## Contents

1 **Introduction** 3
   1.1 Prelab questions 3

2 **Theory** 3
   2.1 Interference 4
   2.2 Interferometry 4
   2.3 Interferometry and wavemeters 4
   2.4 Measurement principles 5

3 **Rubidium excitation** 6

4 **Equipment** 7
   4.1 The wavemeter 8
   4.2 The external cavity diode laser 8
   4.3 The rubidium cell and infrared camera 8

5 **Procedure** 9
   5.1 Unknown laser alignment 11
   5.2 Measuring the wavelength of the unknown laser 11
   5.3 Adjusting the wavelength of the unknown laser 12
   5.4 Scanning the wavelength over a particular range 13
   5.5 Measuring the wavelengths of rubidium ground state excitations 14
   5.6 Further analysis 15
1 Introduction

In this experiment you will be introduced to the concepts of atom optics. You will be using a Michelson wavemeter as your measurement device, and will begin by tuning it, and using it to measuring the wavelength of a tunable laser. You will then use the wavemeter to find the wavelengths of atomic transitions in rubidium.

1.1 Prelab questions

1. What conditions must exist for light waves to interfere? What properties must they have in common?

2. What is happening during destructive interference? Why don’t we observe any light?

3. Find an expression for the wavelength of the unknown laser, $\lambda_U$, in terms of the number of fringes counted for each laser and the wavelength of the reference laser, $\lambda_R$ (see Eq. [1]).

4. Using Fig. [1] or otherwise, show that $N_R = 2d/\lambda_R$. Diagrams may be useful.

5. Estimate how far the wavemeter cart (moving mirror, M1 in Fig. [1]) must be moved in order to get a resolution of 1 part in $10^6$. (Hint: you will probably need to count at least as many fringes as the accuracy you want to get).

2 Theory

The term ‘atom optics’ might initially seem confusing or daunting. Are we imaging objects with atoms? To quote the atom optics research group here in physics,
Atom optics is a field of research exploring the possibilities of manipulating beams of atoms in the same way that conventional optics controls light beams.

While we aren’t doing that exactly here, we are nonetheless beginning our journey into the area. It’s important to first understand how beams of light interact and interfere, and to have experience with optical alignment, but we will also look at the atomic transitions of rubidium, an element commonly used in research-level atom optics experiments.

2.1 Interference

The phenomenon utilised by a wavemeter is the interference of light waves. Under certain conditions, two light waves will interfere and produce an interference pattern. The principle of superposition explains that the amplitude of the resulting wave at any point will be the sum of the individual wave amplitudes at that point. Two waves ‘in phase’ will interfere constructively (producing a larger amplitude wave), while those ‘out of phase’ by exactly half a wavelength ($\lambda/2$) will interfere destructively (producing a zero amplitude wave). This holds true for sound waves, light waves, ocean waves...

2.2 Interferometry

But is there a way to apply the principles of constructive and destructive interference to measurement? Yes. This is known as interferometry. By measuring the conditions of interference it is possible to determine properties either of the system or the light used for measurement.

For example, the number and spacing of fringes in a two-slit interference pattern could give you information about slit size, slit spacing, and so on. We can then employ the same ideas about interference in other situations, such as imaging, astrophysics, etc...

2.3 Interferometry and wavemeters

We are able to ‘easily’ measure the wavelength of a laser using properties of interference, in the form of a Michelson interferometer.

The basic layout of a Michelson interferometer is shown schematically in Fig. 1. As mirror M1 is moved, the path length difference between the two interferometer arms changes. This results in changes in the phase difference between the two beams. As the phase difference changes the amplitude at any point on the detector also changes, ranging from some maximum to some minimum number.

If we move the mirror smoothly and continuously in one dimension, the interference pattern at any point will oscillate from dark (zero amplitude) to light (maximum amplitude) in a sinusoidal fashion. The number of light/dark oscillations, or fringes, as the mirror moves is described by the equation:

$$N_R = 2d/\lambda_R$$

where $N_R$ is the number of fringes, $d$ is the distance moved, and $\lambda_R$ is the wavelength of the laser, which we will label the ‘reference’ laser. We are using a Helium-Neon (HeNe) laser,
Figure 1: The basic geometry of a Michelson interferometer. The beamsplitter partially transmits and partially reflects incident light.

with $\lambda_R = 632.823$ nm. Identically, if we use an unknown laser, the number of fringes is written as $N_U = 2d/\lambda_U$.

If we now consider a reference laser and an unknown laser propagating through an interferometer simultaneously, we can construct a wavemeter. The design of the wavemeter in this experiment is shown in figure 2. If you follow the output of the reference laser by following the arrows, you can see that it splits at the top left corner of the beamsplitter, and after passing along each path to the corner cubes (CC1 and CC2), it recombines at the bottom right corner of the beamsplitter, before passing through to the detector, NR. The two corner cubes are fixed on a moving stand, generating path and thus phase differences as the stand moves.

The unknown laser travels in the opposite direction (counter propagating) to the reference laser. This output is incident on a second detector, spatially separated from the first, and allows you to more easily align the unknown laser. The two beam paths from the unknown laser recombine at the top left of the beamsplitter.

2.4 Measurement principles

Wait a second, we’ve just discussed how we can use Eq. [1] to measure the wavelength of a laser. But we already know the wavelength of the reference laser, so can’t we just leave that out, and count the number of fringes generated by the unknown laser?

Technically, we could. If we knew the distance, $d$, very accurately. We could ask you to measure the length of the track the mirrors travel along with a high-precision instrument, but that wouldn’t be instructive, nor would it be accurate. Instead, we can invert the fringe equation to write:

$$d = N_R/2\lambda_R$$

(2)
So, by using a laser with a well-known wavelength, we can accurately measure the distance! We can then use this distance to determine $\lambda_U$ after we count the number of fringes!

Okay so now you know why we need both lasers. But how does the system know when to stop counting fringes over the distance? This is a mechanical question and should be discussed with your demonstrator.

*If any of this isn’t clear, you should re-read it, draw diagrams, etc, and make sure you understand both why and how we’re measuring the wavelength of the unknown laser*. 

### 3 Rubidium excitation

There are two naturally occurring isotopes of rubidium, both of which are present in your vapour cell. Each isotope has a ground state hyperfine splitting giving rise to four rubidium ground states, two for each isotope. We distinguish each ground state for a particular isotope by its total angular momentum,

$$F = I + J$$  \hspace{1cm} (3)

where $I$ is the total nuclear spin of the atom, and $J$ is the total orbital angular momentum of the electron. The energy required to excite an atom from one of these ground states to the $5P_{3/2}$ excited state is different for each ground state, as shown in Fig. 3. As you change the wavelength of your laser, you are changing the photon energy $E = h \nu / \lambda$. Hence, for a particular wavelength, you are exciting atoms from a particular ground state to the excited state.

**Question 1** Discussion point: Which transitions are we observing on this diagram? That is, label them and convert them into laser wavelengths.

### 4 Equipment

**Safety**

Lasers can be exceptionally damaging to the eyes. This particular unknown laser emits in the infrared spectrum, so here your typically eye-saving blink reflex is **non-existent**! Stray reflections should be eliminated (be careful when placing objects in the beam path and remove your jewellery) and you should **NEVER** lower your head to the height of the laser beams.

**NEVER EVER LOWER YOUR HEAD TO THE HEIGHT OF THE LASER BEAMS!**
4.1 The wavemeter

The wavemeter is displayed schematically in Fig. 2. Do not open the perspex box, it contains dangerous, delicate and expensive components. Realignment of the components inside takes several hours. The wavemeter cart (with corner cubes, CC1 and CC2) is on an air track to reduce friction. Don’t touch the regulator on the wall as the air flow should be low.

The black box in front of the wavemeter controls both the HeNe power, the counter and the photodetectors. There is a switch at the back to turn it on. When this switch is turned on, the HeNe laser output will turn on. Unknown out is the output from the detector labelled $N_U$ in Fig. 2. HeNe out is the output from $N_R$ in the same figure.

To make a measurement, the cart travels the length of the track, from right to left. Springs are at each end of the track and only a slight push is needed for measurements. The standard deviation in the measurement result is less than 0.001 nm, which is at the limit of the counting resolution of the device. The absolute accuracy, however, is limited by systematic errors.

4.2 The external cavity diode laser

This is the unknown laser. It is tunable, hence the big control box. Do not adjust any controls until you are explicitly told to change something.

4.3 The rubidium cell and infrared camera

Rubidium gas ignites in the presence of oxygen. Do not touch, move or place any objects near the glass cell and do not pass anything over the cell.

The infrared (IR) camera is used to observe rubidium fluorescence. When the unknown laser is correctly tuned, the rubidium atoms will absorb the light and become excited. The atoms will then emit light of the same wavelength as they decay to the ground state. This emitted light will be observed on the IR camera as fluorescence.
5 Procedure

When you come in, you should see an optics bench with a number of mirrors on it. The first thing you should do is stand back and identify the various components of the wavemeter. In particular, which is the reference laser, which is the unknown laser, and how does the setup you see compare with the diagram below?

Figure 4: Geometry of the complete setup. Arrows show beam directions. Reference HeNe laser is small arrows, unknown laser is large arrows. NB: PD is not the photodiode mentioned in the following alignment section, it is a separate photodiode used to investigate rubidium atoms in the final section.

Question 2 What is the purpose of including the collimator? What are they normally used for, and how would our experiment be affected if we removed it?

Question 3 Why do we include mirror M4? Why don’t we just use mirrors M3 and M5 at right angles?

For now, don’t worry about following the beam paths. Just get a general sense of the components. When ready, first check there is nothing in the beam path, then turn on both lasers as follows:

1. Turn on the switch at the back of the small black box attached to the wavemeter. The red display should light up and bright red laser light should be visible on the mirrors.

2. Before turning on the unknown laser’s (external cavity tunable diode laser) control box, let’s familiarise ourselves with the front panel (see Fig. 5 below).
Figure 5: Front panel of unknown laser’s (external cavity tunable diode laser) control box.

- Pay careful attention to panel number 3 and note where the Track button is.
- Switch on the AC Power to I (i.e. ‘on’) and immediately press the Track button. This is crucial in stopping the Picomotor (a patented design that uses a piezo to turn a screw, the screw tilts the tuning mirror in the laser head) from driving itself to one position. This automatic driving needs to be stopped as it can end up jamming the mirror. If you’re successful, the characteristic driving sound (a whirring) will cease and this indicates the Picomotor is not moving.
- Now press the Laser Power power button and the green LED will flash a few times. When the flashing stops, the unknown laser should be switched on and emitting.

The two beams need to be precisely collinear and parallel to the track so that interference fringes are generated consistently as the cart moves. The reference laser is already aligned and is used as a guide for aligning the unknown laser. **Do NOT adjust any of the plane mirrors (M1–M5), this alignment is already complete.** The bright red HeNe laser should be visible on \( N_R \). Check the output of the photodetector \( N_R \) on an oscilloscope as follows:

1. Connect a BNC cable between the **HeNe out connection** on the wavemeter box and channel 1 on the oscilloscope.
2. Try these settings: CH 1 - 1V/DIV, TIMEBASE - 5 \( \mu \)s, TRIG - CH 1.
3. Do you see a sinusoidal signal that varies with amplitude as the wavemeter cart moves? The alignment is sufficient if the amplitude remains roughly constant.
4. If the alignment is adequate coming from the **HeNe out connection**, you can commence the alignment process for the unknown laser.

**Question 4** Why is the signal a varying sinusoidal? What causes this?

**Question 5** Note both the maximum and minimum peak-to-peak amplitudes you observed for the HeNe laser on the photodetector \( N_R \). Comment on exactly what the amplitudes correspond to physically.
5.1 Unknown laser alignment

Now that the reference laser is properly aligned, we want to introduce the unknown laser into the system. There is an infrared-sensitive card that you need to use to view the unknown laser spot, unlike the reference laser. The card needs to be recharged occasionally by pointing it at the room lights for a few seconds.

1. Align the unknown laser with the wavemeter using the mirrors $M_X$ and $M_Y$. Each mirror has a fine adjustment knob to control vertical and horizontal tilt.

2. **Do not adjust the unknown laser other than using these knobs.** Don’t move the laser itself or the beamsplitter.

3. We want to perform the alignment so that the beam spots from both lasers overlap on both $M_X$ and $M_Y$. Fixing these two points will ensure both lasers are fully counter-propagating. The following procedure is one method of aligning the unknown laser.
   a) Position the IR card at position $P_X$ as shown in Fig. 4 with the active region facing toward $M_X$. By ‘chopping’ your hand behind the IR card, you should notice there are two spots visible on the IR card. The one you are chopping is the HeNe.
   b) Position the IR card at position $P_Y$, with the active region facing the beamsplitter. By chopping your hand between the mirrors $M_X$ and $M_Y$, you should notice there are also two spots visible on the IR card. The one you are chopping is again the HeNe.
   c) When the card is in position $P_X$, adjust the knobs on mirror $M_Y$ to overlap the two spots. When the card is in position $P_Y$, use mirror $M_X$ to overlap the beams. It is helpful to align only one axis at a time. Alternate between axes. Repeat this ‘stepping’ alignment until the spots overlap at both $P_X$ and $P_Y$.
   d) This stepping process is iterative, and can take up to 30 minutes. Once correct you should see the bright HeNe laser incident on the output hole of the unknown laser.

4. To confirm alignment, check the **Unknown out connection** from the wavemeter box on channel 1 on the oscilloscope. As with the known laser, you should see a sinusoidal signal that is roughly constant.

5. If the oscilloscope does not trigger, first try adjusting the trigger level. If nothing, verify your alignment is incident as well as collinear on the photodetector $N_U$. 

**Question 6** Note down in your logbook both the maximum and minimum peak-to-peak amplitudes you observed for the unknown laser on the photo detector $N_U$. Is the variation less than the photo detector $N_R$? Explain.

5.2 Measuring the wavelength of the unknown laser

Now we’re ready to measure the unknown laser wavelength! We need to get that cart moving to introduce path differences, so turn on the air supply and give the cart a gentle push along
When you see a stable sinusoidal signal on the oscilloscope, press the Count button on the Wavemeter box. This should start the wavemeter counting. The numerical display should start counting.

Some notes to ensure the cart/wavemeter system is working correctly:

- If the wavemeter stops counting as it travels from right to left and displays a number, your alignment is good.
- Can you ensure that you can consistently measure the same number to within the last digit? If you can, your alignment is finished.

If the wavemeter does not stop counting, or counts erratically, make sure there is nothing in the beam path. Also check that the function generator next to the unknown laser controller is OFF. Then, check the consistency of your numbers again. If no improvement, consult your demonstrator.

**Question 7** What wavelength have you measured? How accurately? And how does this wavelength compare to the HeNe laser wavelength?

### 5.3 Adjusting the wavelength of the unknown laser

Now to turn our attention back to the rubidium cell. We first need to change the unknown laser wavelength to match the wavelength at which rubidium absorbs light, approximately $\lambda = 780.033$ nm in air. We again focus our attention to panel 3 of the control box (see Fig. 5) and first need to learn how to adjust the wavelength output of the unknown laser. To do this:

- Two modes exist for the Track button (above Wavelength Adjust knob): Track Mode and Ready Mode.
- When in Track Mode, you can use the Wavelength Adjust knob to change the wavelength. (Note: unfortunately it seems the LED on Track button is not working, this would illuminate to indicate you’re in this mode. But it’s ok, we can use two checks to see if we’re in Track Mode as you turn the knob: (1) you can hear the Picomotor’s characteristic whining or clicking sound; (2) the Wavelength readout is changing in the last two significant figures, i.e. the decimal places). The Picomotor moves slowly and may continue to scan for a period after you have finish scanning the laser to reach your desired wavelength, setting the wavelength on the display.
- When in Ready Mode and you try to adjust the Wavelength Adjust knob, the Wavelength readout doesn’t change and just flickers (first decimal place only). Basically wavelength adjustment is disabled in Ready Mode. Due to nature of wavelength control scheme, the wavelength of the laser is much more stable in Ready Mode than it is in Track Mode. So switch between both modes depending on what you’re doing in the experiment.

**Note:** The Wavelength readout has units of nm. It displays 0.01 nm resolution for setting wavelength but only 0.1 nm resolution once the operating wavelength is chosen. This is due
to the precision with which you can set the wavelength being greater than the accuracy of the Wavelength readout.

**Question 8** Get the cart moving again and count the wavelength at the Wavemeter a few times. Do these values match Wavelength readout you just adjusted on the control box? How different are they? Why could they be giving different readings?

### 5.4 Scanning the wavelength over a particular range

From Question 1, you should of calculated that the hyperfine transition wavelengths range from 780.000 – 780.100 nm. We can set the control box of the unknown laser to do this scan and access the appropriate wavelength range.

But before we do this, hopefully you observed the Wavelength readout from the unknown laser’s control box is different to the Wavemeter count readout. It turns out the Wavelength readout from the control box is incorrect and has drifted slightly as the hardware electronics have aged. It shouldn’t have drifted much as evidenced by your measurement of $\lambda_U$ in Sec. 5.2.

Now let’s do an **automatic** scan of a the wavelength range of the hyperfine transition wavelengths of the rubidium isotopes.

- First, turn on the LCD screen. This will be your video feed from the IR camera which observes what is occurring within the Rb cell as the wavelength is scanned.
- Setting the start and stop wavelengths for the scan (Panel 3 of Fig. 5):
  - Press the multipurpose (scanning and temperature) paddle switch up toward Start and hold it there. The Wavelength readout changes when you do this to show you the starting wavelength for scanning. You can now change the start-of-scan wavelength by turning the Wavelength Adjust knob (Note: keep holding the multipurpose switch up).
  - Setting the end-of-scan wavelength is just as easy as setting the starting wavelength. This time you hold the multipurpose switch down toward Stop while you use the Wavelength Adjust knob to change the stop wavelength.
  - Set the starting wavelength to: $\lambda_{\text{start}} = (780.00 - x)$, where $x$ = difference between control box’s Wavelength readout and Wavemeter count. To the nearest decimal place with respect to the lower precision on the Wavelength readout.
  - The stopping wavelength should be set to $\lambda_{\text{stop}} = \lambda_{\text{start}} + 0.1$
- Setting the scan speed
  - The next step is to set the scanning speed. If you hold the Scan Speed switch up you will see a number between 1 and 100 on the Wavelength readout. This number is the scanning speed from the start wavelength to the stop wavelength. The units are relative; 100 means the fastest possible speed while 1 is the slowest. Experiment to find the best number. To set the scan speed, turn the Wavelength
Adjust knob while holding the Scan Speed switch up. The return scan (stop to start) speed can also be set, while holding down the Scan Speed switch.

- Performing the scan
  - To start a scan, push the Scan button. If the laser is at the start wavelength, it will begin scanning at the scan speed. Otherwise it will go to the Start wavelength ($\lambda_{\text{start}}$) at the return scan speed and wait. Push the Scan button again and the laser will begin scanning. When the laser arrives at the Stop wavelength ($\lambda_{\text{stop}}$) it will stop and wait there. If you push the Scan button again, the laser will reset to the Start wavelength.

- Stopping the scan
  - If you push the Scan button in the middle of a scan or a reset, it will stop, leaving you in Ready Mode. If you push the Track button in the middle of a scan or a reset, the scan will be halted, and the controller will be in Track Mode.

**Question 9** Do you notice any flashes as you can from your start to stop wavelengths? What could these flashes be? That is, due to what physical phenomenon?

### 5.5 Measuring the wavelengths of rubidium ground state excitations

We’re now ready to measure specific excitation wavelengths manually using the Wavemeter set-up via counting.

- Set the wavelength back to $\lambda_{\text{start}}$ (Wavelength Adjust knob in **Track Mode**).
- Set the control box to **Ready Mode**.
- Now we adjust the Piezo Voltage knob (Panel 2 of Fig. [5]) and its readout which allows us fine (sub-angstrom) wavelength tuning. A piezoelectric transducer (PZT) is used to make adjustments in the tuning mirror angle that are too small to make by the Picomotor. The readout is a percentage of the maximum PZT voltage from 0 to 100%. If you adjust the Piezo Voltage control when the laser is in Track Mode, the Picomotor will counter the piezo motion and try to keep the laser wavelength constant.

- Do you see any obvious greater intensity (i.e. a much brighter glow on the LCD screen) as you scan the PZT voltage from 0 to 100%?
  - If not, set it back to **Track Mode** and iterate the wavelength by 0.01 nm. Repeat the PZT voltage procedure (Remember to be in **Ready Mode**).

- When you think you have an obvious brighter glow (this is most likely due to one of the hyperfine transitions!), get the cart moving and wait for a stable interference pattern on the oscilloscope and then count the wavelength. Count it a few times to see if the Wavemeter readout is consistent.

- Repeat the procedure to find the other three hyperfine transitions.
**Question 10** How do all of your wavelengths compare to the calculations you made for rubidium excitation wavelengths? How much error is associated with each measurement?

**Question 11** How accurately do you think you can measure a ground state excitation wavelength with this experimental setup? Explain your reasoning.

### 5.6 Further analysis

**Question 12** The blackbody distribution of room temperature ($T=298$ K) rubidium atoms has a FWHM (full width at half maximum) of approximately $v_{\text{FWHM}} = 400$ m/s centred at $v = 0$. What is the resulting FWHM of the Doppler broadened $^{85}\text{Rb} \, 5S_{1/2} (F = 3) \rightarrow 5P_{3/2} (F' = 4)$ transition?

Recall that the relativistic Doppler shift is given by

$$f' = f \sqrt{\frac{1 - v/c}{1 + v/c}}$$

(4)

where $f = c/\lambda$ and $c = 2.99792 \times 10^8$ m/s.

**Question 13** A Rydberg atom is an excited atom with an electron with a very high principal quantum number. This causes the atom to behave very differently than an atom with lower level excitations. Do you think we could produce a Rydberg atom using our setup with our tunable laser?