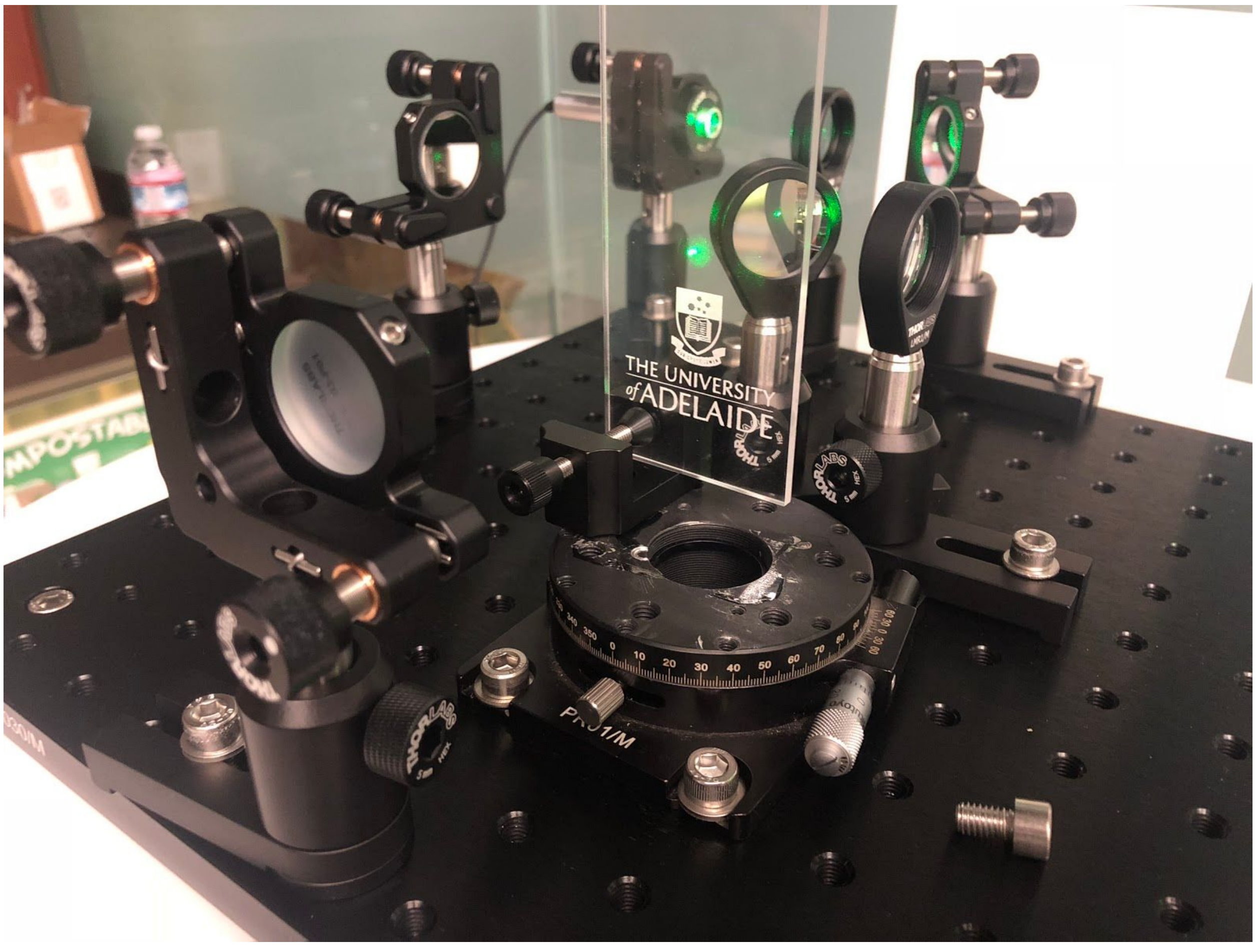
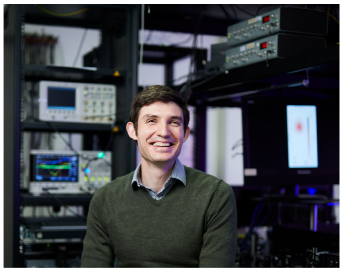
# Laser Interferometer Demonstration Instructions

Craig Ingram, Ben Sparkes -
Institute for Photonics and Advanced Sensing, School of Physical Sciences, University of Adelaide
Australian Research Council Centre of Excellence for Gravitational Wave Discovery



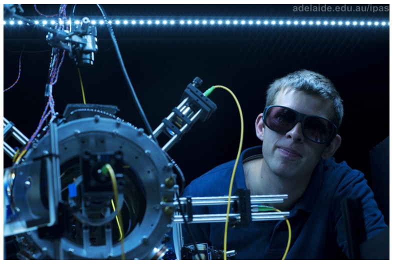


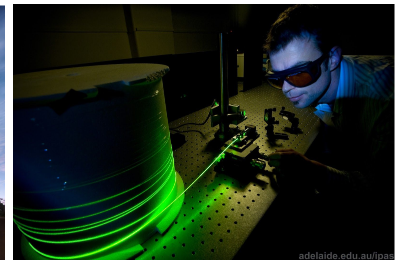
**Dr Ben Sparkes** is an Australian Research Council Discovery Early Career Research Fellow at the Institute for Photonics and Advanced Sensing, University of Adelaide. Current projects involve developing a fully-integrated fibre-based platform for a quantum information network. His research and school outreach activities led to him being named the South Australian Tall Poppy of the Year for 2018 - an award acknowledging the achievements of Australia's outstanding young scientific researchers and communicators. In 2019 Ben has been awarded a Fulbright Futures Scholarship to pursue his research in extending the distance of optical quantum communications at Columbia University.

www: https://researchers.adelaide.edu.au/profile/ben.sparkes e: ben.sparkes@adelaide.edu.au

**Mr Craig Ingram** is a masters student at the University of Adelaide (UoA). His research involves investigating the properties of materials (in particular absorption in fused silica glass) for the next generation of gravitational-wave detectors. Mr. Ingram has also recently completed his bachelors of teaching at the same institution. Craig is the president of the UoA OSA student chapter and an active member of the Australia Research Council Centre of Excellence for Gravitational-wave Discovery (OzGrav) outreach program including the development of the AMIGO (Adelaide Michelson Interferometer for Gravitational-wave Outreach) interferometer, as well as being a part of the LIGO collaboration.

e: craig.ingram@adelaide.edu.au





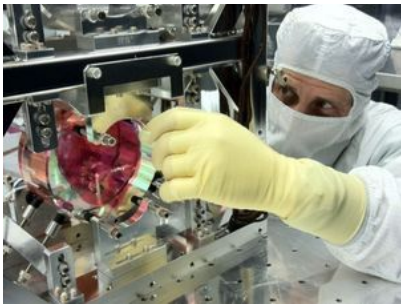
**The Institute for Photonics and Advanced Sensing (IPAS)** is one of 6 research institutes at the University of Adelaide, these institutes exemplify research excellence. The mission of IPAS is to use the power of light to make the world a safer, healthier and wealthier place. We are doing this by building unique sensors which harness the powerful properties of light to learn about the environment: this might be inside the human body where we are building tools to diagnosis disease, inside an aircraft where we can search for hidden corrosion, inside a nuclear reactor where we want to measure radiation, or mapping methane leaks.

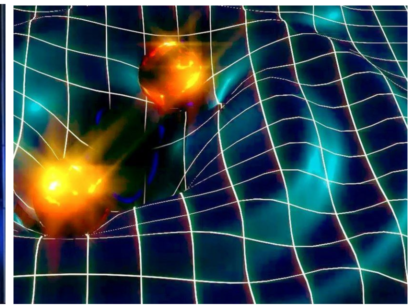
Many of the challenges we face as a society can only be solved by pursuing a transdisciplinary approach to science. IPAS has been created to bring together experimental physicists, quantum physicists, chemists, material scientists, biologists, experimentally driven theoretical scientists and medical researchers to create new sensing and measurement technologies.

We engage with many market sectors to understand the measurement challenges they face, that if solved, would transform industry productivity. We harness the core capabilities and form interdisciplinary teams around a wide array of funded research projects. The outcome and impact of these projects range from new Scientific Discoveries and innovations to Spin-Out companies and the creation of new jobs.

IPAS research targets applications in seven key areas:

- Defence Technologies
- Quantum Communications and Computing
- Medical Diagnostics and Devices
- Mining and Mineral Processing Sensors
- Extreme Astronomy
- Environmental and Agricultural Monitoring
- Food and beverage Analysis





**The Australian Research Council Centre of Excellence for Gravitational Wave Discovery (OzGrav)** is a $40M collaboration involving Swinburne University, the Australian National University, Monash University, University of Melbourne, University of Adelaide and University of Western Australia, along with other national and international partner organisations.

Gravitational waves were first predicted by Albert Einstein in 1915 in his theory of General Relativity, which described how gravity warps and distorts space-time. Einstein predicted that massive accelerating objects (such as ultra-dense stars or black holes orbiting each other) distort both space and time and emit a new type of radiation, known as gravitational waves.

The predicted gravitational waves are incredibly tiny. They went undetected for one hundred years until recent advances in instrumentation allowed scientists to detect passing gravitational waves generated by two colliding black holes over one billion light years away. The arms of the gravitational wave detector changed their length by the equivalent of just the width of a human hair at the distance of the nearest star!

The Nobel Prize-winning discovery of gravitational waves in 2015 was followed shortly thereafter in 2017 by another landmark discovery; a pair of merging neutron stars in a nearby galaxy. That violent event was felt on Earth by gravitational wave detectors, and remarkably, telescopes around the world also witnessed the merger through the cosmic fireworks display that it triggered.

OzGrav's mission is to use these historic detections to understand the extreme physics of black holes and warped spacetime, and develop instruments and techniques for use in next generation gravitational wave detectors. OzGrav brings together a broad range of research activities into a focussed national program, cross-fertilising across disciplines that extend from laser development and radio instrumentation to big data and astronomy.

OzGrav is also using the intriguing concepts of black holes and gravitational waves to inspire young people into careers in science and technology, educate the public about the nature of our Universe, and explain how the scientific method works and can be trusted.

## The Michelson Interferometer

With its incredible sensitivity, the Michelson Interferometer has been central to a number of key experiments in physics spanning the last 130 years. This is despite consisting of only a few simple optics, namely two mirrors and a beamsplitter (Figure 1a). The Michelson Interferometer achieves its high resolution by making use of the wave-like nature of light: two intersecting waves with the same phase will add together to produce a brighter wave, while two waves that are completely out of phase will cancel each other out (Figure 1b). This is called the superposition principle.

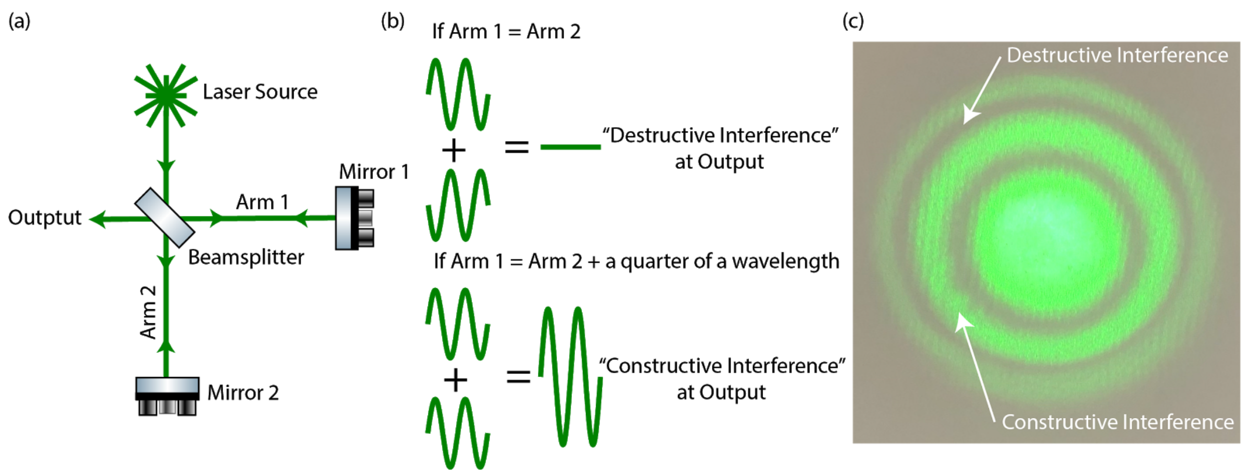



*Figure 1 - (a) Michelson Interferometer set-up; (b) Constructive and destructive interference; (c) Interference pattern from an expanded beam out of a Michelson Interferometer.*

When light enters the interferometer, half is sent into each arm by the beamsplitter. The light in each arm then reflects off the mirrors and returns to the beamsplitter where the two waves superimpose (or "interfere") with each other. The type of interference ("constructive" or "destructive") will depend on the relative lengths of the arms. For instance, if the two arms are equal in length then no light will exit the output port of the interferometer ("total destructive interference"), while if one arm length is increased by only a quarter of a wavelength (of order 100 nm) then all the light will exit at the output port ("total constructive interference").

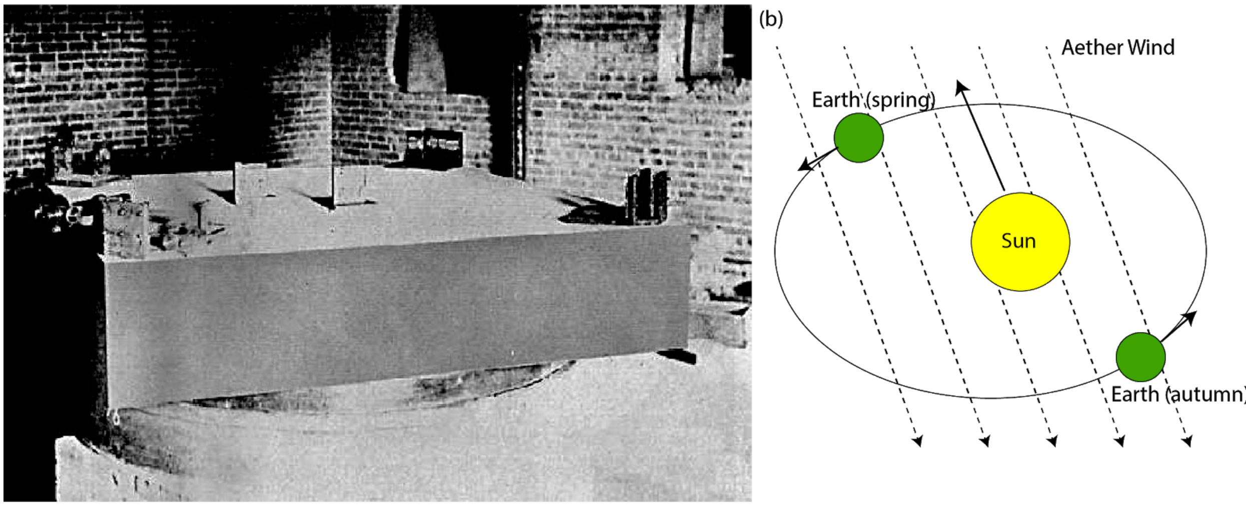



*Figure 2 - (a) Michelson-Morley Interferometer [Casey Western Reserve University, c1887]; (b) How the Michelson-Morley Interferometer aimed to measure the change in the speed of light due to the relative direction of the Earth to the Aether Wind.*

One of the first, and most famous, uses of a Michelson Interferometer was in an experiment which attempted to measure the *luminiferous aether* - the medium through which light was postulated to travel in the late 19th century. For this experiment, Albert Michelson and Edward Morley placed their interferometer on a stone slab on top of a pool of mercury for stability (Figure 2a) and attempted to observe a change in the relative phase over a year due to the postulated change in the speed of light that would occur as the earth moved with or against the *aether wind* (similar to the Doppler effect - Figure 2b). This experiment remains one of the most famous null results in physics.

Fast forwarding to the 21st century and Michelson Interferometers are again in the spotlight. This time for their use in the detection of gravitational waves, a postulate of Einstein's theory of General Relativity. When a gravitational wave passes through an object, it causes the object to expand in one spatial direction while contracting in a perpendicular one. Unfortunately, gravitational waves have only a very small effect on matter, changing the length of an interferometer arm by 1/10,000th the width of a proton. This meant that researchers at the Laser Interferometer Gravitational-Wave Observatory (LIGO) collaboration had to play many tricks to increase the sensitivity of their device. For instance, they constructed 4 km beam paths (Figure 3a) with optical resonators in each arms causing light to undertake 280 round-trips, for an effective arm length of 1,120 km (Figure 3b). This, as well as many heroic engineering solutions to remove other sources of vibration in the arms and using two (or more) interferometers to enable multi-site confirmation, has led to the detection of 11 gravitational waves to date and instigated the dawn of gravitational-wave astronomy.

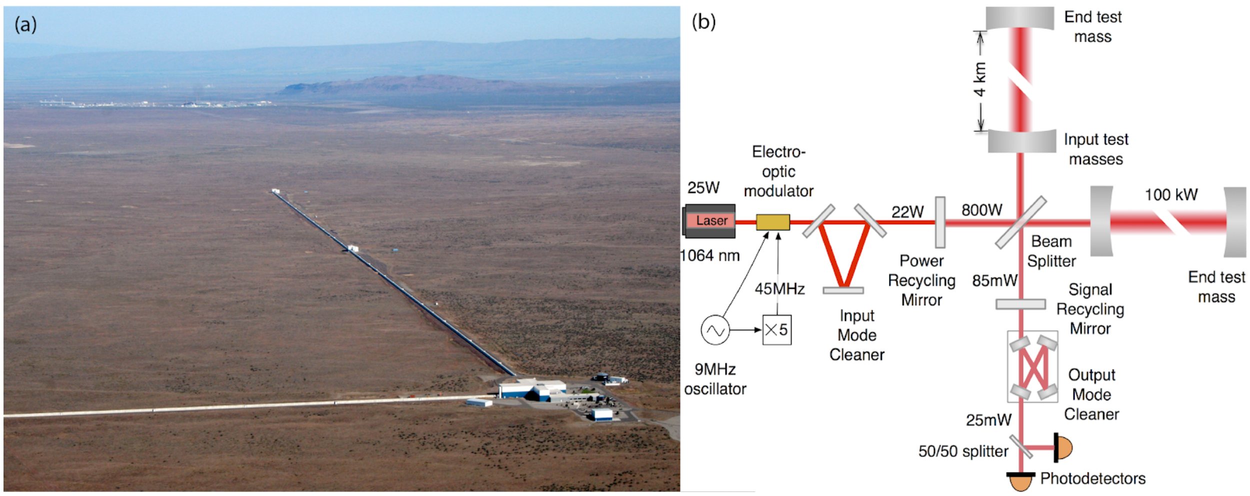



*Figure 3 - (a) Aerial view of LIGO Hanford [LIGO Laboratories]; (b) A simplified schematic of the inner workings of LIGO [D. V. Martynov et al., Phys. Rev. D* ***93****, 112004 (2016)].*

Through the following experiments we hope that you can experience first-hand the incredible sensitivity of a Michelson Interferometer as just one example of the many applications of photonics in the 21st century.

*- Craig Ingram, Andre Luiten & Ben Sparkes - 23 January 2019*

## References


Michelson interferometer; Michelson-Morely Experiment - Wikipedia

What is an Interferometer?; LIGO's Interferometer - LIGO lab, Caltech

# Interferometer Experiments

## Experiment 1 - Measuring Wavelength

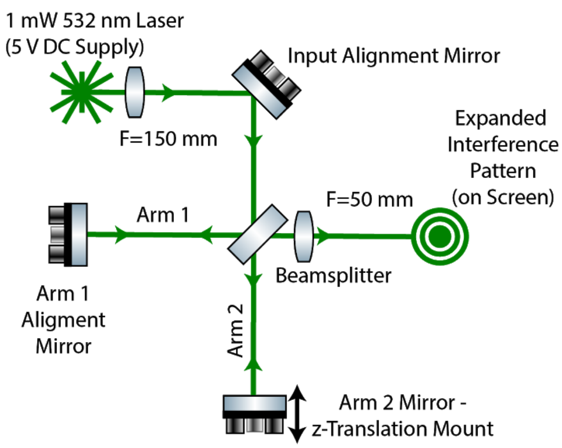
### Background

A Michelson Interferometer offers an elegant way to carry out a measurement of the wavelength of a laser. This is because the interferometer works on the principle of interference (Figure 1b) - where a change in path length difference between the interferometer arms corresponds to light-dark-light transitions in the output port. A single light-dark-light transition corresponds to a path length difference of a wavelength λ. By counting the number of light-dark-light transitions *N* as the path-length $\Delta x$ is changed we can determine the wavelength of the laser via:

$$N\lambda = 2\Delta x \Rightarrow \lambda = \frac{2\Delta x}{N}$$

The factor of two comes from the fact that, as the path-length is changed, the round-trip path of the laser in Arm 2 changes by $2\Delta x$.

## Description



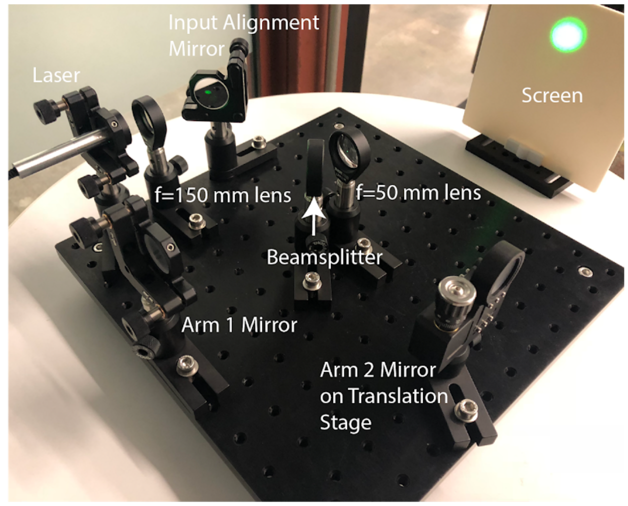




*Figure 14 - Interferometer set-up for measuring the wavelength of light*

Use the micrometer actuator knob on the z-translation mount to change the path length of Arm 2 while recording the number of light-dark-light fringes (see Table 1). Using the equation above, the wavelength can be derived from noting the start and end values of the micrometer screw and the number of light-dark-light transitions that occured. One scale division of the screw corresponds to one micrometer. Observing numerous transitions is recommended in order to minimise the error.

*Tip: Rather than performing the measurement by hand, try inserting a 2 mm Allen key into the actuator and only turn the Allen key to be more precise and avoid exciting drum modes of the breadboard.*

*Tip: While taking measurements, move the mirror in only one direction, as reversing the direction can lead to backlash[1] of the stage.*

For reference, the value of the laser wavelength is 532 nm.

[1] Backlash is movement or "play" in a mechanical system caused by a gap between parts that make contact. This spacing between gears helps minimise binding in a mechanical system it can lead to error in measurement when reversing gearing direction.

| **Mirror Position ($x$ - $\mu$m)** | **Mirror Displacement ($\Delta x$ - $\mu$m)** | **Number of Fringes ($N$)** | **Cumulative Fringes ($Nt$)** | **Wavelength ($\lambda$ - $\mu$m)** |
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*Table 1 - Calculating the laser wavelength by counting the number of fringes for a measured translation distance (see equation above).*

# Experiment 3 - Measuring Refractive Index

## Background

In this experiment we will use the sensitivity of the Michelson Interferometer to measure the refractive index *n* of a material. As the interferometer measures a *change* in path length, we will have to continuously alter the amount of material in the beam path. This is achieved by slowly rotating the object in one arm of the interferometer.

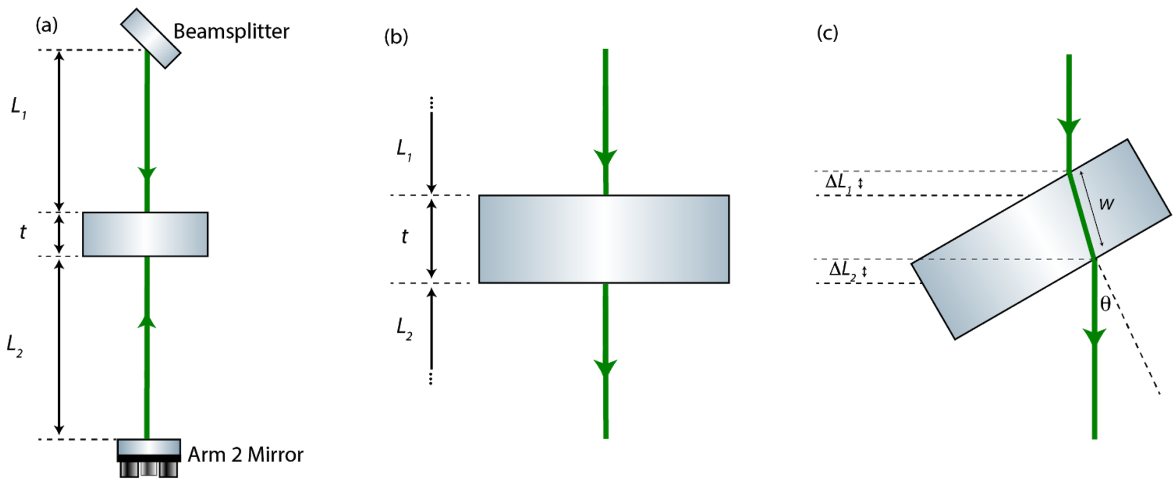


*Figure 17 - (a) Placing a plate with refractive index n perpendicular in an interferometer arm; (b) Close-up of the perpendicular plate; (c) The change in optical path length with a change in angle.*

The situation is shown in Figure 17 above, with the solid placed in Arm 1 of the interferometer. The physical length of Arm 1 when the plate is exactly perpendicular to the beam is given by:

$$L_{phys} = L_1 + t + L_2$$

where $t$ is the thickness of the plate. In contrast, the optical path length is given by:

$$L_{opt} = L_1 + n\,t + L_2$$

where *n* is the refractive index of the plate (assuming the refractive index of air is 1).

If the plate is rotated, as in Figure 17c, both the physical and optical path lengths change:

$$L_{phys} = L_1 - \Delta L_1 \ + w + L_2 \ + \Delta L_2$$

$$L_{opt} = L_1 - \Delta L_1 \ + n \, w + L_2 \ + \Delta L_2$$

The change in optical path length between the perpendicular and angled positions of the plate is then given by:

$$\Delta L_{opt} =- \Delta L_1 \ + n \, (w - t) + \Delta L_2$$

We know from Experiment 1 that:

$$N \, \lambda = 2 \, \Delta L_{opt}$$

where the factor of two again comes from the fact that the beam passes through the plate twice.

Using trigonometry we can rewrite the above equation and solve for refractive index in terms of the angle of rotation $\theta$:

$$n = \frac{(\frac{N\,\lambda}{2\,t} + Cos\,\theta - 1)^2 + Sin^2\theta}{2(\frac{-N\lambda}{2t} - Cos\theta + 1)}$$

Therefore, if we know the wavelength of the laser and the thickness of the plate, we can calculate the refractive index by counting the number of light-dark-light fringes *N* as a function of rotation angle from perpendicular.

## Description

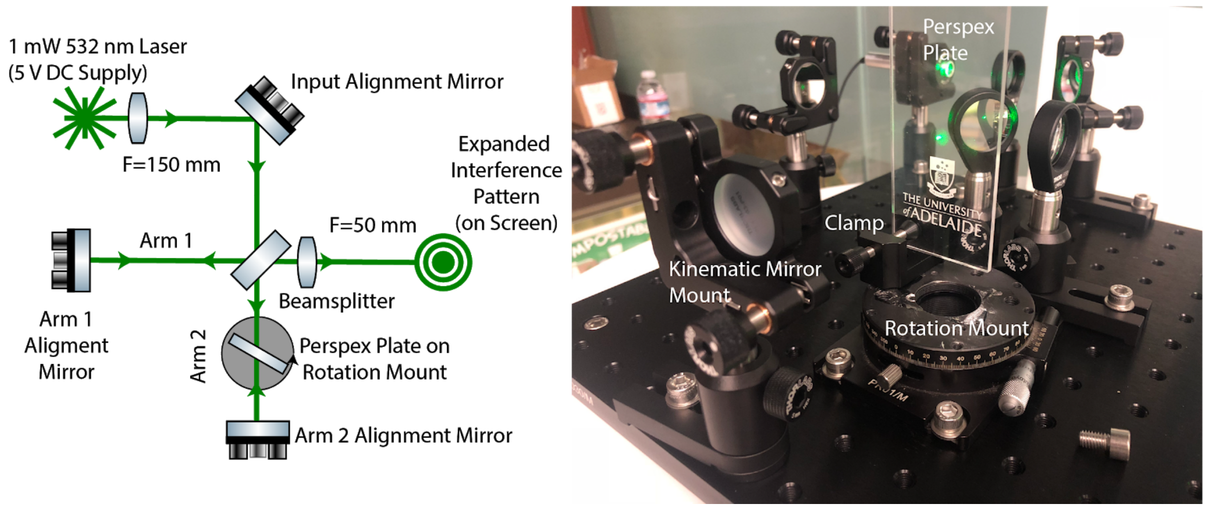


*Figure 18 - Interferometer set-up for measuring the refractive index of materials*

Measure the thickness of the perspex plate with the calipers (if not measured previously). Adjust the plate so that it stands perpendicular to the beam. To ensure this is the case, first remove both lens from their post holders. You will now probably see more than one spot on the screen due to the reflections of the laser at the air-perspex boundary. Rotate the stage until the spots lie on top of each other (or are parallel if there's also a slight tilt - see Figure 19).

*Tip: To understand the workings of the rotation platform, when the small set screw at the front is tightened the entire platform is turned by the fine adjustment screw. If the set screw is not tightened, the fine adjustment screw does not engage and one can rotate the platform manually by greater angles. Start by loosening the set screw and turning the fine adjustment screw as far in as possible.*

Now the plate is perpendicular to the beam and you can replace the lenses.

Coarsely rotate the rotation mount after noting the starting angle on the scale. Record the number of light-dark-light transitions (use Table 3 below).

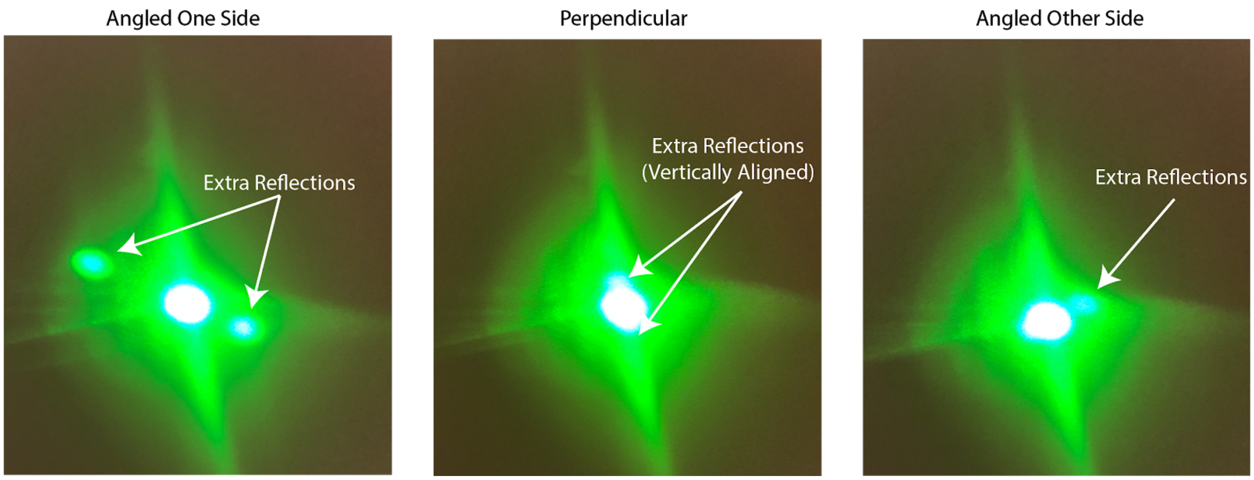


*Figure 19 - Determining perpendicular plate position through alignment of extra reflections.*

*Tip: There is a Vernier scale on the platform to aid in precisely reading the angle.*

Perform the same experiment with the other material provided.

For reference, the refractive index of perspex is 1.495 and of the glass sides is 1.526 (Schott D 263M glass).

| **Angle reading on rotation stage (degrees)** | **Angle from perpendicular ($\Theta$ - degrees)** | **Number of Fringes (*N*)** | **Cumulative Fringes (*Nt*)** | **Refractive Index (*n*)** |
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*Table 3 - Calculating the refractive index of a material by counting the number of fringes for a measured rotation angle from the perpendicular (assuming the wavelength of the laser and thickness of the material is known - see equation above).*

## Acknowledgements

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