X.5   An Introduction to Optics

1   Introduction

Optical methods and spectroscopy are used in every branch of chemistry from the most biological to the most physical. Wave properties, which light exemplifies, also underlie the modern ideas of atomic structure and chemical bonding. The purpose of this experiment is to give a grounding in the principles of optics as used in chemistry and introduce the use of lasers.

2   Safety

The He/Ne laser provides a weak beam, but one which can damage an eye if it enters it directly. Never look along the line of the beam. For the same reason avoid bringing your eye to bench level; carry out all alignment operations from a standing position, and if you need to find where the beam is, follow it using a white card.

3   Care of the apparatus

The surfaces of optical components (lenses, prisms, polarisers etc.) are delicate and can be damaged by contact with fingers. Handle unmounted components only by their edges. If any component is dirty do not clean it yourself; consult a technician.

4   Write-up

This experiment is designed to be written up as you go along, so that you can have it signed off before you leave the laboratory on the second day available for its completion.

4.1 Refraction and focussing

If the laser is not on (red light on top lit), turn it on now to warm up. For the time being, block the beam with the cap provided.

Refraction occurs whenever light (or electromagnetic radiation in general) travels in a medium other than a perfect vacuum. Two main effects are important in chemistry; first, the velocity of light in the medium, v, is reduced by a factor n, the refractive index, compared with its velocity in vacuum, c.

$$c \ / \ v = n$$

Secondly, the direction of travel of a light ray crossing the boundary between two different media changes at the boundary according to Snell's law (Fig. 1.)
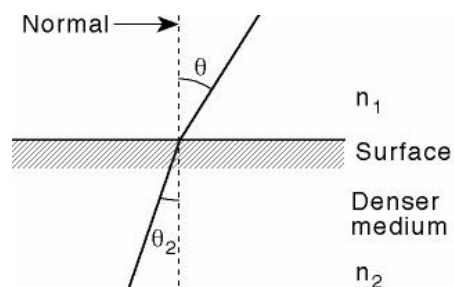
$$n_1 \sin \theta_1 \ = n_2 \sin \theta_2$$

where θ_1 and θ_2 are the angles in the two media, both measured from the surface normal, a line perpendicular to the surface at the point where the ray hits it. For visible light in air, the refractive index is very close to unity ($n_{air} \approx 1.0005$) and can be taken as 1.0 for this experiment.

The refractive index is a strong function of the wavelength of light; the index n is normally greater for blue light than for red. The value of n, and its variation with wavelength, are related to the electronic properties of the molecules and can be used to learn about their electronic structure. The refractive indices of solutions are also functions of the concentration; the variation is used in chemistry, in medicine and in many technologies (eg. brewing) as a means of analysis. The variation of refraction with wavelength is the basis of spectroscopic techniques such as uv-vis spectroscopy which may use prisms to separate different wavelengths of light. Refraction makes focussing using lenses possible in cameras, telescopes and microscopes, and is a major part of the scientific explanation of rainbows.

4.1.1 Focussing by lenses

Convex (magnifying) lenses are called *positive*, concave (reducing) lenses are *negative*. Both types are characterised by their *focal lengths*, positive for the first, negative for the second. For a positive lens, the focal length, *f*, is the distance beyond the lens where a parallel beam of light is brought to a focus. For a negative lens it is the distance in front of the lens from which a parallel beam hitting the lens appears to diverge (Fig. 2, below).
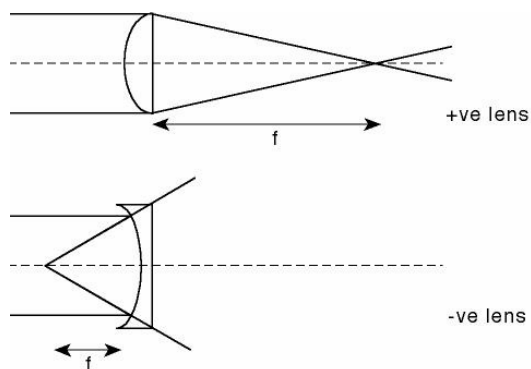
A positive lens forms a real image (an image you can see on a screen) if the object is further than one focal length away from the lens. If the distance from object to lens is *u* and the distance from lens to image is *v*, the focus law is

$$\frac{1}{u} + \frac{1}{v} = \frac{1}{f}$$

This is illustrated in the figure to the right.
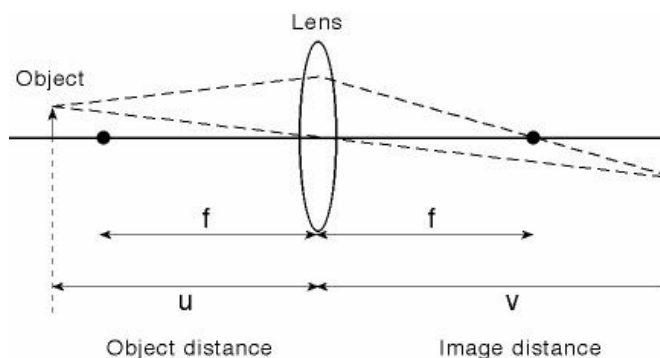
Experiment 1 Verify the focus law and check the focal length of a +125 mm lens

This experiment uses the illuminated "object" (black cylindrical lamp housing with flat top and holes, flex), the 125 mm lens, the white screen card and two rod holders on rectangular bases. Notice that if you bring the illuminated object as close as possible to the optical bench where the ruler sticks out on the left, the zero of the scale just touches the surface of the object. The object will always be at zero on the scale so long as it is kept up against the benchtop.

Photographs on display in the optics experiment area show the physical arrangement of components on the optical bench for several experiments; you may wish to consult these photos if you are unsure how to set up an experiment.

1. Put the 125 mm lens, in its mounting, into one of the rod holders so the lens is parallel to the long axis of the rectangular base. (The rods fit snugly in the bases; if you can't get one in, check that the locking screw on the side of the rod holder is loose.) On one side of the base is a mark showing the position of the lens; put this side against the ruler so you can slide it along and read off the position.

2. Put the screen card in a bulldog clip and mount it at the right hand end of the ruler.

3. Turn the lamp in the object cylinder on and position it to locate the cross "object" at the same distance from the ruler as the lens. The lamp needs to stand on a metal block ("lamp stand") to bring the object to a convenient height.

4. Adjust the height of the lens until you have a (probably fuzzy) image of the cross on the screen. Adjust the position of the object and the height of the lens until the image stays at almost the same spot on the screen, both up/down and sideways, as you move the lens along the ruler.

5. Record the positions at which you get sharp images of the cross. It is best to fix the lens each time and move the screen to find the best focus position. Start with the lens at about 15.5 cm and shift it to the right in two steps of 0.5 cm, 3 of 1 cm, 2 of 2 cm, 2 of 4 cm, 2 of 8 cm and 2 of 16 cm, to reach about 65 cm finally. For each position write the lens position and screen position in the table below. For a few well-separated positions, measure the height of the image using the mm-ruled card.

6. When the readings have been taken, work out the image distances from the lens (screen position minus lens position) and plot $1000/v$ versus $1000/u$ on regular graph paper. (Before drawing your axes, estimate where the intercepts will be to make sure they will be on scale.) You should get a good straight line of unit negative slope which intercepts both axes at $1000/f$. The value $1000/f$ is the strength of the lens in "dioptres", the measure used by opticians.

7. Write down your best result for the actual focal length of the "125 mm" lens. Also show that the magnification (height of image/height of object) is equal to v/u. The object is 5 mm high.

Lens position u	Screen position $u + v$	Object distance v	$1000/u$	$1000/v$	Image height /mm

4.2 Telescopes (beam expanders/reducers)

Two lenses of different focal length, either both positive or one positive and one negative, combine to form a simple telescope. The telescope with two positive lenses is named after Kepler and the one with a positive and a negative lens is named after Galileo, the respective inventors. The focus condition for both types is that the distance between the lenses should be equal to the difference of the absolute focal lengths. The magnification of both telescopes is given by the ratio of the focal lengths. All astronomical telescopes are of the Keplerian type; the Galilean telescope is used in opera glasses and as a beam expander/reducer for lasers.

Experiment 2   Simple telescopes

1. Make a Keplerian telescope using the 125 mm and 50 mm lenses, holding the lenses (by the rods) in your hands a suitable distance apart. Hold one lens near your eye and move the other lens until you see an image in focus. Answer the following questions by experiment:

Which lens is next to your eye for a magnifying telescope?

Is the image upside down, right to left, or both ?

2. Next estimate the magnification experimentally, by looking through the telescope at a distant regularly repeating object such as the brick wall of the Dyson Perrins laboratory opposite. The best way is to keep both eyes open so you can see the unmagnified object and its magnified image side by side at the same time. This may take a little practice. You should be able to verify the theoretical magnification.

3. Now replace the 50 mm lens by the (unmarked) negative lens provided. Measure the magnification and note the image orientation as before. From your result estimate the focal length of the negative lens.

Magnification of Galilean telescope:

Hence focal length of negative lens:

Comment on the image orientation:

You will use one of these telescopes as a laser beam reducer later.

The formulae given above refer to *thin* lenses, those whose diameter is a small fraction of their focal lengths. For thick lenses (eg. camera lenses) the focus conditions are more complicated. Because the refractive index depends on wavelength, simple lenses have

different focal lengths for light of different colours. When using white light and visual estimation, as here, we obtain the focal lengths in the green (about 500 nm), where the eye is most sensitive. Telescopes made with lenses were improved enormously in 1758 when Dollond invented "achromatic" lenses, which have a positive element of one glass and a negative element of another. By correct choice of glasses and of strengths, the focal length can be made independent of wavelength, at least over the range most important for vision.

4.3 Introduction to the laser: Aligning a laser beam using mirrors and use of the beam to measure refractive index

Apart from the interesting but small effects of gravitational fields, unobstructed light travels in straight lines (in a uniform medium). This fact may be obscured by the complexity of optical layouts, but is always the basis of positioning of optical elements. Your next task is to set up a convenient "optical axis" defined by the laser beam, near the front of the optics table. In doing this you will use two front-surface mirrors, on kinematic mounts. **NB. the surfaces of the mirrors are extremely easily damaged. Do not touch the surfaces with fingers.**

### Experiment 3 Alignment of a laser beam

The laser is already mounted but the exact position and direction of the laser beam are arbitrary. The two mirrors and the iris set up at the left hand end of the optical bench allow you to generate a beam of precisely fixed starting point and fully controllable direction.

> 1. Check that the two irises are set at the same height (125 mm above the table). If they are not, set both to 125 mm. Position the first iris on the left hand side of the table between the two mirrors.
>
> 2. Uncap the laser and ensure that its beam hits the first mirror fairly centrally. Adjust the two screws on the back of the mirror so that the beam passes through the centre of the iris. The iris defines a position for the laser beam that is 125 mm above the table and centrally over a mounting hole.
>
> 3. Adjust the position of the second mirror so that the beam strikes it centrally at about 45°.
>
> 4. Place the second iris in the rod holder at the right side of the bench. Adjust the fine controls of the second mirror so that the beam passes through this iris.

The laser beam is now travelling at a constant height of 125 mm above a line of mounting holes. This arrangement makes it easy to pass the beam centrally through optical elements fixed to the table.

4.4 Total internal reflection

When a ray passes a boundary between a dense medium and air, the angle between the ray and the surface normal is always greater in air than in the medium, as Snell's law shows. If the angle at which the ray in the medium hits the boundary increases, a critical angle q_c is reached where the angle made by the outside ray should be 90°; the ray should be along the surface. For all values of θ greater than θ_c no light passes through the boundary; it is totally internally reflected. At the critical angle, Snell's law becomes $n = 1/\sin\theta_c$, so the refractive index can be determined.
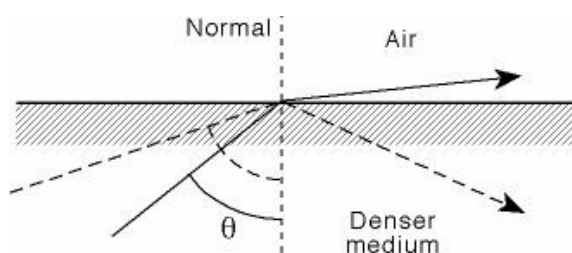
Total internal reflection is part of the explanation of the rainbow, and is used in light guides (optical fibres), "catseyes" (now no longer set in roads) and many optical devices. An important chemical instrument, which you may use in later practicals, is the Abbé refractometer, where total internal reflection is used to determine the refractive indices of liquids with great accuracy.

Experiment 4 Refractive index by total internal reflection

In this experiment you use a hemicylindrical (half-circle) prism on a rotating stage to vary the angle at which rays hit the boundary within a dense medium. Single rays that hit the curved surface of the prism along a radius are not deflected and strike the plane face at the angle set by the stage. In practice the rays form a bundle of finite width, where only the central ones are along the radius; the non-central rays are focussed by the curved boundary and cause spreading of the beam spot. It is therefore helpful to close down the first iris to reduce the width of the beam.

1. Mount the rotating stage, with its hemicylindrical prism attached, in a rod holder towards the middle of the bench so that the laser beam hits halfway up the prism; do not screw the holder down at first. It will be convenient if the small knob for rotating the stage is located on the side towards the incoming beam.

2. Rotate the stage using the knob until the beam hits the flat face more or less perpendicularly.

3. Adjust the position of the whole stage on the bench so that the back-reflected spot from the prism hits the first iris as near as possible to the centre, at the same time as you make the transmitted beam strike the second iris centrally too. To do this you'll need to adjust the angle of the prism. (If you find it difficult to to get both laser beams in position simultaneously, you probably have not aligned the beam sufficiently well in step 3.) Gently screw the stage mounting down in this position - it should be held

in place firmly, but not tightly. You will find it easier to screw down the base if the slots in the base are perpendicular to the laser beam.

4. Record the angle of the stage which conforms to the above conditions.

5. Rotate the stage by exactly 180°, so that the laser beam passes through the curved face of the prism and exits the flat face along the surface normal. This is your zero angle. (**Do not attempt to move the prism on the stage.**)

6. Now turn the stage and note how the exit beam moves; follow it with a handheld piece of card until it disappears and note the angle again. Do this at least twice on each side, ie. turning the prism both ways away from the zero angle. Obtain a best (average) estimate of the critical angle and calculate the refractive index.

Zero angle reading:

Reading of stage angle	Difference from zero stage angle

Average critical angle:

Hence refractive index of prism:

Calculate the effect on your answer of a change of 1° in θ_c. How precisely do you think you have actually determined the angle? Hence estimate the uncertainty (error) in n.

You will need the rotatable prism in the same position again later. Leave the rod holder in position, but remove the stage.

Question. To construct an optical fibre, chemists make two glasses of different refractive index and draw a fibre with a core of one glass and a sheath of the other. To confine light inside the fibre, should the outer glass sheath have a higher or lower refractive index than the core ?

4.5 Polarisation of light

Light is a transverse electrical and magnetic wave: the electric and magnetic fields are perpendicular to the direction of travel. If the electric field is confined to a single plane, the light is said to be linearly polarised. Some lasers, including the one in this experiment, produce light that is "born" linearly polarised. Another pure form is circular polarisation where the electric field direction spirals around the direction of propagation in either a right or a left handed screw motion. Elliptical polarisation is similar, but the trace of the electric field vector is an ellipse around the propagation direction instead of a circle.

Unpolarised light has its electric field oscillating randomly in all possible ways, but always perpendicular to its travel. The lasers provided for this experiment produce linearly polarised light, but this is converted to elliptical polarisation on leaving the laser housing. For the purposes of the experiment, the light behaves as if it were almost unpolarised.

Polarised light is important in chemistry because some "optically active" compounds can rotate the plane of polarisation of a linearly polarised beam. The same compounds also absorb right and left-circularly polarised light to different extents (circular dichroism). All chemicals also show these properties when placed in a strong magnetic field. These interactions of matter with polarised light can be used for analysis and especially for structure determination. All living matter on Earth is built from molecules that rotate the plane of polarisation in one direction only; why this is so is one of the great unsolved mysteries of science.

Unpolarised light or circularly polarised light can be turned into linearly polarised light with an efficiency of 50% by passing it through a polariser. The effect of a polariser is to resolve all incoming light into components either parallel or perpendicular to a chosen direction, then remove the unwanted components from the beam. If light which is already polarised encounters an ideal (lossless) polariser, it may pass through unaffected if the polariser has its favourable direction along the established polarisation, or the light intensity may be reduced to zero if the polarisation direction is set at right angles. What happens in between is the subject of the experiment below.

Experiment 5 Effect of the polariser angle (Malus law)

The polarisers in this practical absorb the unwanted components, and are called "dichroic". They were invented in 1928 by E.H. Land, of Polaroid. They are made by strongly stretching a thin film of polyvinyl alcohol so that all the long molecules line up in one direction. The stretched film is treated with iodine (as in starch indicator) which is absorbed along the molecule lines and acts as molecular-scale conducting wires. Light with its oscillating electric field along the wire direction induces currents in the wires (eddy currents), which are damped out by the wires' resistance, so taking energy out of the light wave. All the components parallel to the iodine "wires" are thus absorbed, and the components perpendicular to the wires, which cannot induce eddy currents, pass through.

1. In the slide box is a square sheet of polariser with the direction of polarisation of the transmitted light shown by a label. Holding it carefully BY THE EDGES ONLY, rotate it in the beam and by watching the transmitted beam spot on a card verify that the transmitted beam intensity varies with the angle of the polariser, but does not fall to zero at any angle. This is a test of the elliptical polarisation.

2. The kit contains a photodiode light detector mounted on a rod, with an electrical lead which can be plugged into a digital multimeter. Remove the second iris and replace it with the photodiode so that the laser beams falls centrally on the square chip in the centre of the detector. Plug it into the sockets marked COM (common) and mA (milliamperes) on the multimeter. Turn the meter's rotating switch to the most sensitive scale of DC current (200 µA). Mount the linear polariser in the beam to produce linearly polarised light at an angle that gives a signal in the range of 50-100 µA.

3. Now take the vertically mounted rotating stage from the optics kit; it has a linear polariser already fitted. Fix it in the laser beam using the postholder previously used for the prism, and investigate the effect of rotating it[1]. There will be two minima and two maxima of intensity on each full rotation. Use the brightness of the spot on a card to locate one of the minima precisely; read the angle and then rotate the polariser by 90°. The new angle (at an intensity maximum) is your zero angle θ_0, where the polariser is parallel to the incoming polarisation; record the angle reading. Measure the light intensity at 10° intervals from the maximum to the minimum and put the data in the table. Turn the meter off after making the measurements.

The theoretical law for the intensity is $I = I_0 \cos^2\theta$. Devise a graphical method to test this using your data.

Transmitted light intensity. $\theta_0 =$

Stage angle θ_{stage}	Signal/µA	Angle from maximum, $\theta_{stage} - \theta_0$

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[1] Note that it is important that the fixed polariser is mounted *before* the rotating polariser. Why do you think this is so?

NB The photodiode may give a significant non-zero reading at the angle of minimum transmission because of stray daylight. Depending on your choice of graph to test the law, you may need to subtract this background signal before making your plot.

4.6 Polarisation by reflection

When light is reflected from a shiny non-metal surface at a glancing angle, it becomes partially polarised. (You can verify this by looking through the polarising film at reflecting surfaces around the lab.) As the angle of reflection varies, some of the light whose polarisation is parallel to the surface (*s*-polarisation) is always reflected, though the fractions reflected and transmitted vary with the angle. For the components with polarisation in a plane perpendicular to the surface (*p*-polarisation), there is a special angle at which all the light goes into the medium and none at all is reflected. This is called Brewster's angle, θ_B. It is measured, as always, from the surface normal and is given by the formula


$$n = \tan\theta_B$$

Because all the light of *p*-polarisation passes into the medium, where it is transmitted if the medium is transparent or absorbed if not, the reflected light is purely of the *s*-polarisation. In apparatus using lasers, the windows that let beams into and out of the sample area or laser medium are often set at Brewster's angle to avoid losses by reflection. Measurement of the angle gives a way of determining the refractive index, which is especially useful for samples which do not transmit light.

Experiment 6 Refractive index from Brewster's angle

For this experiment the beam needs to be horizontally polarised; insert one of the polarisers to achieve this. The idea of the experiment is that if the beam hits the flat face of the rotatable plastic prism at Brewster's angle it will all be transmitted and none reflected.

> 1. Replace the prism on its rotatable stage in the rod holder and check its position using the reflected spot as before. Find the zero angle where the beam hits the centre of the flat face of the prism and passes through undeviated. Open the first iris wide for maximum intensity. Use a screen to follow the spot of light reflected
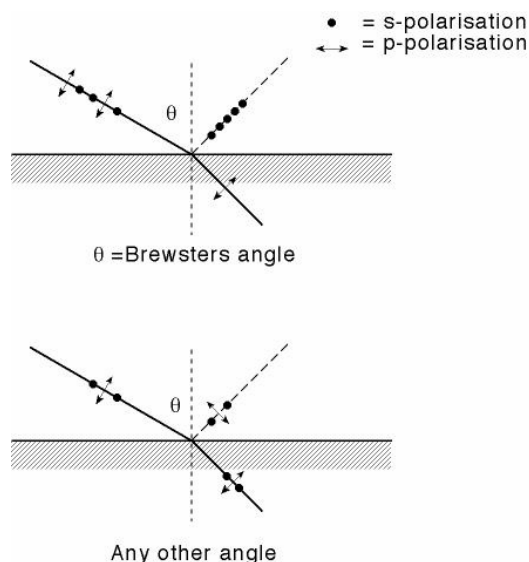
from the flat face of the prism as the angle is changed, and determine the angle of minimum reflection. Again, do this at least twice on both sides to get a precise reading.

2. Calculate the refractive index from the formula given above, and see if it agrees with your result from total internal reflection. The prism is made from polymethyl methacrylate, whose nominal refractive index is 1.50.

Stage reading at "zero" angle:

Angle readings for minimum reflection of horizontally polarised light

Stage angle	Brewster angle

Best average value of Brewster angle with estimated uncertainty:

Hence refractive index of prism:

Effect of an error of $1°$ on calculated refractive index:

Hence, uncertainty of the value of n:

Question: Which method for determining n is more precise ?

Question: Polarising sunglasses are intended to cut out glare from reflections. Should they be set for horizontal or vertical polarisation and why ?

4.7 Polarisation in scattering

Light can be scattered by particles both larger and smaller than the wavelength of the light; the scattered light carries information about the particles which is very useful in chemistry. It is used to measure concentrations, to determine particle (molecule) size and shape and as the basis of Raman spectroscopy. The underlying mechanism is that the electric field of the light induces an oscillating electric dipole in the particle; the oscillating dipole reemits light

of the same frequency. A characteristic of all scattered light is that it is at least partially polarised; the degree of polarisation is greatest if the particles are spherical.

Experiment 7 Polarisation and scattering

1. A sample vial containing a dilute suspension of colloidal particles is provided. Mount it on the wooden block so that the laser beam passes through it centrally. The beam should be visible by its scattered light, but not necessarily brightly so. (Do not shake the sample: to do so will produce strong scattering but weak polarisation.)

2. Use the square of linear polariser to examine the scattered light visually, and answer the following questions:

What is the direction of polarisation of light that is scattered at right angles to the direction of the laser beam?

From what viewing angle is the polarisation strongest ?

3. Use the polariser mounted in the vertical rotating stage to linearly polarise the beam before it enters the scattering cell. Observe the effect of the angle of polarisation on the intensity of scattering as viewed from the side.

For what directions of polarisation of the incoming light is the scattering (a) most intense, (b) least intense when viewed perpendicularly in the horizontal plane ?

You should be able to explain all your observations in terms of the nature of light and scattering, using ideas already mentioned in the practical script. Give your explanation below; if you don't feel able to explain the phenomena at all, consult a demonstrator ! If the sky is clear you can also verify that the light of the blue sky is quite strongly polarised by scattering in exactly the same way as demonstrated in this experiment.

Explanation of the scattering phenomena

4.8 Further information on polarisation

Polarised light can be converted from any pure form such as linear, circular right or left, to any other pure form with 100% efficiency without work being done and in the exceedingly short time it takes for the light to pass through a small transparent object. This is an amazing property, particularly when light is thought of as a stream of particles (photons); each photon can change freely and almost instantaneously from one polarisation state to another. It is a manifestation of the fact that light is a purely quantum mechanical phenomenon. No other particle is so versatile.

Conversion of any pure light form (linearly or circularly polarised) to any other pure form is accomplished by means of *retarders*. The effect of a retarder is to resolve the incoming light into two orthogonal pure forms, usually perpendicular plane polarisations, and provide different refractive indexes for the two. The velocities are therefore different, and one form takes longer than the other to pass through the retarder before the two recombine on emerging. The amount of relative retardation is usually stated in fractions of a wavelength; for instance, a "quarter wave plate" converts linearly polarised light to circular polarisation.

Reflection from metals occurs by different mechanisms depending on the frequency of the light. For frequencies higher than a critical value for each metal, the plasma frequency, behaviour is similar to that of insulators. Below the plasma frequency, which is the condition for shiny metals in visible light, light is reflected at all angles independent of the polarisation. Coloured metals (Au, Cu) have their plasma frequencies within the visible range.

4.9 Use of the compound microscope

The compound microscope consists of two lenses; an objective lens of short focal length and an eyepiece of longer focal length.   The eyepiece lens is used to examine the magnified image of an object created by the objective. For quantitative measurements a divided scale "graticule" is placed in the same plane as the image. In practice, there are several adjustments to be made in using any optical instrument, including the microscope. The main object of this experiment is to give practice in use of the instrument and at the same time to make some measurements which will be used in the next part of the practical.
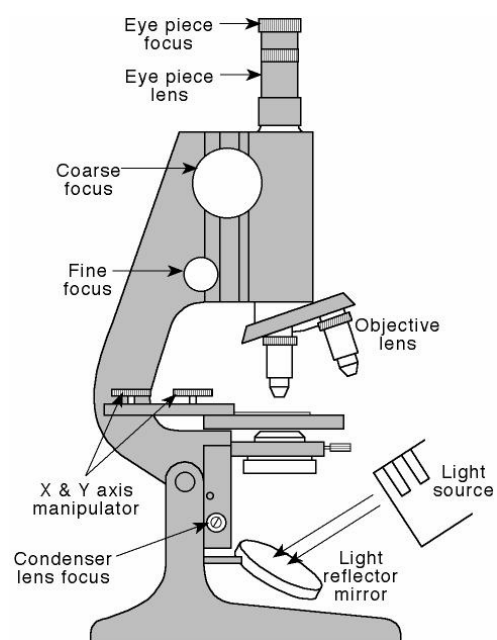
Experiment 8 Use of the microscope

1. Identify the parts of the microscope. There are four major focus controls:

> to focus the eyepiece on the graticule
> coarse focus on the sample
> fine focus on the sample
> focus of the light on the sample from below.

2. Turn the microscope light on and adjust the mirror to get the maximum amount of light through the microscope lenses. Raise the tube using the coarse focus control to bring the tube well clear of the stage.

3. Focus the eyepiece on its inbuilt graticule. (If you wear glasses it is best to remove them unless you have strong astigmatism.)

4. Place the calibrated "stage micrometer" on the microscope stage in the X-Y manipulator. Locate it near centre.

5. Rotate the objective lens mounting so that the shorter "10x" lens is in line with the tube.

6. Turn the coarse focus control until the micrometer scale comes into focus. Adjust to precise focus with the fine control. Adjust the position of the condenser lens below the stage for best illumination and contrast.

7. Rotate the objective lens mounting to bring the longer "40x" lens into line with the tube.

8. Refocus using the fine focus control

9. Calibrate the inbuilt eyepiece graticule by lining it parallel to the stage graticule (rotate the whole eyepiece as necessary without changing its focus).

    Calibration (mm/division):

10. Raise the tube, remove the calibrated stage micrometer and replace it with the slide marked "Slits" from the slide box. Change back to the "10x" objective before lowering the tube to focus again. Change to the 40x objective to measure the spacing of the slits.

    Slit spacing in mm:

11. Replace the slits slide with the diffraction grating slide. Go through the same stages of coarse and fine focus using the two objectives and adjust the illumination to make the grating lines visible.

12. Measure the line spacing by counting the number of lines in each division of the graticule. Calculate the number of lines per mm from your measurement.

Grating lines/mm:

4.10 Diffraction

Diffraction is used to determine the structure of matter at the atomic level in molecules and in ordered or disordered solids and liquids. Not only X-ray diffraction, but also diffraction of electrons and neutrons is applied to liquids and gases and to surfaces as well as to solids. Diffraction by artificial or natural (crystal) gratings is the basis of modern spectroscopy in most regions of the electromagnetic spectrum. The main purpose of this part of the experiment is to let you investigate how different aspects of structure are reflected in diffraction patterns, and thus how diffraction patterns can be interpreted.

Diffraction arises from interference between coherent beams, that is beams whose light waves have a definite and constant phase difference. When the path length difference between two combining coherent beams is a whole number of complete wavelengths, the interference is constructive and an intensity maximum is seen. If the optical path difference is an integer number of half wavelengths, destructive interference gives an intensity minimum.

In the following experiments, different slides containing small target patterns will be mounted in the laser beam near the left hand end of the bench, and the diffraction patterns will be observed on a card at the right hand end of the bench. Some patterns, or parts of them, may be quite faint; it may be a good idea to exclude extraneous light in order to observe them clearly. The patterns will be easier to see if the laser beam diameter is reduced by use of a (reversed) telescope, as introduced earlier.

### Experiment 9 Effect of a beam reducer

1. Set up a screen at the end of the bench and aim the laser beam to hit it centrally.

2. Mount one of the slides (e.g. the one marked "circles, 25, 4") in a clip holder a few inches after the second mirror. Adjust the position of the slide so that the laser beam passes though the central patterned area; it may help to look at the back of the slide and see where the emerging laser beam spot looks brightest. Make fine adjustments by moving the laser beam with the mirror. Note the appearance of the diffraction pattern, particularly how far out from the centre you can see the dots.

3. Using the +125 mm lens and the negative lens, construct a beam reducer in the arm of the beam path between the two mirrors. Place the two lenses at a distance apart roughly equal to the difference of their focal lengths; carefully adjust the lens positions so that the beam path is not changed. Fix the exact distance between the lenses to minimise the size of the laser spot at the distant screen (having removed the diffraction slide).

4. Replace the diffraction slide and observe the pattern again. It should be considerably sharper and brighter.

Experiment 10 Young's slits

1. Place the slide marked "slits" in the holder and manipulate the slide and beam until you see the diffraction pattern.

2. Measure the spacing s of the spots and the distance D from the slide to the screen. The spots' spacing can be measured easily by replacing the plain white card screen with a graph paper screen.

Verify (from your knowledge of basic trigonometry) that the path difference between the beams passing two slits a distance d apart and making an angle θ to the axis is $d\sin\theta$. The angle (in radians) between two successive diffraction fringes is small enough to allow the approximations:
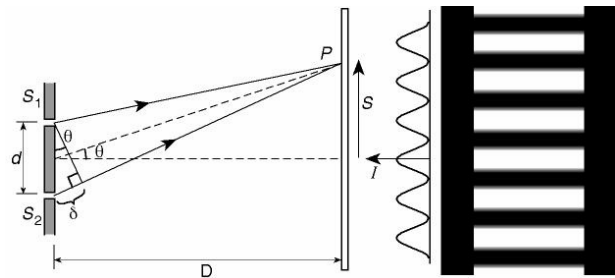
$$\sin\theta = \theta = s/D. \quad \text{(Angle } \theta \text{ in radians)}$$

Using the wavelength of the laser (632.8 nm), calculate the slit spacing from your diffraction results and see if it agrees with the measurement using the microscope.

Experiment 11 Diffraction for structure determination

In the slide box there are slides with plane two-dimensional repeating figures (target patterns) suitable for diffraction. You should examine the diffraction patterns produced by all the different slides, working systematically, to find out how diffraction patterns give information on each of the following:

1.   Element spacing in a regular array

2.   Size of the elements of an array
3.   Shape of the elements in an array
4.   Symmetry of the array.

The slides are marked with the shape of element, the element spacing, the size of element and the symmetry of the array if not cubic. All the slides have cubic arrays unless specifically marked otherwise. You can verify details of the patterns using the microscope, and should do so if in doubt. An example is "Squares, 25, 4". This means a repeating cubic array of squares with relative spacing of 25 and relative size (side of each square) of 4. The slides marked "Circles" do not all have good circular target array elements because of difficulties in production: discover the true element shapes from the diffraction patterns and/or by viewing the slides under the microscope.

Hint: Aspects of the diffraction patterns produced by the laser beam which are relevant to structure determination include the spacing of the dots, the pattern of the dots and the intensity distribution. The shape of the dots in a diffraction pattern is **not** relevant.

Question: What is the orientation of the diffraction patterns from the hexagonal array relative to the orientation of the target array ?

4.11 Spectroscopy using a diffraction grating

All modern spectrometers that disperse light use diffraction gratings as the wavelength selective element. A good grating is always superior to a prism in light intensity for a given resolution, though prisms have advantages in some special circumstances. In this section of the practical you will construct a simple spectrometer and use it to measure the spectrum of a light source.

A diffraction grating can be visualised as a large number of parallel slits with very small and precisely constant spacing. The angle at which a beam of a given wavelength is diffracted is exactly the same as if there were just two slits at the same separation. The difference is that as the number of slits is increased the diffracted beam becomes more and more sharply confined to a single angle. As with the two slits, constructive interference can occur for a path difference (between rays from adjacent slits) of any integer number of whole wavelengths; the integer number is called the *order*.

Experiment 12 Grating orders and line spacing

1. Using the laser (the light from which has a wavelength of 632.8 nm), investigate the diffraction pattern of the grating. Note the sharpness and clear separation of the spots as compared with those seen from two slits.

How many orders are visible under normal incidence ?

2. Measure the positions of the dots for the first order in normal incidence on a suitably placed screen, and hence calculate the line spacing; see if it agrees with what you found from the microscope and what is printed on the grating holder. Use the grating formula for normal incidence

$$m\lambda = d\sin\theta$$

where m is the order and d is the line spacing.

Experiment 13 Spectrum of a long-life lamp

1. Turn on the lamp in the black housing, used earlier as the object for the experiment on focussing by a lens. Examine the light coming from the slot (on the opposite side of the housing from the cross), by looking at it though the diffraction grating. Hold the grating close to your eye to do this, and stand well back from the light source to get the best resolution.

You should get some idea of the sheer beauty of optical spectra; also notice that there are spectra in several orders and that the spectrum is brighter on one side of the direct view of the slit (central image) than on the other. The concentration of light into one order is achieved by shaping the individual grating lines ("grooves") to send the light preferentially in one direction. A grating made with this property is said to be "blazed".

Experiment 14   Building a spectrometer

In a spectrometer the light hitting the grating should be a parallel beam, so that all parts of the beam hit at the same angle (here assumed to be along the normal), and get diffracted at the same angle of diffraction according to the wavelength. A spectrometer thus has three parts:

1   a slit and lens as collimator to make light parallel,
2   a grating or prism to separate wavelengths,
3   a lens and slit or detector where images of the slit are formed in light
         of each wavelength at different locations.

1. To make light from the slit parallel, mount the 125 mm positive lens 125 mm away from the slit and at the same height.

2. Mount the grating in the (parallel) beam from the lens, and put the + 50 mm lens after the grating to form a spectrum on a screen about 50 mm away. Experiment with the position and angle of the screen to get the sharpest spectrum. To record the spectrum you could trace it on the screen with a pencil. If you have a suitable camera

and are so inclined, you could make an attractive permanent record of the spectrum by putting the camera in place of the 50 mm lens and screen.

Experiment 15   Measuring the wavelengths

Although the light hitting the grating should be parallel for best resolution, a spectrum can also be formed using a single lens and the grating, and this has the advantage that it allows the wavelengths to be measured absolutely.

1. Move the + 125 mm lens to 25 cm from the slit and verify that a white-light image of the slit is formed about 25 cm further on.

2. Now put the grating in place just after the lens and look for the best spectrum you can get with the screen perpendicular to the undiffracted beam.

3. Measure the distance of the screen from the grating, and the positions of the undiffracted image and the green and orange lines. It is easiest to do this by marking their positions on the screen card with a pencil, and measuring them afterwards.

4. Calculate their wavelengths using the grating formula from the line spacing in the grating which you determined using the laser.

Wavelength of green line:
Wavelength of orange line:

5. The lamp contains more than one element, but you may be able to guess at least one by comparing your result with the following list of strong lines from some possible culprits:

H	656 nm	He	587, 447 nm
Na	589 nm	Cd	644, 509, 480 nm
Hg	579, 546, 436 nm		

Turn off the lamp and laser when you have finished the experiment.