. In: *J. Phys. B: At. Mol. Opt.* 47.075006 (2014). DOI: [10.1088/0953-4075/47/7/075006](https://doi.org/10.1088/0953-4075/47/7/075006). URL: <https://iopscience.iop.org/article/10.1088/0953-4075/47/7/075006>.

-
- [47] O. Kock et al. “Laser controlled atom source for optical clocks”. In: *Scientific Reports* 6.37321 (Nov. 2016). DOI: [10.1038/srep37321](https://doi.org/10.1038/srep37321). URL: <https://www.nature.com/articles/srep37321#citeas>.
- [48] M. Yasuda et al. “Laser-Controlled Cold Ytterbium Atom Source for Transportable Optical Clocks”. In: *Journal of the Physical Society of Japan* 86.125001 (Nov. 2017). DOI: [10.7566/JPSJ.86.125001](https://doi.org/10.7566/JPSJ.86.125001). URL: <https://journals.jps.jp/doi/10.7566/JPSJ.86.125001>.
- [49] S. Mulholland et al. “Laser-cooled ytterbium-ion microwave frequency standard”. In: *Applied Physics B* 125.198 (2019). DOI: [10.1007/s00340-019-7309-6](https://doi.org/10.1007/s00340-019-7309-6). URL: <https://link.springer.com/article/10.1007/s00340-019-7309-6>.
- [50] S. Ravi-Kumara et al. “Laser Ablation of Polymers: A Review”. In: *Procedia Manufacturing* 34.2351-9789 (2019), pp. 316–327. DOI: [10.1016/j.promfg.2019.06.155](https://doi.org/10.1016/j.promfg.2019.06.155). URL: <http://www.sciencedirect.com/science/article/pii/S2351978919308832>.
- [51] A. Pöschl. “Laser Ablation Loading and Single Ion Addressing of Strontium in a Linear Paul Trap”. In: *Stockholm University* (2018). URL: <https://kth.diva-portal.org/smash/get/diva2:1203307/FULLTEXT01.pdf>.
- [52] G. Vrijsen et al. “Efficient isotope-selective pulsed laser ablation loading of 174Yb^+ ions in a surface electrode trap”. In: *Optics Express* 27.23 (2019), pp. 33907–33917. DOI: [10.1364/OE.27.033907](https://doi.org/10.1364/OE.27.033907). URL: <https://www.osapublishing.org/oe/fulltext.cfm?uri=oe-27-23-33907&id=422939>.
- [53] L. Torralbo-Campo et al. “Light-induced atomic desorption in a compact system for ultracold atoms”. In: *Scientific Reports* 5.14729 (2015). DOI: [10.1038/srep14729](https://doi.org/10.1038/srep14729). URL: <https://www.nature.com/articles/srep14729>.
- [54] T. Karaulanov et al. “Controlling atomic vapor density in paraffin-coated cells using light-induced atomic desorption”. In: *Phys. Rev. A* 79.012902 (Jan. 2009). DOI: [10.1103/PhysRevA.79.012902](https://doi.org/10.1103/PhysRevA.79.012902). URL: <https://journals.aps.org/pra/abstract/10.1103/PhysRevA.79.012902>.

-
- [55] Gustavo Telles et al. “Light-induced atomic desorption for loading a sodium magneto-optical trap”. In: *Phy. Rev. A* 81.032710 (Mar. 2010). DOI: [10.1103/PhysRevA.81.032710](https://doi.org/10.1103/PhysRevA.81.032710). URL: <https://journals.aps.org/pr/abstract/10.1103/PhysRevA.81.032710>.
- [56] D. S. Barker et al. “Light-induced atomic desorption of lithium”. In: *Phys. Rev. A* 98.043412 (Oct. 2018). DOI: [10.1103/PhysRevA.98.043412](https://doi.org/10.1103/PhysRevA.98.043412). URL: <https://journals.aps.org/pr/abstract/10.1103/PhysRevA.98.043412>.
- [57] P. F. Griffin, K. J. Weatherill, and C. S. Adams. “Fast switching of alkali atom dispensers using laser-induced heating”. In: *Review of Scientific Instruments* 76.093102 (Sept. 2005). DOI: [10.1063/1.2038167](https://doi.org/10.1063/1.2038167). URL: <https://aip.scitation.org/doi/10.1063/1.2038167>.
- [58] H. Szelagowski, I. Arvanitidis, and S. Seetharaman. “Effective thermal conductivity of porous strontium oxide and strontium carbonate samples”. In: *Journal of Applied Physics* 85.193 (Dec. 1998), p. 7. DOI: doi.org/10.1063/1.369468. URL: <https://aip.scitation.org/doi/10.1063/1.369468>.
- [59] A. Mitsuru et al. “Partial Pressures of Strontium and Strontium Oxide over Strontium Oxide Heated on Platinum”. In: *Bulletin of the Chemical Society of Japan* 45.1 (1972), pp. 82–87. DOI: [10.1246/bcsj.45.82](https://doi.org/10.1246/bcsj.45.82). URL: <https://www.journal.csj.jp/doi/10.1246/bcsj.45.82>.
- [60] Tobias Bothwell et al. “JILA SrI optical lattice clock with uncertainty of 2.0×10^{-18} ”. In: *Metrologia* 56.6 (Oct. 2019), p. 065004. DOI: [10.1088/1681-7575/ab4089](https://doi.org/10.1088/1681-7575/ab4089). URL: <https://iopscience.iop.org/article/10.1088/1681-7575/ab4089>.