Modern Interferometry

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1 Introduction

Interferometry means to measure using interference. The Michelson interferometer (simplest of all interferometers) splits one beam of light into two arms and then recombines them. This will give an interference pattern due to the combining beams interacting. Depending on the change in length in one arm will depend on how that pattern will change. From this, we can calculate many things, in this experiment we will use it to: measure the wavelength of light, calculate the refractive index of transparent solids, and observe how magnetic fields can change the size of metals.

-Objectives: This lab is split up into five weeks, with each week having an experiment to perform (as per contents above). The first week is essentially putting together the Michelson interferometer, while the remaining weeks will be used to perform different experiments on this set up, representing how the same interferometer can be used for testing and observing many things.

-You will: Measure the wavelength of light, learn observe and test the refractive index of a transparent solid, observe the effects of magnetostriction, and use as well as observe how useful Fourier transform spectroscopy can be.

2 Theory

Interferometry is a very important tool in science. Used as far back as 1887 by Michelson and Morley to prove the existence of the "Aether", of course proving the opposite and that light has a constant speed and can indeed travel through the nothingness of space. Now used in the Laser Interferometer Gravitational-Wave Observatory (LIGO) and its discovery in 2015 of gravitational waves. Michelson was awarded the Nobel Prize for his work and the LIGO team may be awarded one for their work, showing the importance of interferometry.

Before LIGO we only had the electromagnetic spectrum to observe the universe, now we can use interferometry to observe it. Opening up a completely new realm in cosmology enabling us to observe black holes merging and more. The experiments in this script are the exact same ones performed at LIGO (except on a much smaller scale), and by Michelson and Morley.

Subjects worth revising for better understanding of these experiments are: Michelson Morley interferometer and its set up, interference patterns and fringes, refractive index and its equations, and the concept of Magnetostriction. All these topics and more can be found on the University of Wollongong's online library from the following eBooks:

- "Fourier-Transform Spectroscopy Instrumentation Engineering" by Vidi Saptari. Chapter 3 and others are good for the Michelson set up and fourier transform (Weeks 1, 2, and 5).

- "Problems and Answers in Wave Optics" by Vladimir P. Ryabukho. Chapters 2 and 4 are good for the refraction and coherence of light (Weeks 2, and 3).

- "Electricity and Magnetism" by Tayal, D. C. Chapter on Magnetic Properties of Matter is good for magnetostriction (Week 4).

These books are not essential reading, and there are other materials out there just as useful, this is just a suggested list.

This script was derived from the TeachSpin "Modern Interferometry MI1-A Instructor's Manual"

Important Preacautions

-**R**ead the laser safety chapter in Appendix B of the TeachSpin manual.

-**Always wear gloves when handling optical elements**. Avoid touching the surfaces of any optical elements (e.g., mirrors, lenses, beam splitters), as described in the TeachSpin manual.

-The interferometry apparatus includes a large number of specialized **components** which are stored in draw below the desk. Each draw includes a list of the contents. You can find a comprehensive inventory of the contents of all the boxes in the literature bin on the bench as well as in the supplementary material on the lab Moodle website.

-**Before assembling a new experiment:**

a. Make a list of the components you will need.

b. Check the inventory pages to identify the boxes in which they are stored.

c. Return unused components to their respective boxes

-Remember that other students will run the experiments after you finished. Please make sure to **return all components to their respective boxes**.

3 Experiments

3.1 Note on Apparatus

-All equipment can be found in the set of draws under the bench, replace all apparatus after use, demonstrators will be checking at start and end of lab sessions.

-You will be using two different sizes of Allen-keys. One smaller size for the adjustment of the upstream/downstream mirrors (also known as mirrors M1 and M2). One larger size for the adjustment of all other objects on the breadboard (Big black table with boltholes). The larger Allen-key also comes in a useful screwdriver form for easier use, so you effectively have two tools for this larger size.

-These are the alignment towers and alignment paddles, in Figure 1 below, you will be using to help align the laser beam. The paddles (Bottom) slot into th mirror/beam splitter mounts, while the towers (Top) simply sit on the bread board as in the picture.

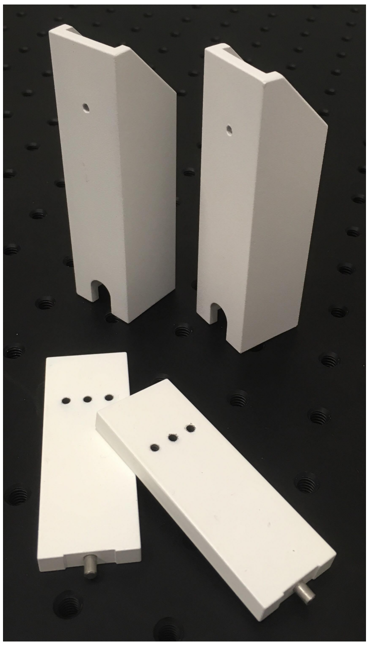

Figure 1: Alignment Towers And Paddles

3.2 Setting up Michelson and finding fringe patterns (Week 1)

-First set up the Michelson interferometer as shown in Figure 2 below.

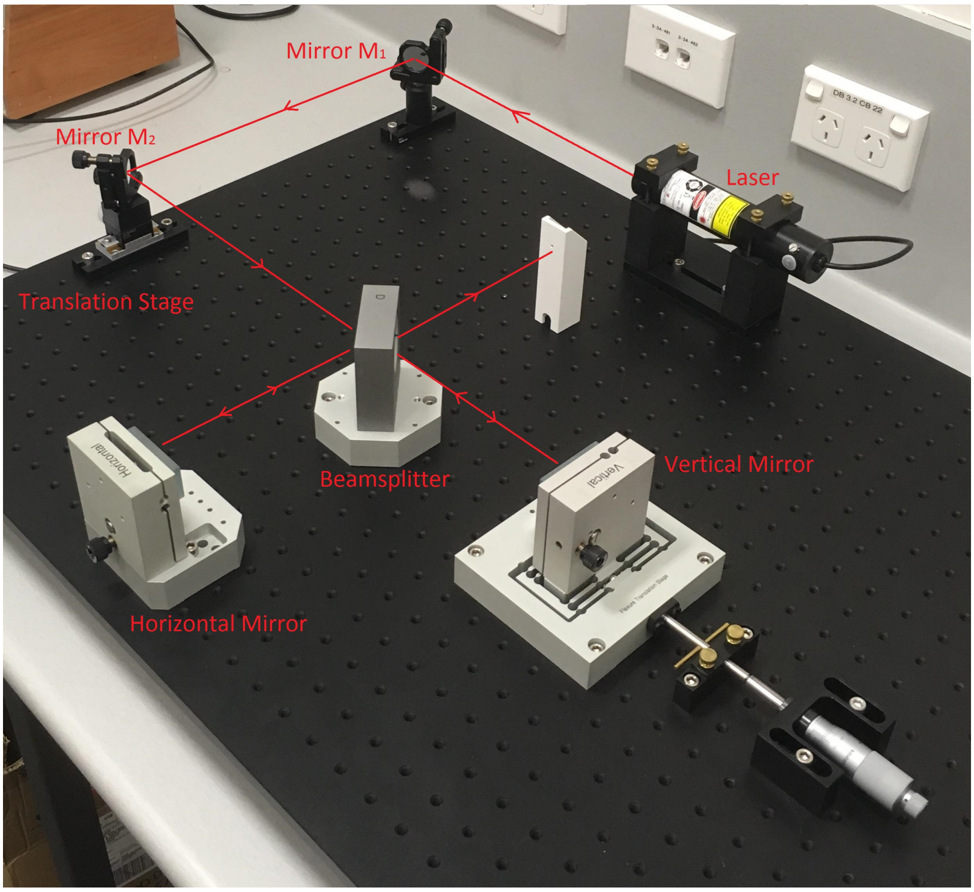

Figure 2: Entire Michelson Set Up

Note: It is important you stick to this image and place the translation stage as the second mirror, you will see why later in the experiment.

Note: Do not touch any of the mirrors surfaces, and do not over tighten bolts when instructed to secure them. Their purpose is simply to reduce vibration.

Note: Do not touch the fine adjustment knobs on the backs of any of the mirrors until instructed to do so.

-There are three different lengths of bolts, and any can be used. Only place the bolts very loosely as you will be manoeuvring all the equipment a lot before tightening each fixture when instructed. You'll notice for the mirror mounts there are several bolt holes, but only three bolts are required to keep them in place. The center bolt hole and the two closest bolt holes either side of it.

-Use the Dielectric-film beamsplitter (yellow or blue sheen), and not the Metal-film beamsplitter (pronounced greyish cast). Denoted by the "D" and "M" on top of the mounts.

-Once the equipoment is set up as per the above picture, turn on the control box (Switch at back of box) and plug the HeNe laser into the back of the box, with its unique plug and socket. Now turn the laser on at the front of the box, making sure to pull the switch towards you before putting it over to the "HeNe laser" option.

WARNING: Do not look directly into the laser beam, and avoid being eye level with the plane of the laser.

Aligning the Laser beam

- Step 1- Guide you through the initial rough set up of the laser.
- Step 2- Guide you through the final and very precise alignment of the laser.
- Step 3- Guide you to align the arms of the interferometer
- Step 4- Guide you on how to recombine the two laser beams.

Step 1 - The basics, rough alignment

-The following method will seem long and perhaps complicated at first, but after doing it once it will be very easy and natural.

-Place the alignment tower next to the mirror M_2, on the side closest to the mirror M_1 as in the Figure 3 below.

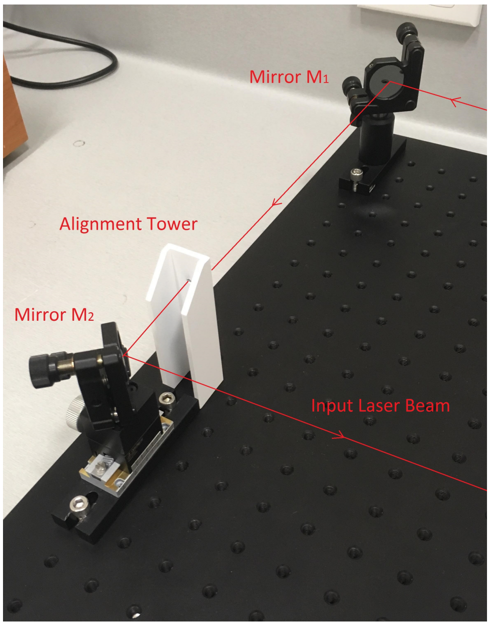

Figure 3: Laser Alignment

-Now you will see why leaving the bolts loose earlier was necessary. "Slop" is a term used for the excess space in the boltholes of all equipment on the breadboard. It is there so that you can move a mount around in its "Slop" with the bolts loosely in place. This is to enable you to help position the instrument before tightening the bolts ready for precise positioning.

-Using this "Slop", adjust the laser so the laser beam hits directly into the centre of M_1, now, using the slop and the main centred bolt in the top of the mirror M_1, adjust the angle of the mirror (Not yet touching the small adjustment knobs on the mirror). Do this until the laser beam runs directly through the centre hole in the alignment tower you placed next to M_2 while still in the centre of mirror M_1. You may have to go back and forth to achieve this but once satisfied tighten the bolts in the laser mount and in M_1's mount, as well as the bolt on the top of the mirror M_1. Finally, remove the alignment tower once done.

-Figure 4 below represents part of the Michelson set up in a birds eye view. The locations (A, B, C, D, and E) refer to the centre holes found in the mounts of the mirrors and beamsplitter where alignment paddles can be placed.

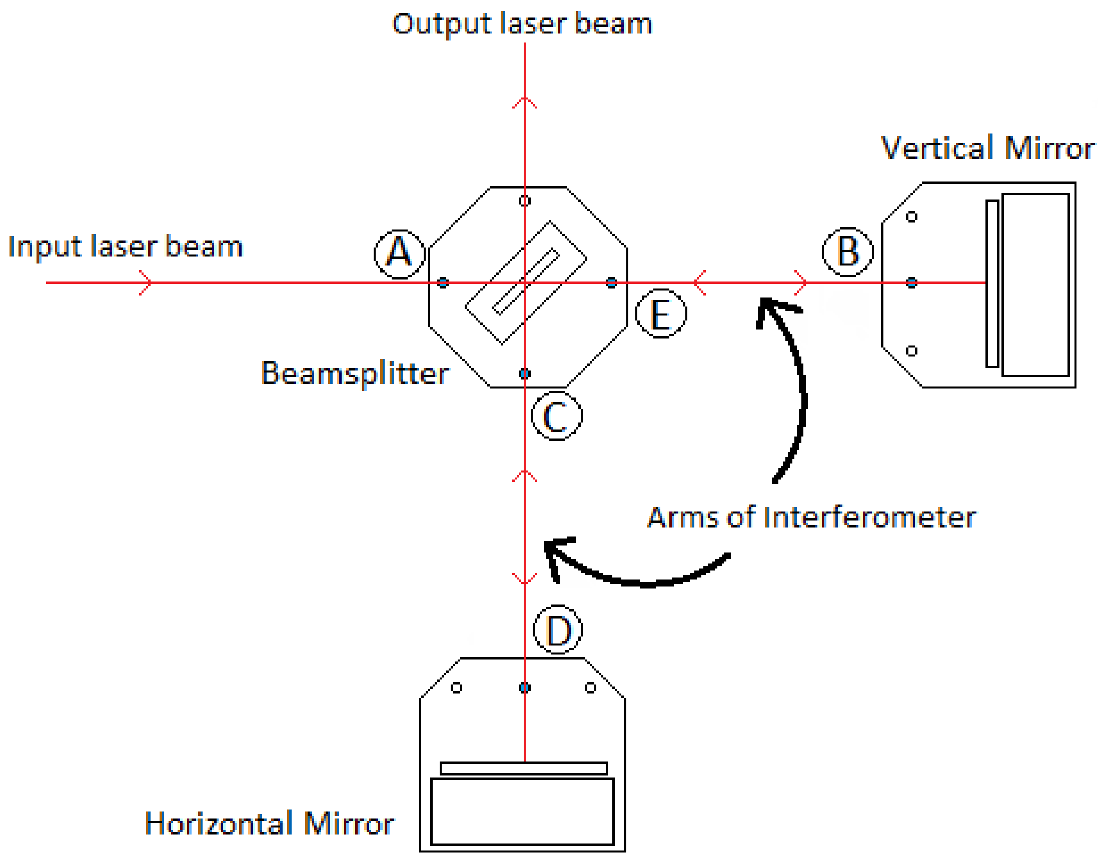

Figure 4: Michelson Set Up (Interferometer Arms)

-Place the two alignment paddles at locations A and B.

-Adjust M_2 so the laser passes through the first paddle at point A. Do this by using the translation stage adjustment, and by loosening the top main bolt holder of the mirror, and the slop in the mounting bolts. Once satisfied, tighten all these bolts.

Note: This above procedure may lead to the laser beam falling off M_2 altogether, if that happens simply start again from the very top, being as precise as possible and use trial and error until you get it.

Note: The mirrors should not be placed at angles and you should stick to the images provided. The better the precision of this stage the easier the later adjustments will be.

Note: The two adjustment knobs on both mirrors M_1 and M_2 should not have been touched yet.

Step 2 - The precise alignment

-The best way to visualize this method is a water stream going through a tube as in Figure 5 below; you have an upstream (M_1) and a downstream (M_2) mirror to control the waters flow through the mythical tubes upstream and downstream ends, wanting to keep it as central as possible.

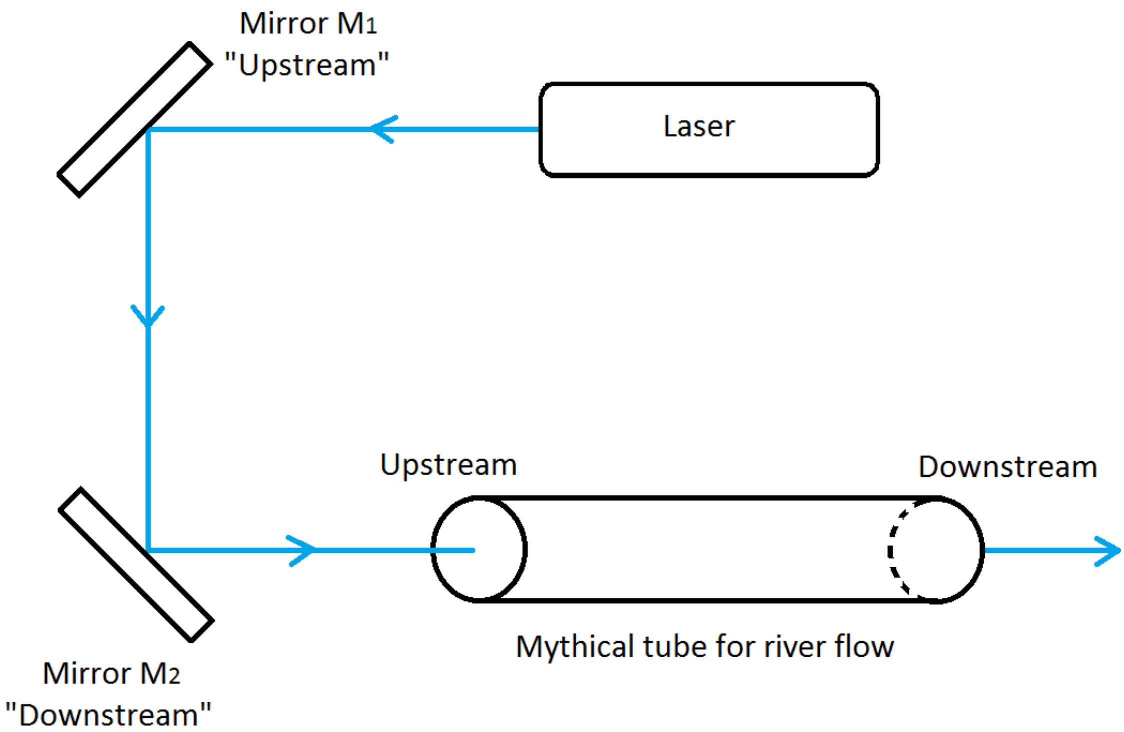

Figure 5: Upstream And Downstream Concept

-The laser beam needs to go into the upstream end and leave at the downstream end without touching this mythical tube. This is why we need two adjustable mirrors: the upstream mirror and downstream mirror, both with horizontal and vertical adjustment capabilities, enabling four degrees of freedom.

-The upstream end of our mythical tube will be our location A and the downstream end will be location B, as per Figure 6 below.

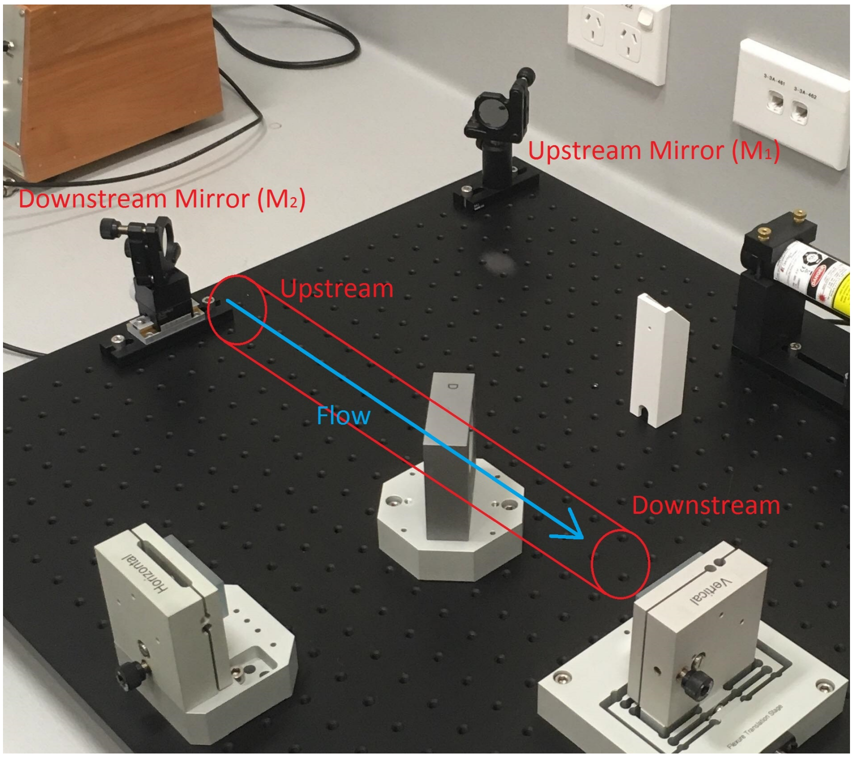

Figure 6: Upstream And Downstream Representation

Step A- Adjust vertical and horizontal knobs on the upstream mirror M_1 so that the laser beam travels perfectly through the centre hole in the alignment paddle at location A (upstream).

Step B-Now correct that alignment by adjusting the vertical and horizontal knobs on the downstream mirror M_2 so that the laser beam travels perfectly through the centre hole in the alignment paddle at point B (downstream).

-Repeat step A, and then step B, and keep repeating in sequential order in a seemingly endless struggle until the laser beam travels perfectly through both alignment paddles.

Step 3 - The alignment of the interferometer's arms

-All bolts on mirrors M_1, M_2 and the laser should have been tightened by this point. While all other bolts should still be loose.

-Now you have the laser fully aligned, it is time to align each of these two individual arms of the interferometer, as well as their reflective beams.

-You should see the beam splitter has allowed half of the light beam to pass through unhindered and onto the vertical mirror via the E-B arm. While the other half of the light, the beamsplitter reflected through the C-D arm and onto the Horizontal mirror.

-This means the light going straight through to the vertical mirror is already aligned as it is untouched, however the return beam, from B to E, needs aligning. As for the other arm of the interferometer, C-D both light beams must be aligned. The one reflecting off the beam splitter and the return beam from the horizontal mirror.

-We will first align the arm C-D outgoing beam, using the Slop in the beamsplitter. Then using the Slop in the horizontal mirror we will align its reflecting beam. Then we will align the other arm, E-B reflecting beam using the Slop in the vertical mirror.

Note: It is sometimes helpful to block off one arm of the interferometer when aligning the other. This is to avoid unwanted reflection, this can be done with an aligning tower.

-Put alignment paddles in positions C and D, use the slop in the beam splitter to move it around until the laser passes directly through the centre of alignment paddle at point D. Then tighten the bolts as much as possible while keeping an eye on the laser beam through this position as it will shift as the bolt is tightened. Try to tighten the bolt as much as possible without misaligning the laser beam.

Note: This will not affect your previous alignments as the laser beam that travels to the vertical mirror, passes straight through the beam splitter unhindered.

-Now using the slop in the horizontal mirror mount, adjust it so that the laser beam passes through the alignment paddle at location C. Again tighten the bolts in this mirror mount once done, while keeping an eye on laser beams movement.

-If you find you cannot get the laser beam directly through any of these holes then you may need to lift the beam splitter or mirror, this can be done by using paper or one of the metal slates provided and sliding them under the mounts. For a more precise increase in height, the beam splitter has a tiny Allen-key bolt that you can tighten to increase height. Both methods are shown in Figure 7 below.

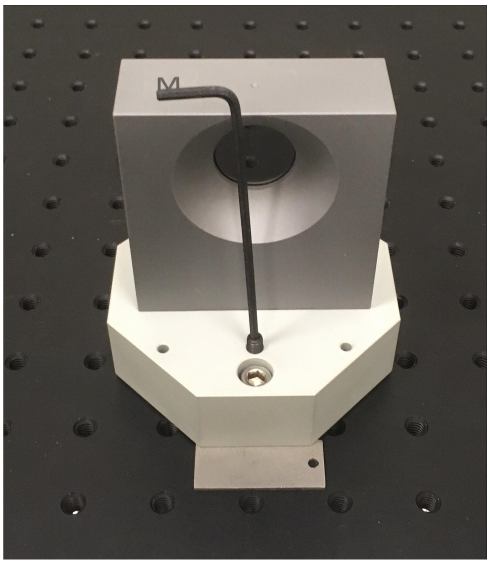

Figure 7: Example of height adjustment

-Put the alignment paddles in positions E and B, the laser beam should still be passing through B fine due to your earlier alignment (Step 2), but now use the Slop in the vertical mirror to adjust the returning laser beam perfectly through alignment paddle E, once done tighten bolts as done before.

-Once all these above steps are complete, your Michelson interferometer is ready to go. All bolts should have been tightened during alignment processes and the adjustment knobs on the backs of the vertical and horizontal mirrors should not yet of been touched.

Step 4 - Aligning the two recombined laser beams

-Now the entire interferometer is ready, the two beams will now leave the beam splitter and you should see two laser spots. Our job is to now perfectly combine these two spots.

-We need to do this so that they interfere with each other and hence create the fringe patterns as seen in Figure 8 below, enabling us to observe and use them.

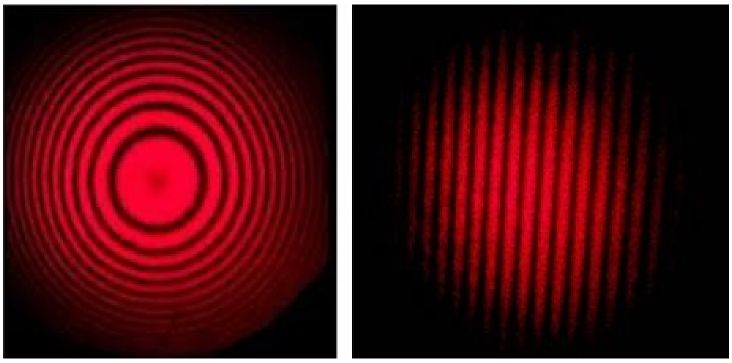

Figure 8: Fringe Patterns To Be Observed

-Above is the fringe pattern that you should see, the right being the most likely. Each bright spot represents constructive interference, and the dark spots destructive interference.

-To achieve this first put either a piece of paper or an alignment tower after the beam splitter in the output beam, leaving around the same amount of distance as one of the interferometers arms. This will enable us to view the fringe patterns easier. You should see two laser beam spots, each comes from each arm of your interferometer. Prove this to yourself by blocking the path of one arm with your hand or the other alignment tower.

-To combine these two spots we have two degrees of freedom from the knobs on the back of the vertical and horizontal mirrors. One mirror will rotate its surface around a vertical axis (hence the name, and label on the mirror) which will give you a horizontal motion on the laser beam. The other mirror will do the opposite, rotating around a horizontal axis to give a vertical movement in the laser beam. Just remember the labels signify the actual movement and not its affect. It seems backwards, however labelling these this way, gives us the realistic movements in what is physically happening.

-Turn the lights off and adjust these toggles until the laser beams are on top of each other as much as possible, at this point you should see one of the fringe patterns above.

Note: At this point you should see how sensitive the interferometer is, leaning on the table or breadboard will cause this fringe pattern to move, as well as loud noises, and any other vibrations of any sort, so be careful where you are leaning when taking measurements.

End of Week 1 Questions

1. Why does adjusting the beam splitter in its Slop not affect the laser beam traveling through points E and B?

2. As we know lights travels at different speeds in different mediums, (as we'll see in our upcoming refractive index experiment), which will cause phase shifts in the light. Our laser beam travels through the beam splitter (which is a different medium), why doesn't this affect our results.

3.3 Measuring the wavelength of HeNe laser (Week 2)

-Now you have the Michelson interferometer set up you can start to make some measurements.

-First, we will start with the most simple, measuring the wavelength (λ) of the HeNe (Helium Neon) laser.

-To do this all we need to do is change the distance (d) of one of the interferometer's arms and record the distance changed as well as the amount of fringes (N) passed. Their relationship is connected by the following Equation 1.

$$\lambda = \frac{2d}{N} \tag{1}$$

-The way we measure the distance is via the Vernier micrometre. To count the fringes we simply watch the pattern and count how many fringes pass a given point. You can use the lens to magnify the fringe pattern so it is easier to see. The best place for it is between the beam splitter and the surface with the pattern, you will have to alter its position to find the focal point.

-Do this several times with different values of N (e.g. 25,50,100), each time making sure not to put pressure on the breadboard during readings.

-To avoid the effects of backlash in the micrometre screw, turn the micrometre handle one full turn before starting the count. Do not turn back the other way once counting, and try to keep the turning constant without stopping.

-The given wavelength of the HeNe laser is on the laser itself (633nm), this is an accurate process so your result should be close to this.

End of Week 2 Questions

1. Why does Equation 1 multiply the distance by two?

2. What do the very brightest spots in the fringe pattern represent

3.4 Calculating refractive index of transparent solids (Week 3)

-Refraction happens when light hits a different medium at an angle as opposed to along the normal (perpendicular to the surface of different medium). The amount of refraction depends on the refractive index of the given medium; and this is a ratio of the speed of light in a vacuum to the speed of light in that medium. This refraction will therefore cause a phase shift in the light wave, due to this change in speed.

-In our interferometer, one arm will continue as normal, whereas the other arm will be subject to this refraction by passing through a transparent solid. When the two laser beams combine, they will interfere, and we will be able to observe this phase shift caused by the refraction.

-We can use this interference pattern to deduce the refractive index of this transparent solid the light is traveling through.

-The goal here is to calculate the refractive index of the glass and quartz slabs provided.

- Glass- Nominal thickness T=1.0 mm
- Quartz- Nominal thickness T=0.5 mm

-The model of taking results is very similar to the previous experiment. Instead of measuring the change in length of the interferometer arm though, we measure change in the angle of the transparent solid, while counting the change in fringes.

-Keep the exact same experimental set up as the previous section (Week 2). With the exception for this you will be adding the miniature rotation stage, Figure 9 below, while putting the glass or quartz slab in its holder.

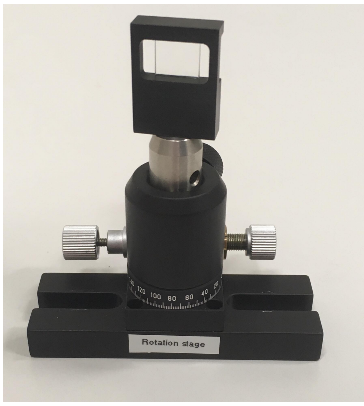

Figure 9: Minature Rotation Stage

-It is best positioned in one of the arms of the interferometer. The glass plane itself must start perpendicular to the laser beam, to allow the laser beam to fall along the normal, preventing refraction on initial readings. Note however, this perpendicular set up will still causes a phase shift in the light due to the different speed within the medium; this will not affect your results, as you will be reading from this new phase shifted beam.

-Once set up and the laser is on, start turning the rotation stage and count the fringes that you see change, repeat this several times, recording both the fringe count (N) and the angle turned (θ).

-Do this several times for different angles, turning the slab in the opposite direction as well. Where you should see, for example, 5^o to the right and 5^o to the left give the same result as each other.

-Be aware that past a certain angle the light beam will be refracted toO much and hence will not fall on the detector/screen, so there is only a certain degree that you can work to, make sure to note this angle.

-Once you have done the above steps for both the glass and quartz and gained results, it is simply a case of using the relationship between fringe count and angle change to calculate the refractive index for both materials.

-The Equation 2 below looks complex but do not be put off, it is quite simple once you split it apart and input the variables. "n" is the index of refraction, while "θ" is the change in angle of the solid.

$$n = \frac{\alpha^2 + 2(1 - cos(\theta))(1 - \alpha)}{2(1 - cos(\theta) - \alpha)} \tag{2}$$

-The alpha variable (α) is solved by the following Equation 3 below where "M(θ)" is the fringe count change over the given angle, and "T" is the thickness of the transparent solid.

$$\alpha = \frac{M(\theta)\lambda}{2T} \tag{3}$$

Extra: If you get time, take the polarizer plate and introduce it into the interferometer. You shouldn't see glass having any dependence on it, where as the quartz you should.

End of Week 3 Questions

1. What causes refraction?

2. Why does the change in angle of the transparent solid cause a phase shift in the light from the laser?

3.5 Detecting Magnetostriction (Week 4)

-Magnetostriction is the change in size of a ferromagnetic material due to magnetism. The external magnetic field aligns all of the molecular dipoles and domains inside the ferromagnetic material with the field; this causes the metal to elongate, shown below in Figure 10, with exaggerated extension for instructional purposes. The opposite is also true, when a metal undergoes stress and contracts it will change the metals magnetic susceptibility, this is called the Villari effect.

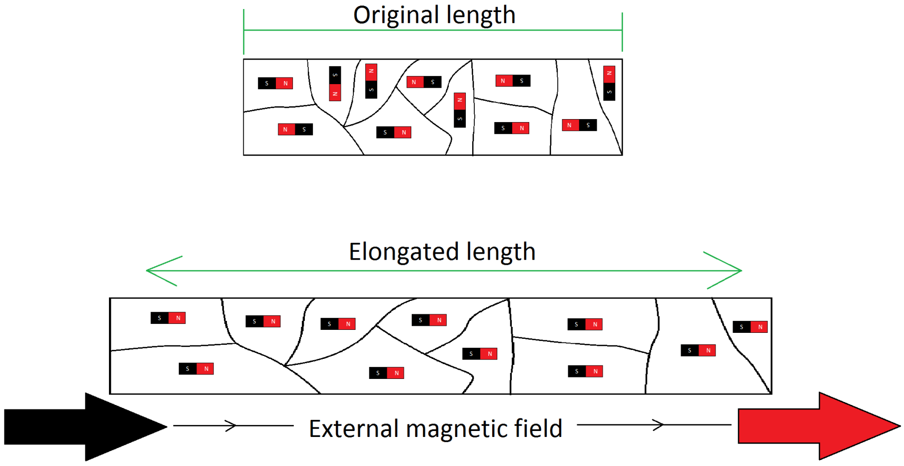

Figure 10: Magnetostriction Causing Elongation

-Once the magnetic field is removed the metal will return to its original size. However this does not happen straight away and there is a time lag between the magnetic field removal and the change in the metals physical size, this lag is called hysteresis, and it is important to bear in mind when taking measurements.

-The metal is most elongated when all the magnetic domains have been aligned, this is called the point of saturation, whereby the metal will not elongate any further. Your task in this experiment is to find this saturation point for a variety of materials.

-Why is magnetostriction useful? Magnetostrictive materials can be used to convert electromagnetic energy into mechanical energy. Enabling them to be able to be used for sensors that measure magnetic fields.

-Different materials have different amounts of these domains with different orientations, meaning some materials are more susceptive than others to magnetostriction.

-In this experiment you will be using a controllable magnetic field on different metals to determine their magnetostrictive properties:

(all in the form of rods; each is of nominal $\frac{1}{4}$ of an inch in diameter)

- Nickel- Ferromagnetic (295mm)
- Steel- Ferromagnetic (Due to its iron content) (300mm)
- Copper- Diamagnetic (305mm)

-The deformation of these metals due to magnetostriction is only small, hence why we need the use of the interferometer to witness the changes.

-The metal will be introduced into the interferometer arm with the mirror on the translation stage. On the other side of the metal the micrometre will be placed as in Figure 11 below.

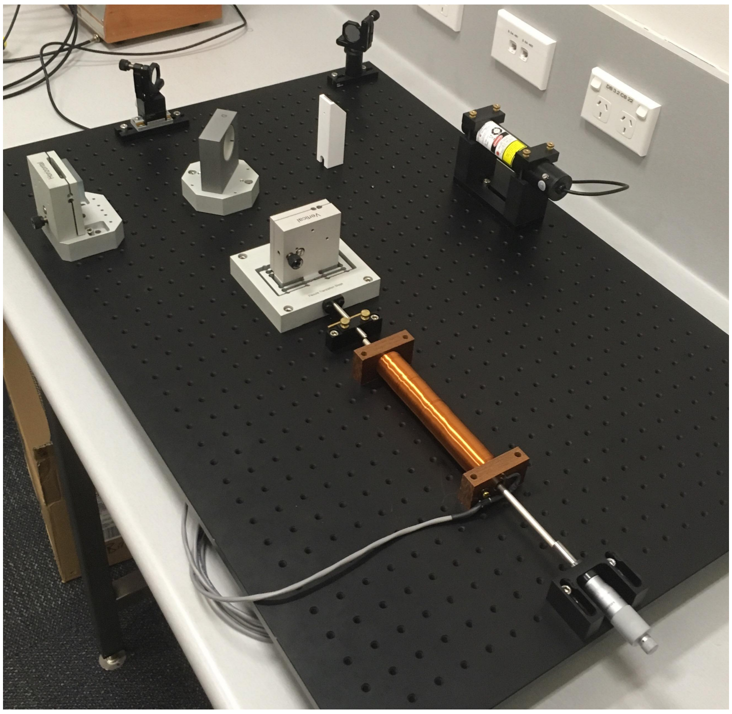

Figure 11: Magnetostriction Set Up

-This means any change in the size of the metal will mean a change in length of the interferometer's arm.

-The micrometre will be a part of the set up but cannot be used to measure these changes due to their small sizes and is simply to keep the rod in place. Instead we will observe the phase shift of the laser beam, by counting the amount of fringes that pass to determine change in size of the metal.

-We can use Equation 1 to find this change in distance with some quick rearranging. Once we have that we can then calculate the magnetostriction of the metal with the following Equation 4 below.

-The degree of magnetostriction can be measured by the magnetostriction coefficient (λ), which is the ratio of the fractional change in length (ΔL), to the magnetostriction of the material (L).

$$\lambda = \frac{\Delta L}{L} \tag{4}$$

-Also known as the strain/change in length (ΔL) divided by the original length (L).

-You should find the magnetostriction for each of the three metals, and discuss their differences as to why some are more susceptible to magnetostriction than the others.

End of Week 4 Questions

1. What is Hysteresis, and why is it important in this experiment?

2. What is the Villari effect?

3.6 Fourier Transform Spectroscopy (Week 5)

-Light is a makeup of many different wavelengths, the wavelength depends on what element the light is being emitted from. Therefore, if we can work out the wavelengths observed then we can deduce the element it is coming from.

-For example astronomers look at light coming from stars, they then break it up into its different components to see what elements are in that star. Using this method we can calculate the elementary make up of stars and planets light years away.

-Different wavelengths of course corresponds to different frequencies. Our aim is to observe all the separate frequencies from our light source using fourier transfrom spectroscopy.

-This is where the interferometer comes in, it allows us to observe all the different frequencies from the light source. The oscilloscope then helps to break these frequencies up using Fourier transforms.

-Remove the magnetic coil and rod and replace the micrometre back how it was set up in first experiment (Week 1).

-Working off the previous experimental set up, remove the horizontal mirror, take it off its mount and place it on top of the "Single axis translation stage". You must first remove the four screws to lift off its top before attaching the mirror, and replacing the top with its four screws.

-The introduction of this stage is to enable you to move both mirrors to almost exact equal distances away from the beam splitter. Making the interferometer arms identical in length. Around 20cm is a good distance for the interferometer arms to be.

-You will need to use the Vernier calliper to do this. On top of the beam splitter, you will see a small circular groove in the centre of its top. You will use this point to measure the distance between it and the mirrors. Use the mirrors mount behind the mirror and not the movable mirror surface itself for the most accurate results.

Note: Do not measure from the mirrors surface, not only will this move the mirror, misaligning your set up, it will also dirty and damage the mirror, not to mention it will not be as a precise.

-Once you achieve this, you should see curved circular fringes.

-Replace the paper or alignment tower with the photodetector. This should be where the two light beams converge, do not ever move the laser beam to meet the detector. Instead always move the detector as much as you want to where ever the laser beam falls.

Acknowledgements

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