

**L6****POLARISATION****OBJECTIVES****Aims**

Once you have studied this chapter you should understand the concepts of transverse waves, plane polarisation, circular polarisation and elliptical polarisation. You should be able to relate this understanding to a knowledge of methods for producing the different types of polarised light in sufficient detail so that you can explain the basic principles of those methods.

**Minimum learning goals**

1. Explain, interpret and use the terms:  
*polarised light, unpolarised light, randomly polarised light, linear polarisation (plane polarisation), partially polarised light, polarising axis, polariser, ideal polariser, analyser, crossed polarisers, Malus's law, circular polarisation, elliptical polarisation, birefringence (double refraction), dichroic material, dichroism, optical activity, quarter-wave plate, polarising angle (Brewster angle).*
2. Describe how plane polarised light can be produced by dichroic materials, by birefringent materials, by reflection and by scattering.
3. State and apply Malus's law.
4. Explain how circularly or elliptically polarised light can be regarded as a superposition of plane polarisations.
5. Describe how circularly polarised light can be produced from unpolarised or plane polarised light.
6. Describe the phenomenon of optical activity and describe one example of its application.

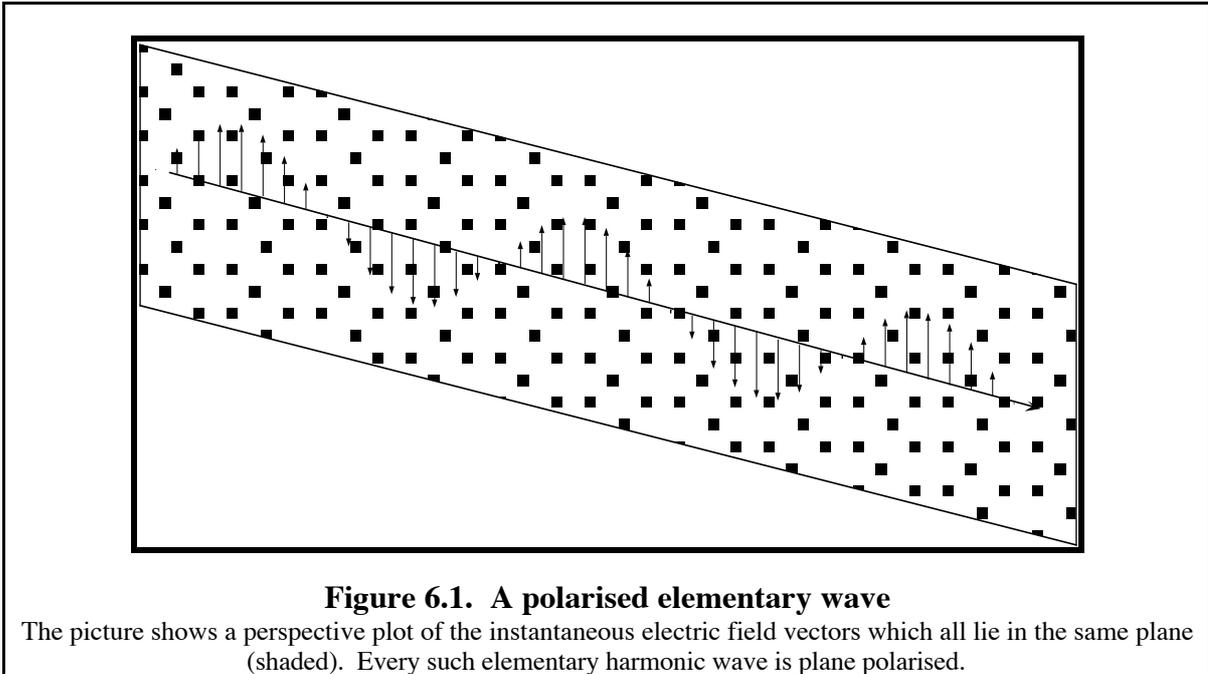
**Extra Goals**

7. Describe and discuss various applications of polarised light and explain how they work.

**TEXT****6-1 PLANE OR LINEAR POLARISATION**

In light and all other kinds of electromagnetic waves, the oscillating electric and magnetic fields are always directed at right angles to each other and to the direction of propagation of the wave. In other words the fields are transverse, and light is described as a **transverse wave**. (By contrast sound waves are said to be longitudinal, because the oscillations of the particles are parallel to the direction of propagation.) Since both the directions and the magnitudes of the electric and magnetic fields in a light wave are related in a fixed manner, it is sufficient to talk about only one of them, the usual choice being the electric field. Now although the electric field at any point in space must be perpendicular to the wave velocity, it can still have many different directions; it can point in any direction in the plane perpendicular to the wave's direction of travel.

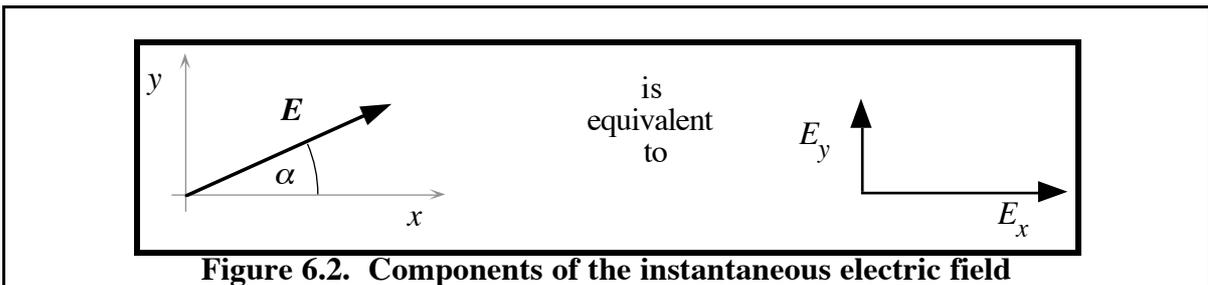
Any beam of light can be thought of as a huge collection of elementary waves with a range of different frequencies. Each elementary wave has its own unique orientation of its electric field; it is **polarised** (figure 6.1). If the polarisations of all the elementary waves in a complex beam can be made to have the same orientation all the time then the light beam is also said to be polarised. Since there is then a unique plane containing all the electric field directions as well as the direction of the light ray, this kind of polarisation is also called **plane polarisation**. It is also known as **linear polarisation**. However, the usual situation is that the directions of the electric fields of the component wavelets are randomly distributed; in that case the resultant wave is said to be **randomly polarised** or **unpolarised**.



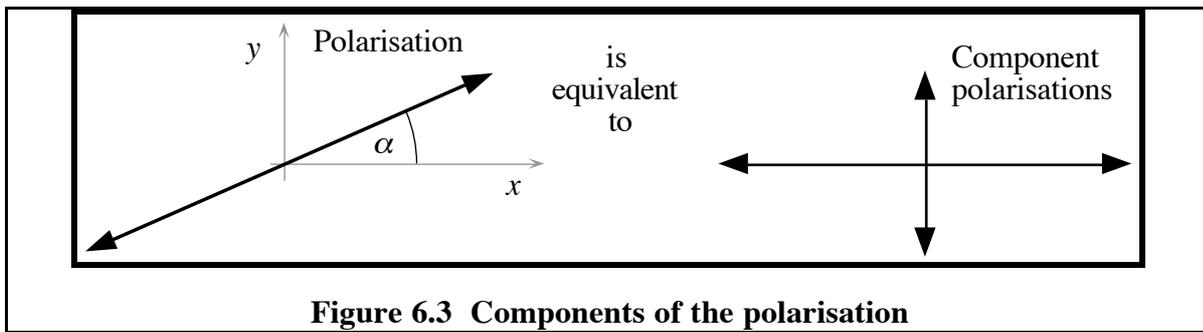
It is quite common to find **partially polarised light** which is a mixture of unpolarised (completely random polarisations) and plane polarised waves, in which a significant fraction of the elementary waves have their electric fields oriented the same way.

### Components of polarisation

Since electric field is a vector quantity it can be described in terms of components referred to a set of coordinate directions. In the case of polarised waves we can take *any* two perpendicular directions in a plane perpendicular to the wave's direction of travel. An electric field  $E$  which makes an angle  $\alpha$  with one of these directions can then be described completely as two components with values  $E\cos\alpha$  and  $E\sin\alpha$ . We can think of these components as two independent electric fields, each with its own magnitude and direction, which are together equivalent in every respect to the original field. So any elementary wave can be regarded as a superposition of two elementary waves with perpendicular polarisations.



In just the same way, any plane polarisation can be described in terms of two mutually perpendicular component polarisations. In the schematic diagrams that we use to represent polarisation such a line can be drawn as a double-headed arrow, representing the two opposite directions that a plane polarised wave can have at any point. The instantaneous value of an electric field (which has a unique direction at any instant of time) will be shown as a single-headed arrow.

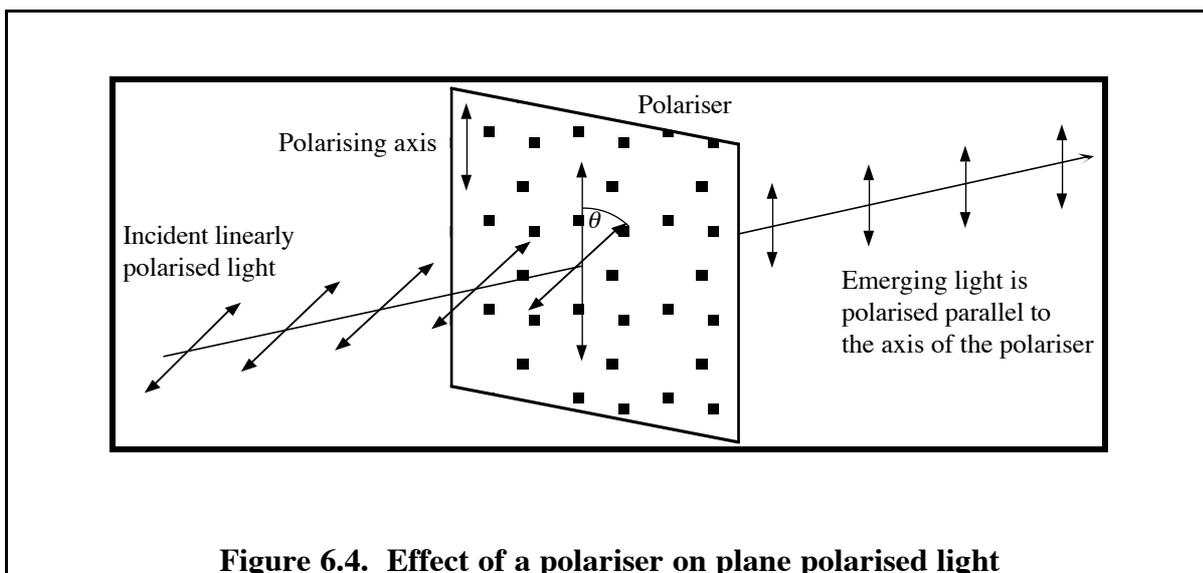


### Polarisers and Malus's law

A **ideal polariser**, or polarising filter, turns unpolarised light into completely plane polarised light. Its action can be described in terms of its effect on elementary waves with different polarisations; waves whose polarisation is parallel to an axis in the polariser, called its **polarising axis**, are transmitted without any absorption but waves whose polarisation is perpendicular to the polarising axis are completely absorbed. An elementary wave whose polarisation is at some other angle to the polarising axis is partly transmitted and partly absorbed but it emerges from the other side of the polariser with a new polarisation, which is parallel to the polariser's axis. This can be described in terms of components of the original wave. Since we can use any reference directions for taking components we choose one direction parallel to the polariser's axis and the other one perpendicular to it. If the angle between the original polarisation and the polariser's axis is  $\theta$ , then the component parallel to the polariser's axis, which gets through, has an amplitude of  $E_0 \cos\theta$ . Since the other component is absorbed, the wave which emerges has a new amplitude  $E_0 \cos\theta$  and a new polarisation. Since the irradiance or "intensity" of light is proportional to the square of the electric field's amplitude,

$$I_{\text{out}} = I_{\text{in}} \cos^2\theta. \quad \dots(6.1)$$

This result is known as **Malus's law**.

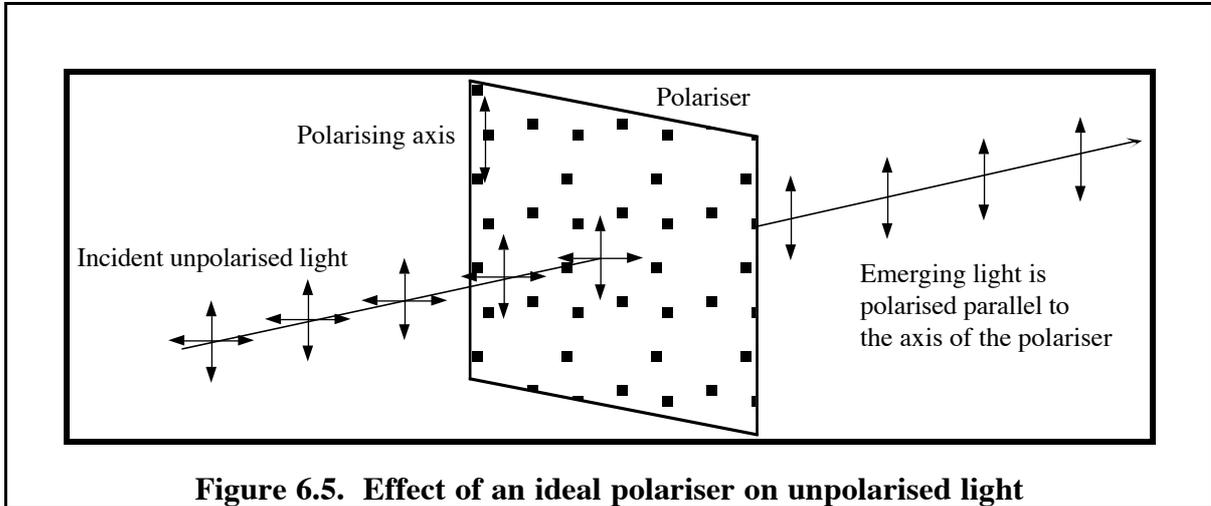


Many practical polarisers do not obey Malus's law exactly, firstly because they absorb some of the component with polarisation parallel to the polarising axis and secondly because some of the component polarised perpendicular to the axis is not completely absorbed.

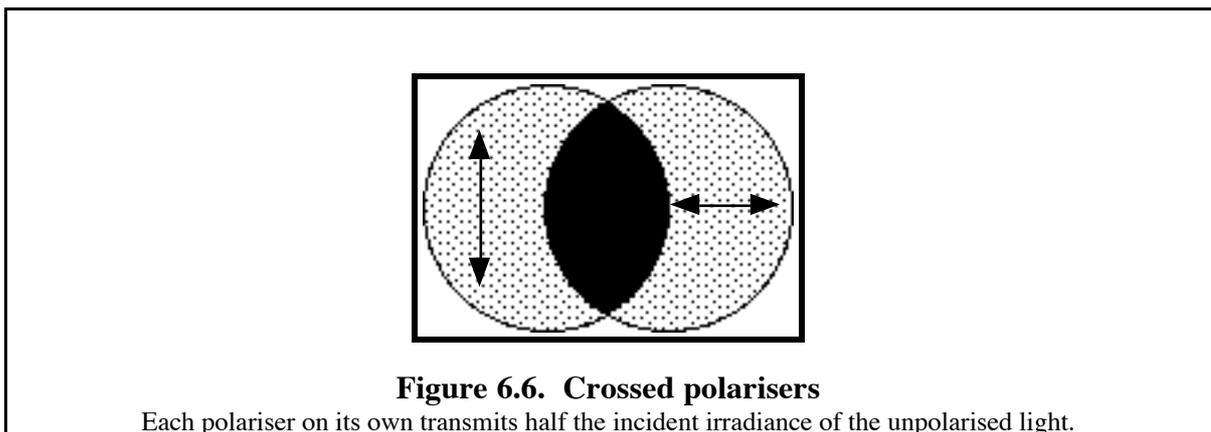
Malus's law also describes the action of an ideal polariser on unpolarised light. Unpolarised light is really a vast collection of polarised elementary waves whose polarisations are randomly

spread over all directions perpendicular to the wave velocity. Since these elementary waves are not coherent, their intensities, rather than their amplitudes, can be added, so Malus's law works for each elementary wave. To work out the effect of the polariser on the whole beam of unpolarised light we take the average value of  $I_{\text{in}} \cos^2\theta$  over all possible angles, which gives

$$I_{\text{out}} = \frac{1}{2} I_{\text{in}}.$$



If we send initially unpolarised light through two successive polarisers, the irradiance (intensity) of the light which comes out depends on the angle between the axes of the two polarisers. If one polariser is kept fixed and the axis of the other is rotated, the irradiance of the transmitted light will vary. Maximum transmission occurs when the two polarising axes are parallel. When the polarising axes are at right angles to each other the polarisers are said to be **crossed** and the transmitted intensity is a minimum. A pair of crossed ideal polarisers will completely absorb any light which is directed through them (figure 6.6). Note that the polarisation of the light which comes out is always parallel to the polarising axis of the last polariser.

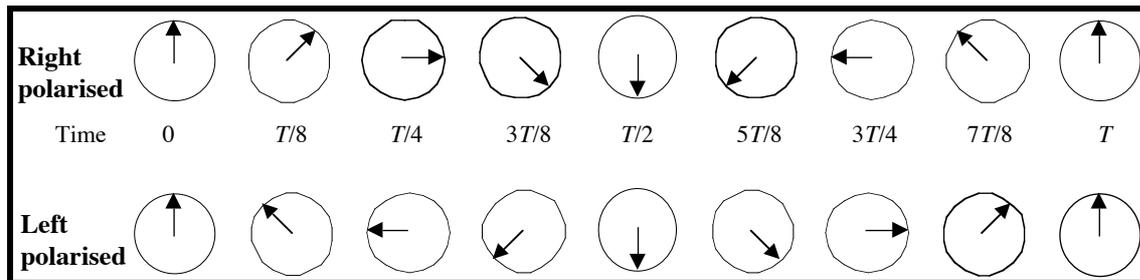


So far we have considered a polariser as something which produces polarised light. It can also be considered as a device for detecting polarised light. When it is used that way it may be called an **analyser**. For example, in the case of crossed polarising filters above, you can think of the first filter as the polariser, which makes the polarised light, and the second filter as the analyser which reveals the existence of the polarised light as it is rotated.

## 6-2 CIRCULAR POLARISATION

Plane polarisation is not the only way that a transverse wave can be polarised. In **circular polarisation** the electric field vector at a point in space rotates in the plane perpendicular to the direction of propagation, instead of oscillating in a fixed orientation, and the magnitude of the electric field vector remains constant.

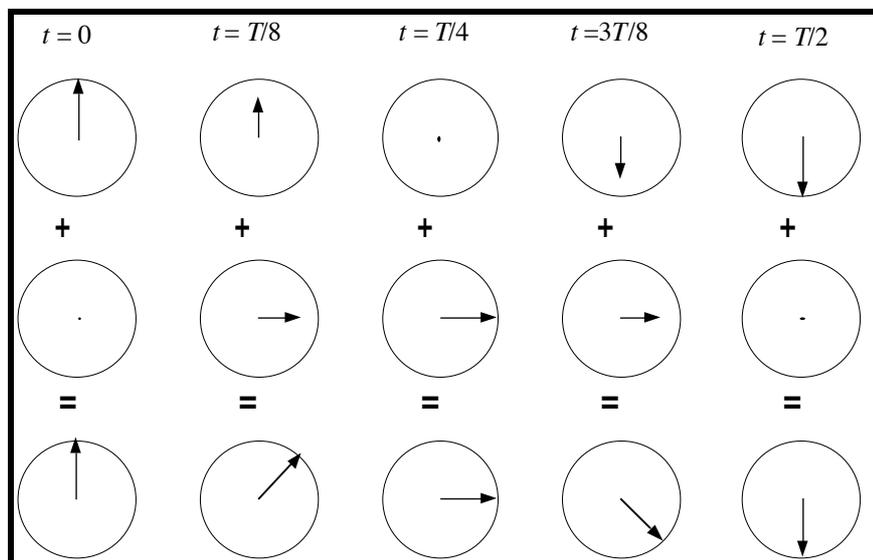
Looking into the oncoming wave the electric field vector can rotate in one of two ways. If it rotates clockwise the wave is said to be right-circularly polarised and if it rotates anticlockwise the light is left-circularly polarised.



**Figure 6.7. Circularly polarised waves**

The diagrams show the electric field vector of an elementary wave at successive time intervals of  $1/8$  of a wave period, as the wave comes towards you.

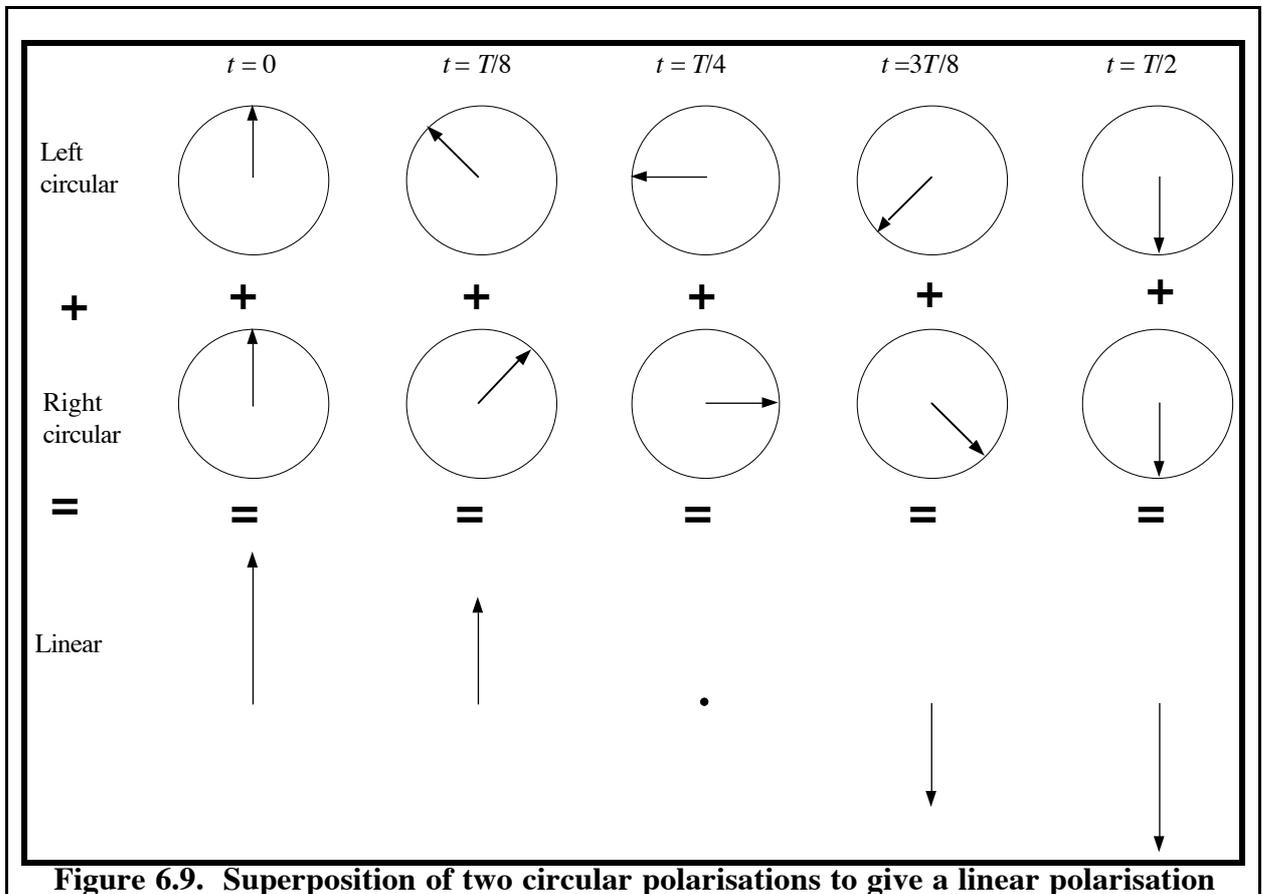
Actually circular polarisation is not anything new. A circularly polarised elementary wave can be described as the superposition of two plane polarised waves with the same amplitude which are out of phase by a quarter of a cycle ( $\pi/2$ ) or three quarters of a cycle ( $3\pi/2$ ). Figure 6.8 shows how.



**Figure 6.8 Circular polarisation as the superposition of two linear polarisations**

The illustrations show the two linearly polarised electric fields with the same amplitude plotted at intervals of one eighth of a wave period. When these are combined the resultant electric field vector always has the same magnitude, but its direction rotates. Note that the amplitude of the circularly polarised wave is equal to the amplitude of each of its linearly polarised components. Its period and frequency are also identical with those of the component waves.

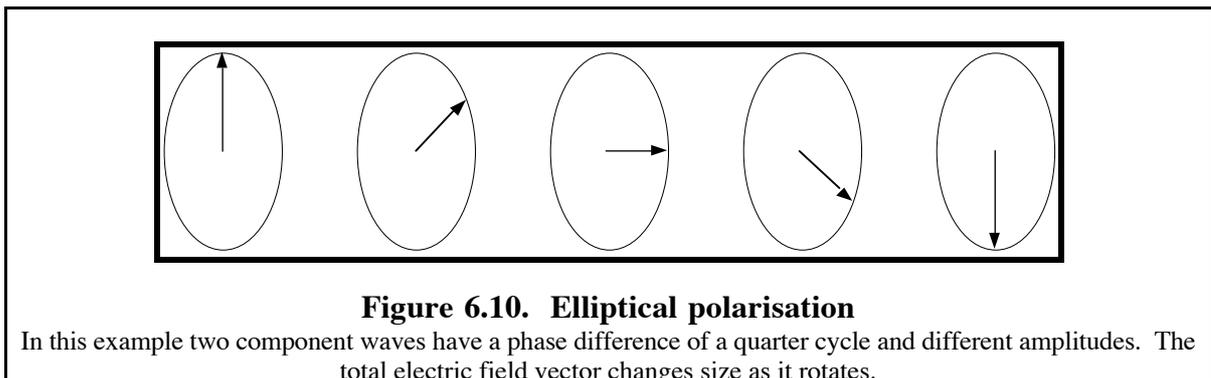
There is an interesting symmetry between the concepts of linear and circular polarisation. Not only can circular polarisation be described in terms of linear polarisation, but linear polarisation can be described as the superposition of two circular polarisations! In figure 6.9, left and right circularly polarised waves with equal amplitudes are added to produce one linearly polarised wave. Note that in this case the amplitude of the linearly polarised wave is the sum of the component amplitudes.



**Figure 6.9. Superposition of two circular polarisations to give a linear polarisation**

### Elliptical polarisation

Circular polarisation can be regarded as a superposition of two linear polarisations with the same amplitude and just the right phase difference,  $\pi/2$ ,  $3\pi/2$  etc. In general the combination of two linearly polarised elementary waves with the same frequency but having unequal amplitudes and an arbitrary value of the phase difference, produces a resultant wave whose electric vector both rotates and changes its magnitude. The tip of the electric field vector traces out an ellipse so the result is called **elliptical polarisation** (figure 6.10). Circular polarisation is thus a special case of elliptical polarisation.



**Figure 6.10. Elliptical polarisation**

In this example two component waves have a phase difference of a quarter cycle and different amplitudes. The total electric field vector changes size as it rotates.

We have already seen that the resultant of two linear polarisations with zero phase difference is also a linear polarisation. Another special case is the combination of two elementary linearly polarised waves whose phase difference is exactly  $\pi$ . The resultant is a linear polarisation but its orientation is perpendicular to the linear polarisation when the component waves have no phase difference.

### 6-3 PRODUCTION OF POLARISED LIGHT

When an elementary light wave interacts with matter, its electric field causes electrons within the substance to vibrate at the wave's frequency. These vibrating electrons then re-radiate the absorbed energy as new electromagnetic waves in all directions. Although this **scattered light** has the same frequency as the incident wave its polarisation depends on the new direction of propagation.

In general, therefore, when light interacts with matter its polarisation may be changed. The main mechanisms by which this happens are :

1. by passing through **dichroic materials**;
2. by passing through **birefringent materials**;
3. by **scattering**;
4. by **reflection**;
5. by passing through **optically active materials**.

### 6-4 DICHROIC MATERIALS

In some crystalline materials, which are described as **dichroic**, the absorption of light depends on the orientation of its polarisation relative to the polarising axis of the crystal. Light whose plane of polarisation is perpendicular to the polarising axis is absorbed more than that which is parallel to it. The most common example is a group of materials sold under the trade name Polaroid which are used, for example, in sunglasses and photographic filters. One variety of Polaroid contains long molecules of the polymer polyvinyl alcohol (PVA) that have been aligned and stained with iodine. The best known example of a crystalline dichroic material is the mineral tourmaline.

Polarisers made from dichroic materials differ from an ideal polariser in the following ways. Firstly, if the polariser is thin, the emerging light may not be completely plane polarised. Secondly there is some absorption of the transmitted polarisation component. Thirdly the amount of absorption usually depends on the frequency of the light, so that the light which comes out may appear to be coloured.

### 6-5 BIREFRINGENCE

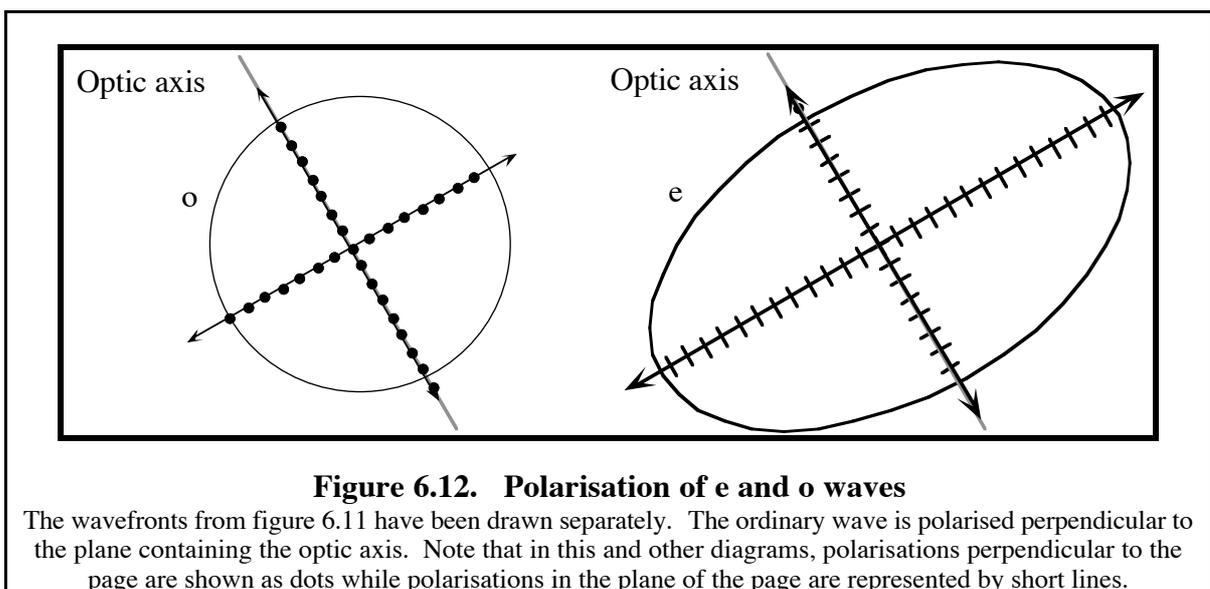
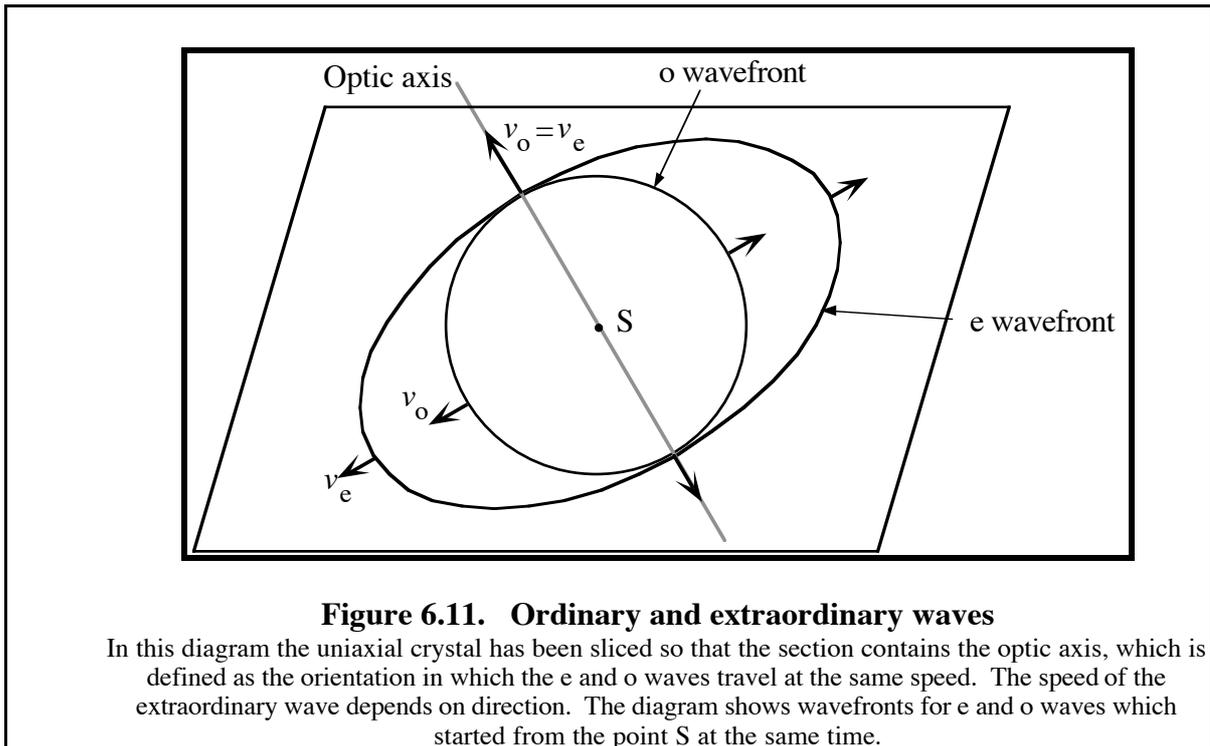
In some materials light with different polarisations travels at different speeds. Since we can regard any wave as the superposition of two plane polarised waves, this is equivalent to saying that one beam of light travels at different speeds in the material, that is the material has different refractive indices for light of the same frequency. Such materials are said to be **doubly refracting** or **birefringent**. Examples are crystals such as the minerals calcite (calcium carbonate) and quartz (silicon dioxide) or materials like Cellophane when it is placed under stress.

The speed of light in a birefringent crystal depends, not only on the polarisation, but also on the direction of travel of the light. As usual we can regard any beam of light as a superposition of two linearly polarised components at right angles to each other. By choosing suitable directions for the polarisation components it is found that one component wave, called the **ordinary wave**, travels at the same speed in all directions through the crystal, but the speed of the other polarisation component, called the **extraordinary wave**, depends on its direction of travel. There are some propagation directions in which all polarisations of light travel at the same speed and a line within the crystal parallel to one of those directions is called an **optic axis**. Some crystals, called **uniaxial crystals** have only one optic axis, while others, the **biaxial crystals**, have two.

Figure 6.11. shows what would happen to light starting out from some point inside a calcite crystal. (This is not as silly as it may seem; Huygens' construction regards each point on a wavefront

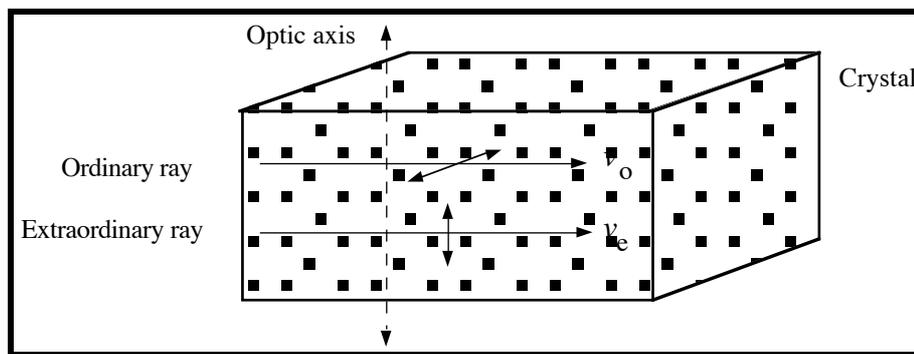
as a source of new waves. So the 'point source' considered here could be a point on a wavefront which originated outside the crystal.)

Calcite has one optic axis, along which the ordinary and extraordinary waves travel at the same speed, and the plane of the diagram has been chosen to include that axis. Two wavefronts are shown. Since the ordinary wave travels at the same speed ( $v_o$ ) in all directions its wavefronts (for light coming from a point source) are spherical, and the section of the wavefront in the diagram is therefore circular. On the other hand, the speed ( $v_e$ ) of the extraordinary wave depends on the direction of travel and the section of the wave front shown is elliptical. In calcite the speed of the extraordinary wave is always greater than or equal to the speed of the ordinary wave, so the extraordinary wavefront encloses the ordinary wavefront. In a crystal where the extraordinary wave is the slower of the two, its wavefront would stay inside the spherical wavefront of the ordinary wave. In figure 6.12 the polarisations are shown. The ordinary wave is polarised perpendicular to the plane of the diagram and the polarisation of the extraordinary wave is parallel to the plane of the diagram.



### Birefringence and circular polarisation

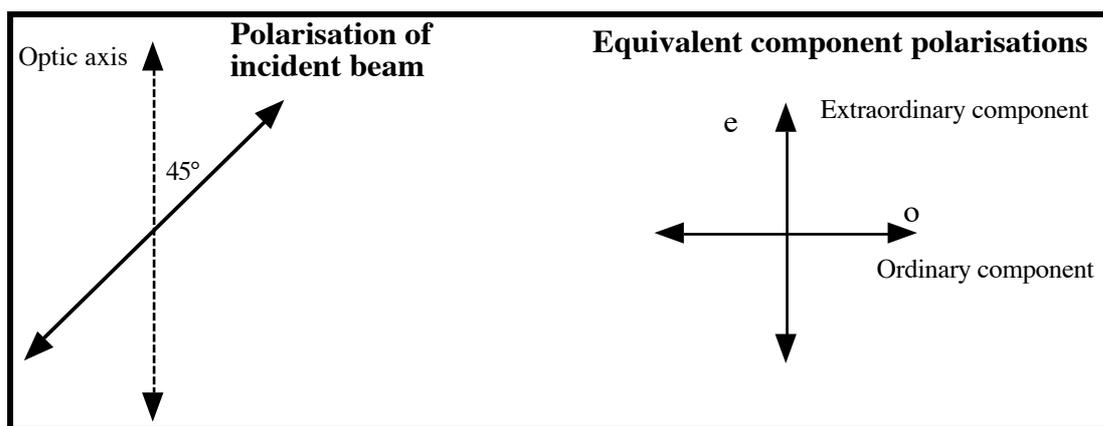
In any direction other than along an optic axis the wave speed depends on the direction of travel and the polarisation. In the following discussion we consider only light travelling in a plane perpendicular to the optic axis (figure 6.13). In this case the polarisation of the ordinary wave is perpendicular to the optic axis. The speed of the ordinary wave does not depend on direction. The component with polarisation parallel to the optic axis is an extraordinary wave. It can be faster or slower than the ordinary wave.



**Figure 6.13. Ordinary and extraordinary rays in a uniaxial crystal**

The faces of this crystal are not natural; they have been cut so that one pair of opposite faces is perpendicular to the optic axis while the other faces are parallel to the optic axis.

Birefringence can be exploited to produce circular polarisation. This can be achieved by letting a beam of plane polarised monochromatic light strike a specially prepared slab of birefringent material with faces cut like the crystal shown in figure 6.13. Light enters the crystal normal to a surface which contains the optic axis, with its polarisation at  $45^\circ$  to the optic axis. In order to analyse what happens, the electric field of the incident light can be resolved into ordinary (o) and extraordinary (e) components, perpendicular and parallel to the optic axis (figure 6.14). Since the angle of incidence is  $90^\circ$  both ordinary and extraordinary waves travel inside the crystal in the same direction (there is no refraction), but with different speeds.



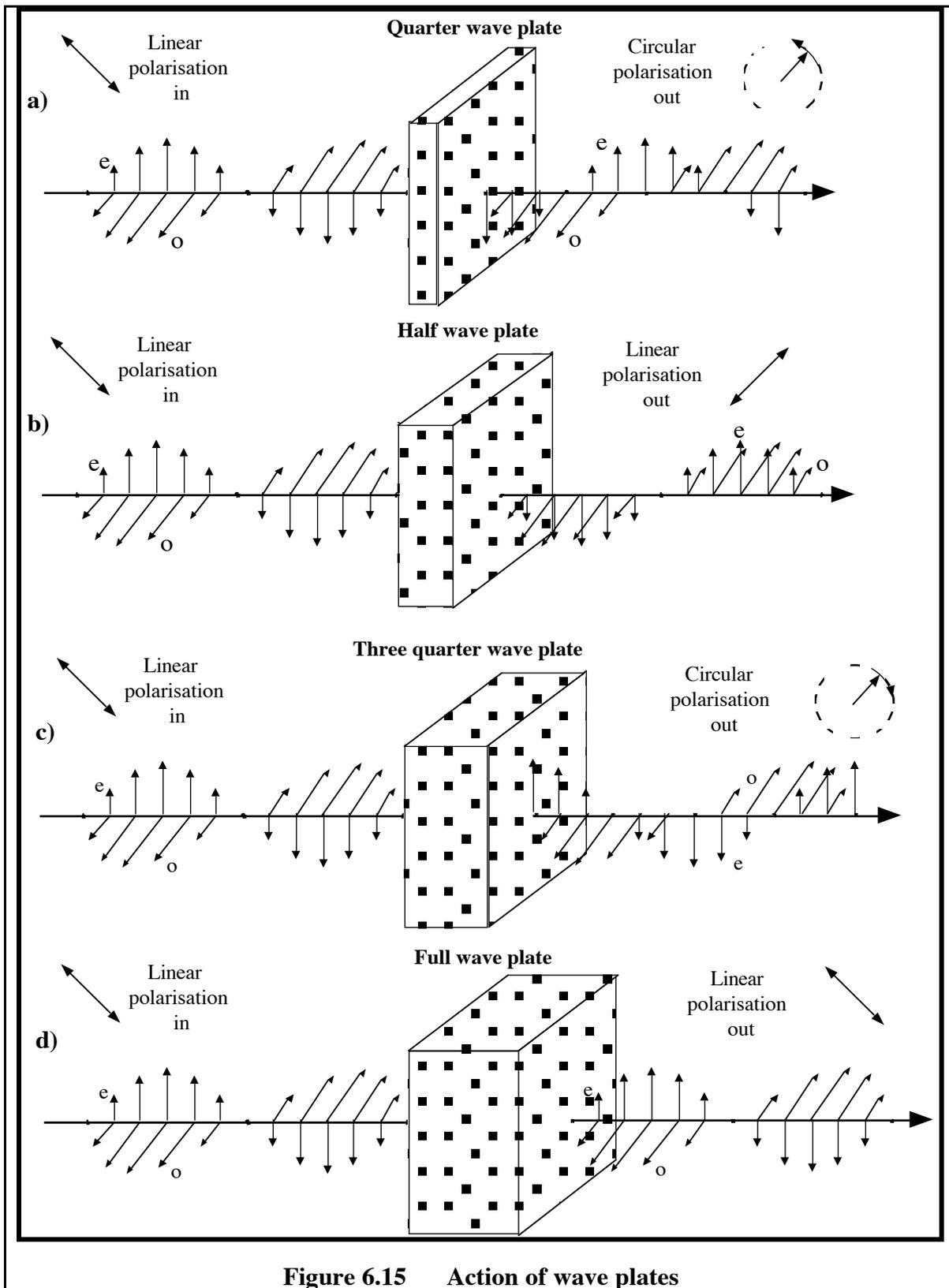
**Figure 6.14 Resolving the plane polarisation into e and o components**

A plane polarised wave enters a crystal with its polarisation at  $45^\circ$  to the crystal's optic axis. The plane polarisation can be regarded two perpendicular plane polarisations with equal amplitudes. Each component is at  $45^\circ$  to the original polarisation. What has happened to the light by the time it comes out the other side of the crystal depends on the thickness of the crystal and is shown in figure 6.15.

Since the ordinary and extraordinary waves travel at different speeds through the crystal, their phase difference and the polarisation of the emerging light will depend on the thickness of the crystal. If the extraordinary wave is faster, it will progressively move ahead of the ordinary wave.

To find the polarisation of the wave that comes out at the second boundary we can add the extraordinary and ordinary components together again. Depending on the thickness of the crystal, any of the following can happen.

- If the extraordinary wave has gained one complete wavelength (figure 6.15d) the phase difference between the ordinary and extraordinary components will be effectively the same as it was originally, so the emerging wave is linearly polarised with the same plane of polarisation as the incident wave.
- If the extraordinary wave has gained exactly half a wavelength (figure 6.15b) the two components will be out of phase by  $\pi$ . This phase relation is maintained at all times. The resultant wave is linearly polarised with its polarisation perpendicular to that of the original wave, i.e. the plane of polarisation has been rotated through an angle of  $90^\circ$ . A slab of birefringent material which produces this effect is called a **half wave plate**.
- If the extraordinary wave has gained a quarter wavelength (figure 6.15a) there is a phase difference of  $\pi/2$  between the e and o waves so the light becomes circularly polarised. (Have another look at figure 6.8.)

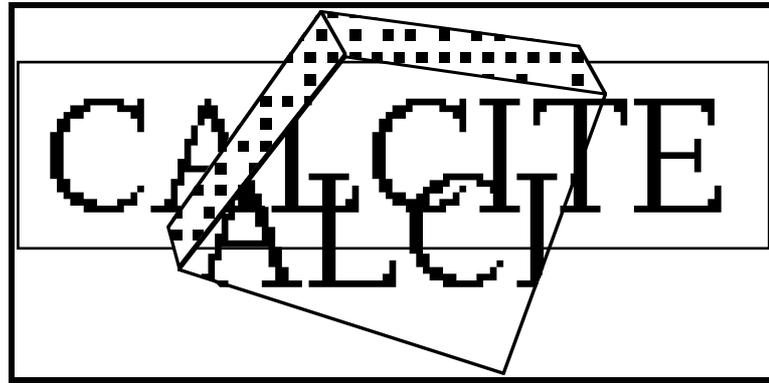


**Figure 6.15** Action of wave plates

- If the extraordinary wave has gained three quarters of a wavelength (figure 6.15c) the phase difference is  $3\pi/2$  and the light is circularly polarised with the resultant electric field rotating the other way.

One can use slabs of birefringent material where the extraordinary wave gains  $\frac{1}{4}$  or  $\frac{3}{4}$  wavelength to produce circularly polarised light from linearly polarised light or vice versa. Such slabs are called **quarter wave plates**. Note that to get circularly polarised light, the incident light must be polarised at  $45^\circ$  to the optic axis; other angles will give unequal e and o components so the light which comes out will be elliptically polarised.

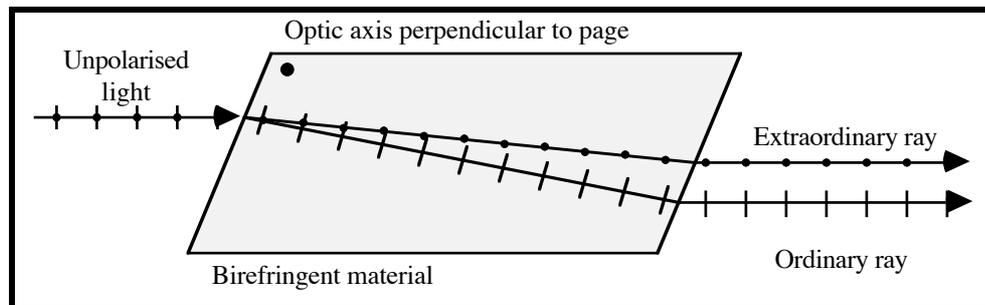
## Double images



**Figure 6.16. Double image in a calcite crystal**

The viewing angle has been chosen so that the ordinary image appears to be undisplaced.

Suppose that unpolarised light propagating in the plane perpendicular to the optic axis of a slab of birefringent material does not strike the surface of the slab at right angles. When the incident beam enters the birefringent material, it separates into two. One beam is polarised perpendicular to the optic axis (ordinary) and the other is polarised parallel to the optic axis (extraordinary). The two polarisations travel in different directions because they have different speeds, and hence different refractive indices. So they are refracted along different paths. One consequence of this is that a single object viewed through a birefringent material will produce a double image (figure 6.16).



**Figure 6.17. How a double image is formed**

The transmitted rays seem to come from different places.

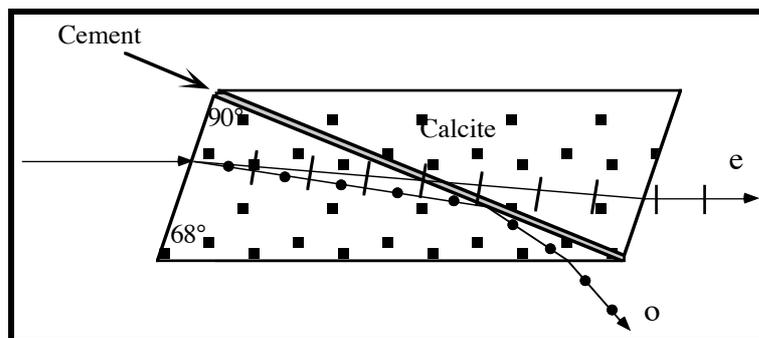
Many birefringent crystals have refractive indices which are very similar but the mineral calcite, one of the crystalline forms of calcium carbonate has noticeably different refractive indices for the ordinary and extraordinary rays.

Crystal	$n_o$	$n_e$
ice	1.309	1.313
quartz	1.544	1.553
calcite	1.658	1.486

**Table 6.1. Refractive indices for some uniaxial crystals**

### The Nicol prism

Since calcite is colourless and absorbs very little of either extraordinary or ordinary light, very pure calcite (called 'Iceland spar') was once used to make a very good kind of polariser, called a Nicol prism. A crystal of calcite is carefully shaped and cut in two. The two parts are then rejoined using a thin layer of transparent glue whose refractive index lies between those for the e and o rays. For a suitable direction of incident unpolarised light, the ordinary rays are totally internally reflected at the boundary with the glue, while the extraordinary rays pass through. This gives a separation of the light into two components with different polarisations, travelling in quite different directions. A Nicol prism has the advantage that the light coming out is completely plane polarised and it is not tinted.

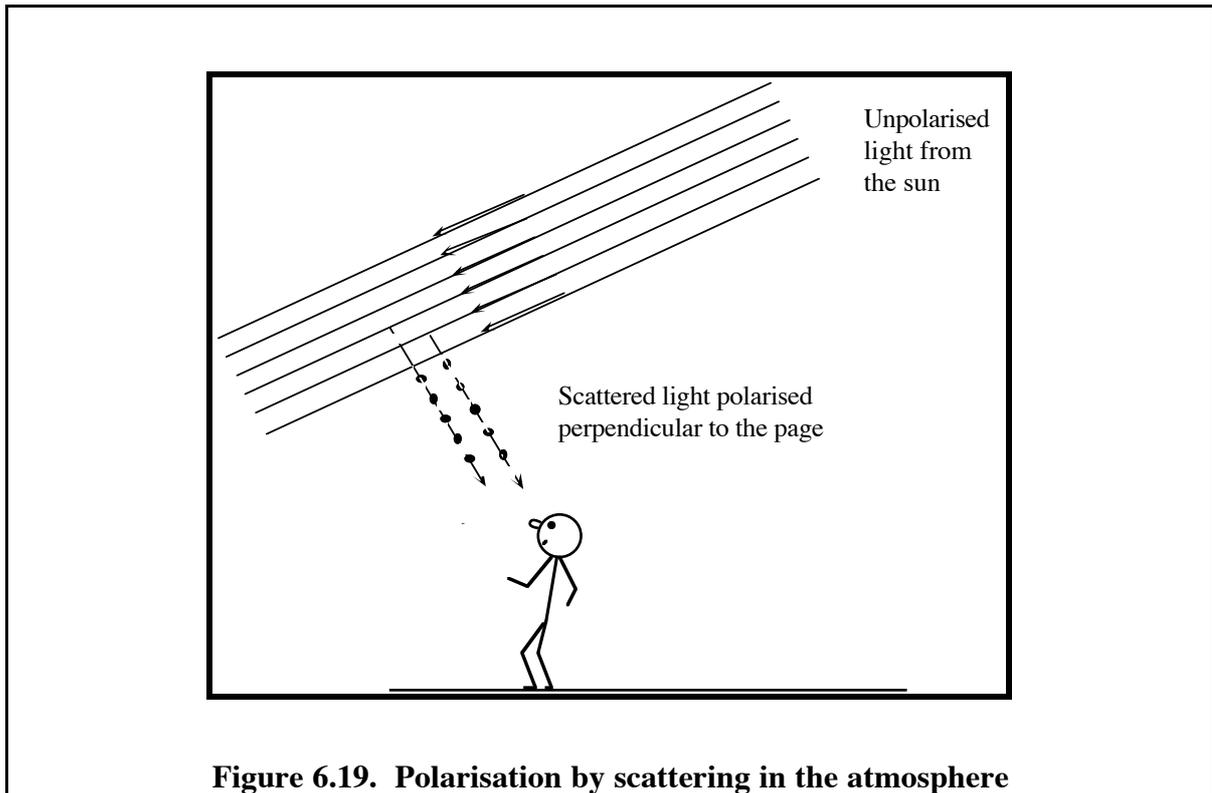


**Figure 6.18. A Nicol prism**

The ordinary ray is totally internally reflected at the cemented joint, leaving the completely plane polarised extraordinary ray.

## 6-6 POLARISATION BY SCATTERING

Light from the sky is sunlight scattered by air molecules; the scattered light propagates from the scattering molecules to the observer. If you look at the sky through a piece of Polaroid in a direction perpendicular to the sun's rays you will observe that the scattered light is polarised with its direction of polarisation perpendicular to the plane containing your line of sight and the sun. In interpreting this diagram you should remember that light is a transverse wave; it cannot have electric field oscillations with components in the direction of propagation.



**Figure 6.19. Polarisation by scattering in the atmosphere**

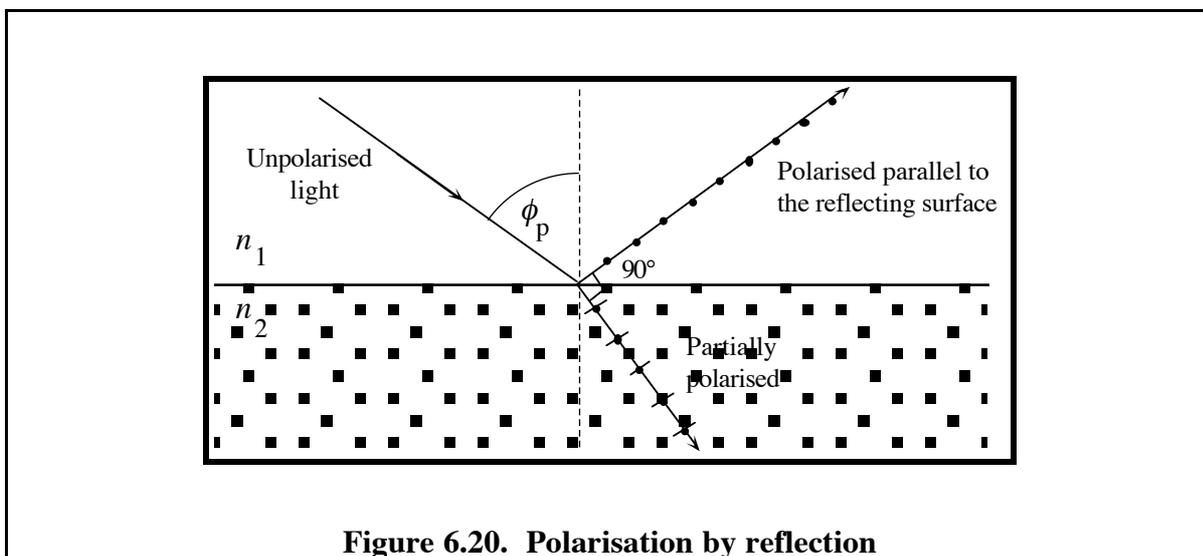
Only light scattered through  $90^\circ$  is completely plane polarised. Scattering at other angles produces partially polarised light. However, when you look at the sky in a direction perpendicular to the direction of the sun, the light that you see is only weakly polarised because most of it has been scattered many times and the polarisation by scattering tends to be randomised.

## 6-7 POLARISATION BY REFLECTION

At boundaries between materials of different refractive index the reflectivity depends on the polarisation of the incident light beam. We can think of incident light as made up of two components, one with its  $E$  field parallel to the surface (in the diagram, normal to the page) and the other with its  $E$  field in a plane perpendicular to the surface (in the diagram, the plane of the page). Each of these components is reflected by different amounts as the angle of incidence is increased. In particular, at a certain angle of incidence, only the component with its  $E$  field parallel to the surface is reflected. This angle is called the **polarising angle** or **Brewster angle**  $\phi_p$  and is given by

$$\tan\phi_p = \frac{n_2}{n_1} \quad \dots (6.2)$$

where  $n_1$  and  $n_2$  are the refractive indices of the two materials. If the first medium is air, the Brewster angle is equal to  $\tan^{-1}n_2$ .



**Figure 6.20. Polarisation by reflection**

Note that when the reflected light is completely plane polarised, the angle between the reflected and refracted rays is  $90^\circ$ . At other angles of incidence the reflected light is **partially plane polarised**.

## 6-8 PRACTICAL AND IDEAL POLARISERS

In general, dichroic materials do not produce completely plane polarised light; the light which comes out is only partially plane polarised. Furthermore the polarised light which does get through is usually absorbed to some extent and this absorption may be greater for some frequencies than for others. Much better, but more expensive, polarisers can be made using devices like the Nicol prism. These devices are much closer to an **ideal polariser**, which will produce completely plane polarised light, with no significant absorption of the transmitted component, for any frequency. Since each frequency component is polarised a Nicol prism can be used to polarise white light, without introducing any tinting.

Similarly polarised light can also be produced using stacks of glass plates arranged so that reflection at successive boundaries takes place at the Brewster angle.

Remember that Malus's law gives accurate results only for ideal polarisers.

## 6-9 OPTICAL ACTIVITY

Some materials (e.g. sugar solutions and many crystals) have different refractive indices for left and right circularly polarised light. This phenomenon is called **optical activity**. The effect of such a material on linearly polarised light can be deduced by resolving the light into left and right circularly polarised components with equal magnitudes. One of these traverses the material faster than the other so it moves ahead. When the two circularly polarised components emerge from the material their phase difference has changed. The combination of the two circularly polarised components is once again linearly polarised light with a new orientation. So optical activity is a rotation of the plane of polarisation of plane polarised light - the thicker the medium the greater the angle of polarisation.

In a technique known as saccharimetry this rotation is used to analyse sugar solutions. Some sugars rotate the plane clockwise; these are described as dextrorotatory. Other sugars which rotate the plane anticlockwise are described as levorotatory. The magnitude of the effect depends on the concentration of sugar in the solution.

## 6-10 PHOTOELASTICITY

Birefringence can be induced in glass and some plastics by mechanical stress. This phenomenon is called **photoelasticity**. Photoelasticity can be used to study stress patterns in loaded engineering structures and other objects. A perspex model of the object (for example an engine part, a bridge or a bone) is constructed and placed between crossed polarisers. When external forces are applied to the model, the internal strains cause birefringence, so that some of the light now gets through and the light patterns reveal the patterns of the internal strains. Since the refractive indices also depend on the frequency of the light the resulting patterns are brightly coloured when incident white light is used.

## 6-11 MISCELLANEOUS APPLICATIONS

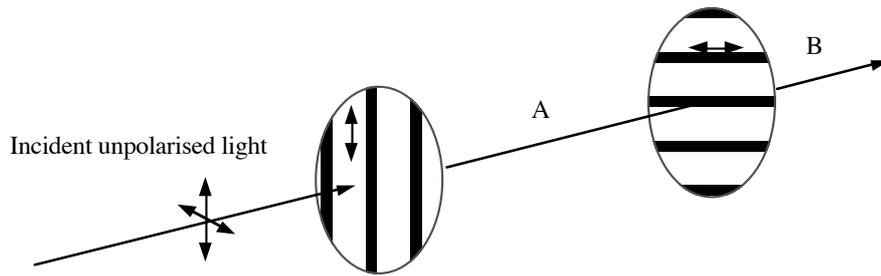
- A pair of polarisers can be used to control the intensity of light by varying the angle between their polarising axes.
- Polarising sunglasses are used to reduce glare. Since light scattered from the sky and light reflected from shiny surfaces such as water or hot roads is partially plane polarised, the appropriately oriented polarising material reduces the intensity of such light and the associated glare.
- When a thin slice of rock is placed between crossed polarisers in a petrological microscope the appearance of the mineral grains depends on their crystal shape, their light absorbing properties and birefringence. This aids in their identification.
- Birefringence can be induced in some materials by high electric fields (a phenomenon known as the Kerr effect). This effect can be used to make fast shutters for high speed photography.

### THINGS TO DO

- Use a pair of polarising sunglasses to examine the polarisation of light reflected from a pane of glass or a shiny tabletop. How can you determine the polarising axis of the sunglasses? Can you measure or estimate the Brewster angle? Can you determine the refractive index of glass or furniture polish?
- Use a pair of polarising sunglasses to examine the polarisation of light from the sky. What is the orientation of the partial polarisation? From which part of the sky does the polarised light come?

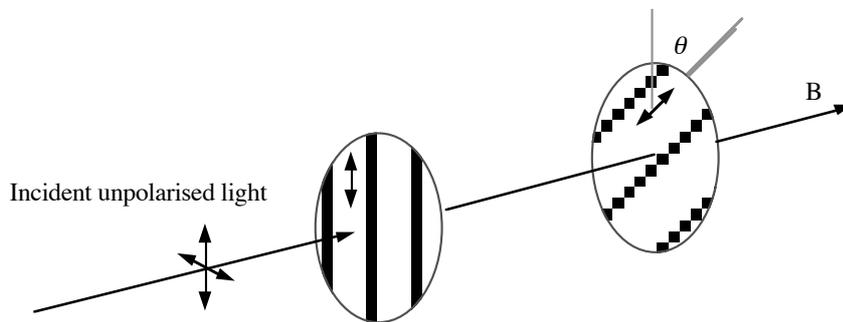
## QUESTIONS

Q6.1 a)

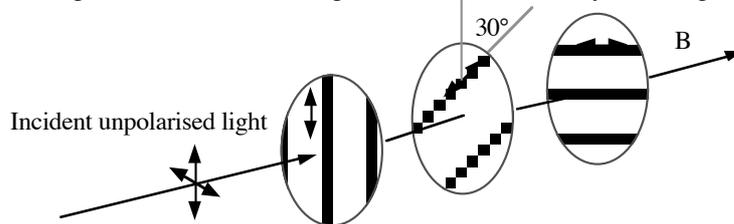


Unpolarised light of intensity  $I_{in}$  is incident on two ideal polarisers which have their polarising axes at  $90^\circ$  to each other. What are the polarisation and intensity of the light at A and B?

b) Suppose that the two polarising axes are at an angle  $\theta$  to each other. What are the polarisation and intensity of the light at B?



c) Suppose that a third polariser is placed between the two crossed polarisers with its polarising axis at an angle of  $30^\circ$  to the first polariser. What are the polarisation and intensity of the light at B?



Q6.2 The refractive indices for ordinary and extraordinary waves travelling at right angles to the optic axis in quartz are  $n_o = 1.544$  and  $n_e = 1.553$ . A quarter wave plate is one for which the two waves get exactly a quarter of a wavelength out of step after passing through it.

What is the thickness of the thinnest possible quarter wave plate for a wavelength of 600 nm?

Will such a quarter wave plate for  $\lambda = 500$  nm be thicker or thinner?

Show that a much thicker piece of quartz is required if it is to act as a quarter wave plate at several visible wavelengths.

Q6.3 Draw a set of diagrams of electric field vector to show how two linearly polarised waves with perpendicular polarisations, the same frequency and phase, but different amplitudes superpose to form another linearly polarised wave. Draw another set of sketches to show what happens if the phase of one the component waves is advanced by half a cycle ( $\pi/2$ ).

Q6.4 A material has a critical angle of  $45^\circ$ . What is its polarising angle?

Q6.5 How do polarising sunglasses reduce glare? Why do they have an advantage over sunglasses which rely on absorption of light only?

Q6.6 An unpolarised beam of light passes through a sheet of dichroic material which absorbs all of one polarisation component and 50% of the other (perpendicular) component. What is the intensity of the light which gets through?

Q6.7 Which would be thicker, a quarter wave plate made from calcite or one made from quartz? See table 6.1.

**Discussion questions**

- Q6.8** How could you distinguish experimentally among beams of plane polarised light, circularly polarised light and unpolarised light?
- Q6.9** Can polarisation by reflection occur at a boundary where the refractive index increases, for example with light going from water to air?
- Q6.10** Ice is birefringent. (See table 6.1.) Why do you not see a double image through an ice block?
- Q6.11** How could you identify the orientation of the optic axis in a quarter wave plate?
- Q6.12** What happens to circularly polarised light when it goes through a quarter wave plate? What happens to it in a half wave plate?
- Q6.13** One way of reducing glare from car headlights at night would be to fit polarisers to headlights and windscreens. How should the polarisers be arranged. Is this a good idea? What are the disadvantages?
- Q6.14** A salesperson claims that a pair of sunglasses is polarising. How can you check the claim before leaving the shop?
- Q6.15** There was once a kind of three dimensional movies based on polarised light. How might such a system work?
- Q6.16** Nicol prisms, which have to be made from very pure crystals of calcite, are very expensive compared with mass-produced Polaroid sheets. What are the advantages of a Nicol prism over Polaroid?
- Q6.17** What happens when circularly polarised light goes through a quarter wave plate? You can work it out by studying figure 6.15. First look at what a quarter wave plate does to linearly polarised light. What do two quarter wave plates do to linearly polarised light?