DIFFRACTION AND POLARISATION

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DIFFRACTION

Think back to Young's double-slit experiment. If the light truly travelled in straight-line paths after passing through the slits, the waves would not overlap and no interference pattern would be seen. In other words, the light deviates from a straight-line path and enters the region that would otherwise be shadowed. This deviation of light from its initial line of travel (in the same medium) is called **diffraction**. It can also be referred to as the bending of light round the edges of an obstacle.

When light passes through an opening that is large compared to the wavelength of light, it casts a shadow, as shown on the left in figure 10.1. But if we pass light through a thin slit we see that the light diffracts. The sharp boundary between the light and the dark area disappears, and the light spreads out like a fan to produce a bright area that fades into darkness without sharp edges. This can be seen on the right below.

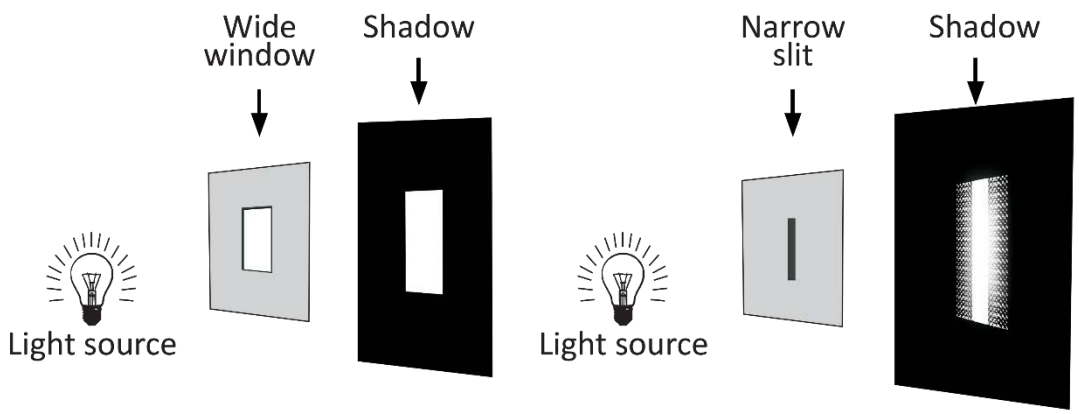


Figure 10.1: *Representation of the principle of diffraction*

Diffraction is not confined by narrow slits or to openings in general but can be seen for all shadows. On close examination, even the sharpest shadow is blurred slightly at the edge.

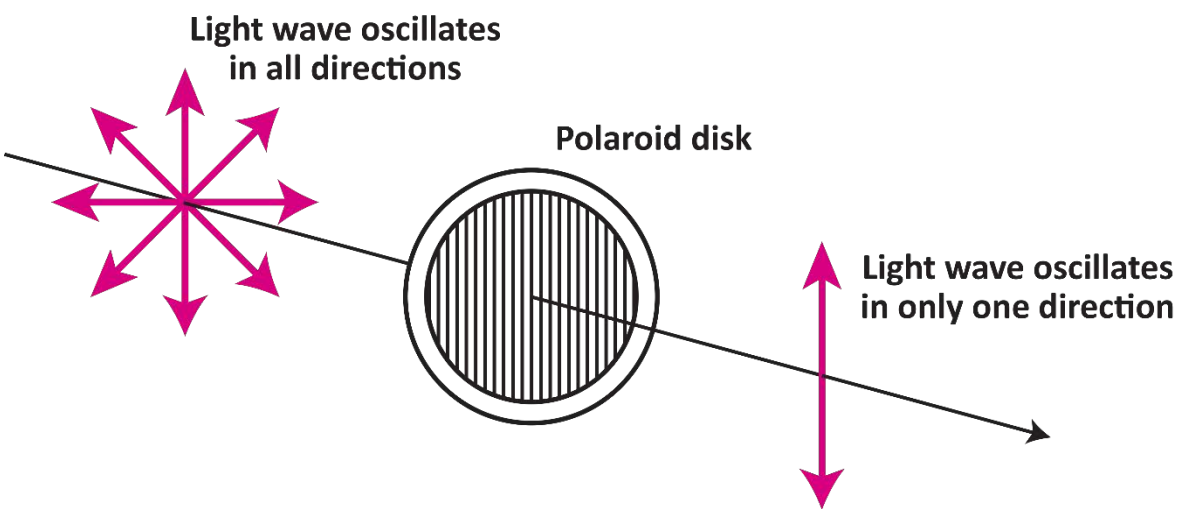
Under ordinary conditions, we seldom notice the diffraction of light. Light sources such as incandescent lamps or the sun are not monochromatic point sources, and the diffraction patterns due to different parts of the source and to different wavelengths usually overlap and obscure each other.

Diffraction is a problem when we wish to see very small objects with microscopes. If the size of the object is about the same as the wavelength of light, the image of the object will be blurred by diffraction. If the object is smaller than the wavelength of light, no structure can be seen. The entire image is lost due to diffraction. No amount of magnification or perfection of microscope design can defeat this fundamental diffraction limit. One of the goals of an optical design is to achieve resolution as close to the theoretical diffraction limit as possible. This is true not only of clinical instruments, but also corrective lenses.

Larger objects viewed with visible light can be seen clearly. A similar situation occurs with very small objects if the wavelength of the waves used to view the object is made very small. This can be done by using a beam of electrons instead of a light beam.

POLARISATION

An ordinary beam of light consists of a large number of waves emitted by the atoms or molecules of the light source. Each atom produces a wave with its own orientation of **E,** the electric field vector, corresponding to the direction of atomic vibration. However, because all directions of vibration are possible, the resultant electromagnetic wave is a superposition of waves produced by the individual atomic sources. The result is an *unpolarised* light wave. The direction of polarisation of the electromagnetic wave is defined to be the direction in which **E** is vibrating.



LEFT: Light waves having all possible orientations of E, RIGHT: Light waves having only ONE orientation of E

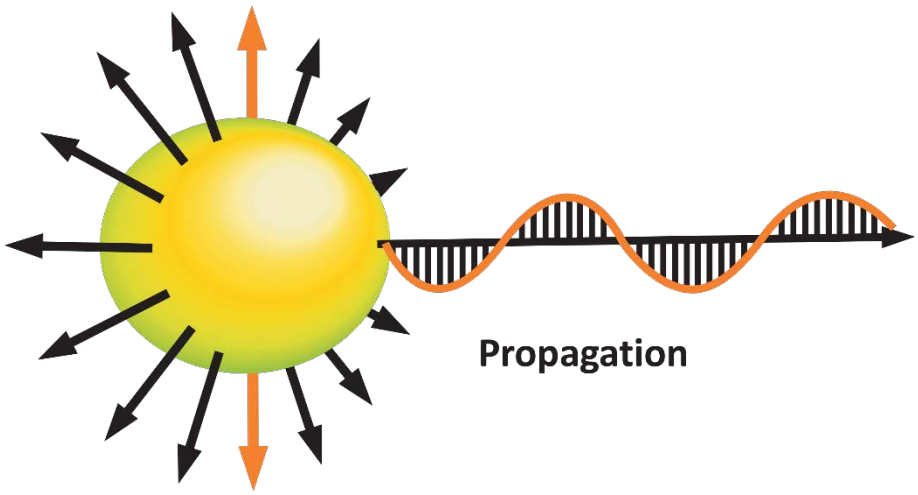


Figure 10.2: *Polarisation*

Note that all directions of the electric field vector are equally probable and all lie in a plane perpendicular to the direction of propagation. **At any given point and at some instant of time, there is only one resultant electric field**, which can be resolved into a vertical and a horizontal component. You should not be misled into thinking that the figure is showing that the electric field vector has a number of directions at a particular time. A wave is said to be linearly polarised if **E** vibrates in the same direction at *all times* at a particular point. Such a wave is described as *plane-polarised,* or simply *polarised.*

The phenomenon of polarisation provides firm evidence of the transverse nature of electromagnetic waves. All waves show interference and diffraction but only transverse waves can be polarised.

It is possible to obtain a linearly polarised beam from an unpolarised beam by removing from it all components except those whose electric field vectors oscillate in a single plane. We shall now discuss some physical processes for producing polarised light from unpolarised light.

POLARISATION BY SELECTIVE ABSORPTION

The most common technique for obtaining polarised light is to use a material that transmits waves whose electric field vectors vibrate in a plane parallel to a certain direction and absorbs those waves whose electric field vectors vibrate in

other directions. Any substance that has the property of transmitting light with the electric field vector vibrating in only one direction is called a *dichroic* substance. Examples of these are tourmaline, and quinine iodosulfate.

Tourmaline has the disadvantage of producing coloured polarised light. In 1932, E. H. Land prepared the first version of *Polaroid* by embedding a thin layer of quinine iodosulfate in a plastic sheet and stretching the plastic. An improved version followed in 1938 which used long polymeric molecules of polyvinyl alcohol that polarized light through selective absorption by oriented molecules. The sheets are stretched during manufacture so that the long-chain molecules align. After such a sheet is dipped into a solution containing iodine, the molecules become conducting.

However, the conduction takes place primarily along the hydrocarbon chains since the valence electrons of the molecules can move easily only along the chains (recall that valence electrons are “free” electrons that can readily move through the conductor). As a result, the molecules readily *absorb* light whose electric field vector is parallel to their length and *transmit* light whose electric field vector is perpendicular to their length.

It is common to refer to the direction perpendicular to the molecular chains as the *transmission axis*. In an ideal *polariser*, all light with **E** parallel to the transmission axis is transmitted, and all light with **E** perpendicular to the transmission axis is absorbed.

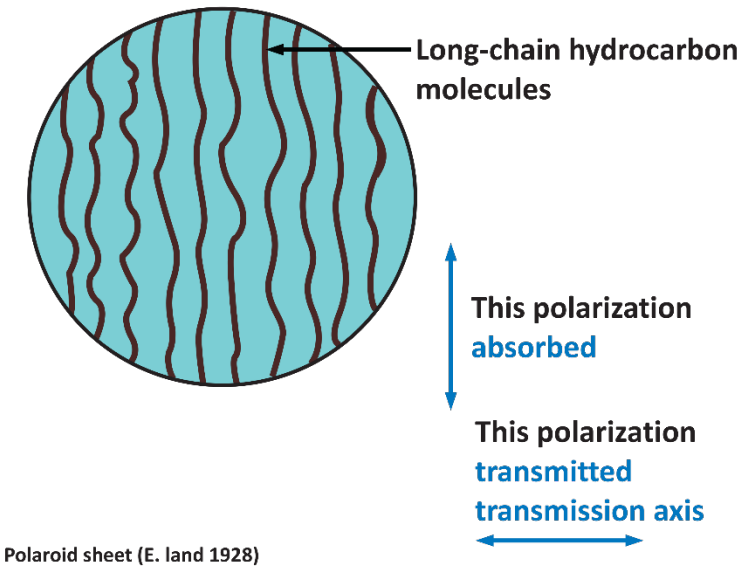
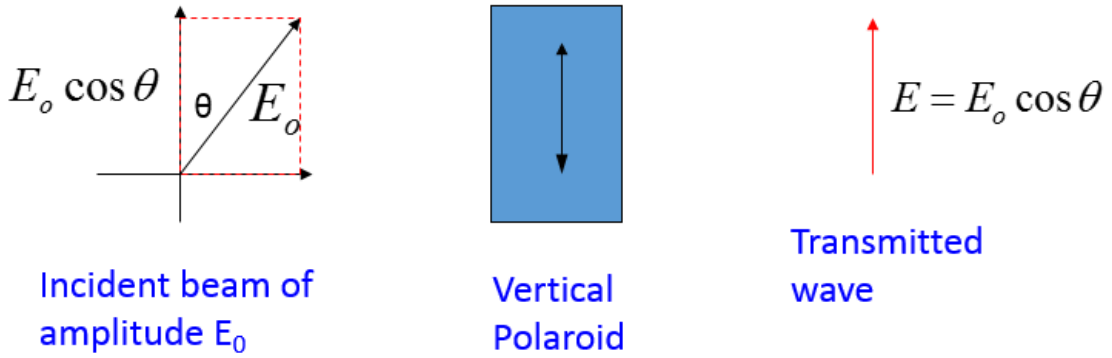


Figure 10.3: *Polaroid sheet*

Why are we only considering these two directions of the electric field vector? This is because all the E vectors can be represented by two vectors at right angles to each other. This arises because any E vector can be resolved into these components.

In the figure, an unpolarised light beam is incident on the first polarising sheet, called the polariser, where the transmission axis is indicated by the straight lines on the **polariser**. The light that is passing through this sheet is polarised vertically as shown, where the **amplitude** of the transmitted electric field vector is $\mathbf{E_0}$. A second polarising sheet, called the **analyzer**, intercepts this beam with its transmission axis at an angle $\theta$to the axis of the polariser. The component of $\mathbf{E_0}$ perpendicular to the axis of the analyzer is completely absorbed, and the component of $\mathbf{E_0}$ parallel to the axis of the analyzer is $\mathbf{E_0}\cos\theta$.



Malus's law gives the intensity of the transmitted light:

$$I = I_0 \cos^2\theta$$

From this expression, note that the transmitted intensity is a maximum when the transmission axes are parallel ($\theta = 0°$ or 180°). In addition, the transmitted intensity is zero (complete absorption by the analyzer) when the transmission axes are perpendicular to each other. When unpolarised light of intensity I_0 is sent through a single ideal polariser, the transmitted linearly polarised light has intensity 0.5 I_0. This follows from Malus's law because the average value of $\cos^2\theta$ is 0.5.

POLARISATION BY REFLECTION

When an unpolarised light beam is reflected from a surface, the reflected light is completely polarised, partially polarised, or unpolarised, depending on the angle of incidence. If the angle of incidence is either 0 or 90° (a normal or grazing angle), the reflected beam is unpolarised. However, for intermediate angles of incidence, the reflected light is polarised to some extent. For one particular angle of incidence, the reflected light is completely polarised. Let's look at that angle.

Suppose an unpolarised light beam is incident on a surface (see figure 10.4). The beam can be described by two electric field components, one parallel to the surface (the dots) and the other perpendicular to the first and to the direction of propagation (the arrows). It is found that the component parallel to the surface reflects more strongly than the other components, and this results in a partially polarised beam. Furthermore, the refracted ray is also partially polarised.

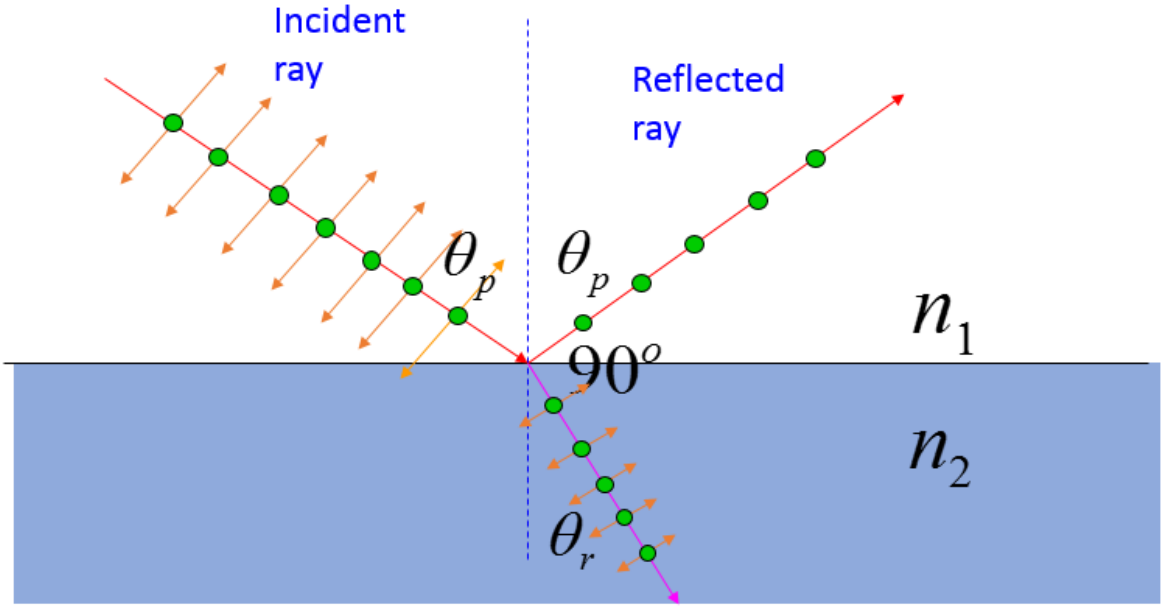


Figure 10.4: *Polarisation by reflection*

Now suppose the angle of incidence is varied until the angle between the reflected and refracted beams is 90°. At this particular angle of incidence, the reflected beam is completely polarizsd with its electric field vector parallel to the surface, while the refracted beam is partially polarised. The **angle of incidence** at which this occurs is called the polarising angle, $\boldsymbol{\theta_p}$.

Applying Snell's Law to the above situation we obtain:

$$n_1 \sin\theta_p = n_2 \sin\theta_r$$

However, note the following:

(i) $\theta_p + \theta_r = 90°$

(ii) $\sin(90° - \theta_p) = \cos\theta_p$

(iii) $\sin\theta/\cos\theta = \tan\theta$

Therefore, $n_1 \sin\theta_p = n_2 \sin(90° - \theta_p) = n_2 \cos\theta_p$

and $\tan\theta_p = n_2/n_1$

If the incident light is in air, n_1 will equal 1. If we simply use **n** to represent the refractive index of the medium from which the light is reflected, we obtain the following expression relating the polarising angle to the index of refraction of the reflecting substance:

$$\mathbf{n = \tan \theta_p}$$

This expression is called **Brewster's Law**, and the polarising angle θ_p is sometimes called Brewster's angle, after its discoverer, Sir David Brewster (1781-1868). Because n varies with wavelength for a given substance, Brewster's angle is also a function of the wavelength.

Polarisation by reflection is a common phenomenon. Sunlight reflected from water, glass, and snow is partially polarised. If the surface is horizontal, the electric field vector of the reflected light will have a strong horizontal component. Sunglasses made of polarising material reduce the glare of reflected light. The transmission axes of the lenses are oriented vertically so as to absorb the strong horizontal component of the reflected light.

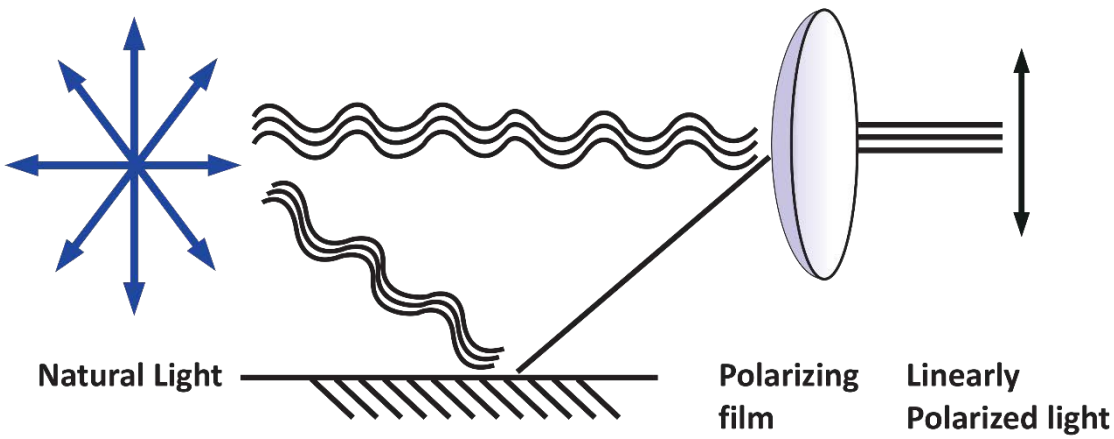


Figure 10.5: *Glare control via polarised filters*

1. Glare is mainly horizontally polarised.

2. Therefore, a vertical transmission axis is needed to reduce glare.

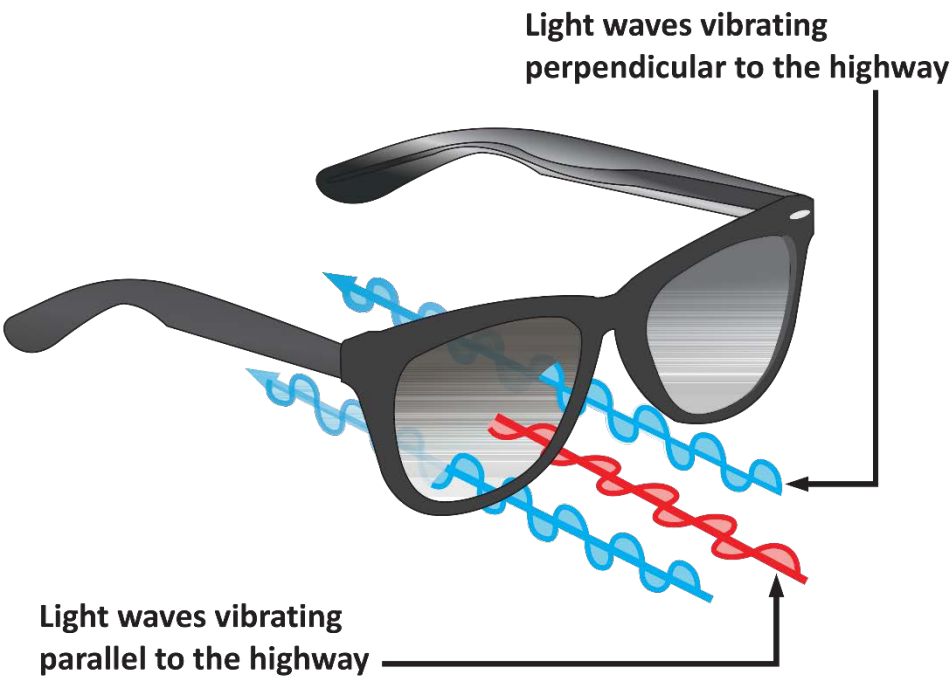


Figure 10.6: *Polarised lenses*

In recent years, instrument panels and car dashboard displays incorporating liquid crystal displays (LCDs) have been introduced. LCD emissions are linearly polarised (for example, check your digital watch display) and may be rendered less visible by polarising sunglasses under some viewing conditions. As a result, the transmission axes of some sunglass lenses may be placed at oblique meridians to ensure that horizontal glare sources are attenuated, while the car LCDs remain visible. In 2012, a photochromic plastic spectacle lens material was introduced that becomes a linear polariser when activated by light.

POLARISATION BY DOUBLE REFRACTION

When light travels through an amorphous material, such as glass, it travels with a speed that is the same in all directions. That is, glass has a single index of refraction. However, in certain crystalline materials, such as calcite and quartz, the speed of light is not the same in all directions. Such materials are characterized by two indices of refraction. Hence, they are often referred to as double-refracting or birefringent materials.

In a crystal such as NaCl, the alternating Na^+ and Cl^- ions have a symmetry that results in the bonding forces being the same in all directions. Birefingent crystals do not have this symmetry and atoms have stronger attraction in certain directions.

Table of refractive indices of some birefringent materials (Reference wavelength is 589.3 nm.)

CRYSTAL	n_o	n_e
Tourmaline	1.669	1.638
Calcite	1.6584	1.4864
Quartz	1.5443	1.5534
Sodium nitrate	1.5854	1.3369
Ice	1.309	1.313
Rutile (TiO_2)	2.616	2.903

Table 10.1: *Refractive indices of some birefringent materials.*

When an unpolarised beam of light enters a calcite crystal, the beam splits into two plane-polarised rays that travel with different velocities, corresponding to two different angles of refraction, as in the figure 10.7. The two rays are polarised in two mutually perpendicular directions, as indicated by the dots and arrows. One ray, called the ordinary (O) ray, is characterized by an index of refraction, n_0, that is the same in all directions. This means that if one could place a point source of light inside the crystal, the ordinary rays would spread out from the source as spheres.

The second plane-polarized ray, called the extraordinary (E) ray, travels with different speeds in different directions and hence is characterized by an index of refraction, n_e, that varies with the direction of propagation. There is one direction, called the **optic axis**, along which the ordinary and extraordinary rays have the same velocity, corresponding to the direction for which the refractive indices are the same.

For directions where there is a difference in velocity for the two rays, the difference is maximal in the direction perpendicular to the optic axis. For example, in calcite n_o = 1.6584 and n_e varies from 1.6584 along the optic axis to 1.4864 perpendicular to the optic axis.

If one places a piece of calcite on a sheet of paper and then looks through the crystal at any writing on the paper, two images of the writing are seen. These two images correspond to one formed by the ordinary ray and the second formed by the extraordinary ray. If the two images are viewed through a sheet of rotating polarising glass, they will alternately appear and disappear because **the ordinary and extraordinary rays are plane-polarised along mutually perpendicular directions.**

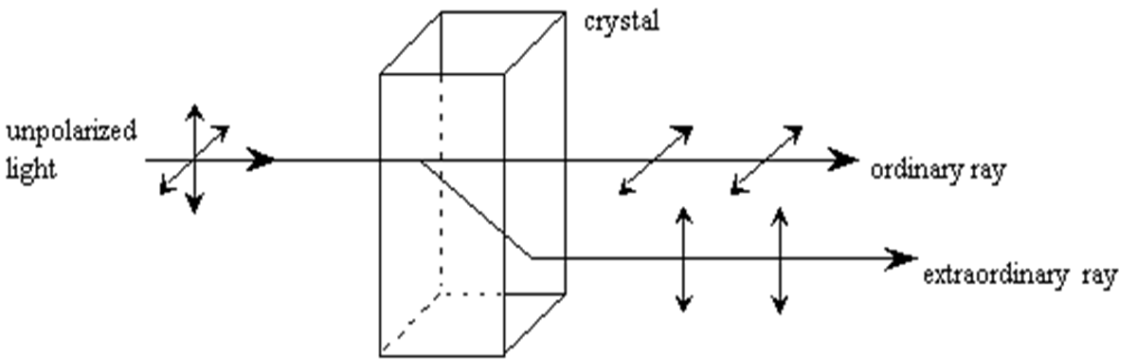


Figure 10.7: Bifringent material

This phenomenon is applied in the detection of stress in materials using crossed polarisers. **Photoelasticity** was first described by the Scottish physicist David Brewster. When stress is present in an object, the forces between atoms and molecules are no longer uniform. This gives rise to (induces) birefringence. Therefore a light ray passing through an object with exhibiting stress areas experiences two refractive indices. Photoelastic materials exhibit the property of birefringence only on the application (or in the presence) of stress and the magnitude of the refractive indices at each point in the material is directly related to the state of stress at that point. When a ray of plane polarised light is passed through a photoelastic material, it gets resolved along the two principal stress directions and each of these components experiences different refractive indices.

The difference in the refractive indices leads to a relative phase retardation between the two component waves because they moved at different speeds inside the material. The two waves are then brought together in a polariscope. Optical interference occurs and we get a fringe pattern, which depends on relative phase retardation. Thus studying the fringe pattern, one can determine the state of stress at various points in the material.

Dichroism of the macular pigment lutein is thought to be the cause of the entoptic phenomenon known as Haidinger's brushes. The lutein molecules are aligned parallel to the radially oriented nerve fibres emerging from the fovea so that linearly polarised light parallel to the molecule axis is absorbed. When looking through a linear polariser at a featureless white background, a small (3 to 5° across) faint yellow bowtie shape may be seen, centered on the fixation point; some observers will also see an even fainter blue or purple bowtie at 90° to the yellow brushes. The effect can be more easily seen if the linear polariser is rotated around the line of sight. Haidinger's brushes can be used to train an observer to use the fovea instead of eccentric fixation.

POLARISATION BY SCATTERING

When light passes through a transparent medium (including a gas mixture such as air) some of the electrons in the material absorb energy from the oscillating electric field. They then vibrate with the same frequency as the light. The electrons then act as tiny antennas reradiating this energy as light travelling in the medium. This process is called **scattering**. A transmitting antenna does not radiate energy along the direction of oscillation of the charge. That is, if an electron is oscillating in the vertical direction, it will not radiate that energy vertically.

This scattering mechanism causes skylight to be partially polarised. The following figure shows a beam of unpolarised light passing through a gas. The energy absorbed by electrons that causes them to vibrate along the *z* direction may be radiated in the positive or negative x direction or in the positive or negative y direction but **not** along either *z* axis. Likewise, the absorbed energy that causes electrons to vibrate along the x direction may be scattered in the yz plane but not perpendicular to it. Thus, scattered light will be enhanced in light polarised in one plane and diminished in light polarised in the perpendicular plane. Acute observers may be able to train themselves to use the Haidinger's brush phenomenon to detect the direction of polarization of skylight. This was reported by early researchers such as Minnaert.

It is interesting to note that in polarization by reflection we have a similar 90° angle between the reflected (polarised) ray and the refracted ray.

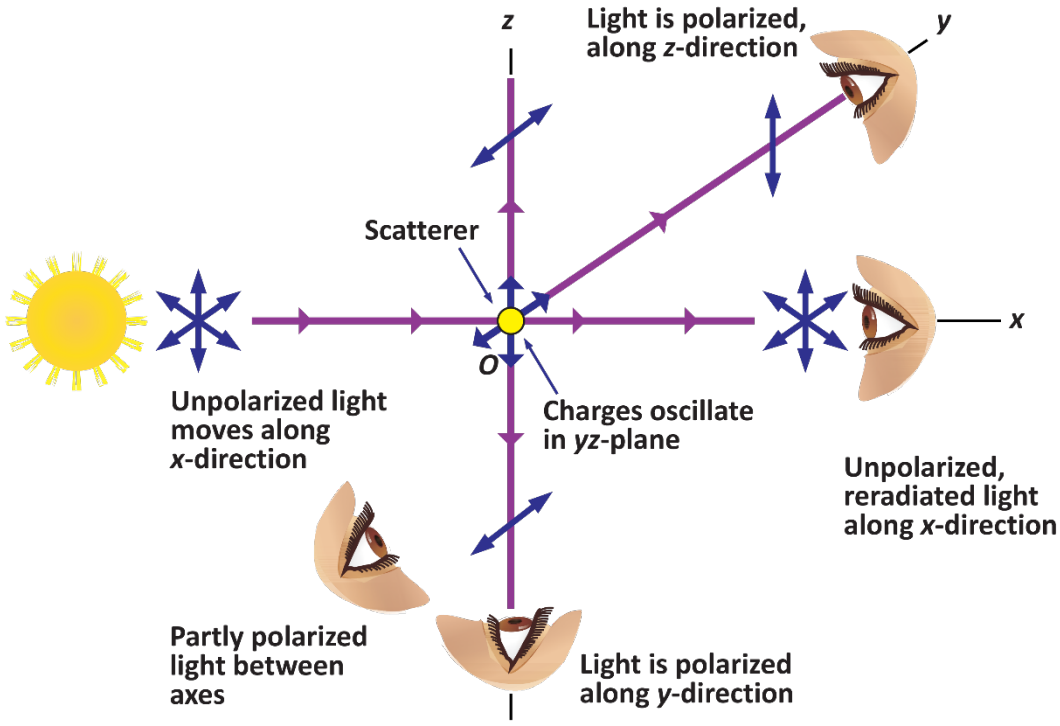


Figure 10.8: *Polarisation by scattering*

Scattering of light by the Earth's atmosphere depends on λ. For particles much smaller than the wavelength of light (such as molecules of air), the particles will be less of an obstruction to long wavelengths than to short ones. The scattering decreases, in fact, as $1/\lambda^4$. Red and orange light is thus scattered much less than blue and violet, which is why the sky looks blue. At sunset, the Sun's rays pass through a maximum length of atmosphere. Much of the blue has been taken out by scattering. The light that reaches the surface of the Earth and reflects off clouds and haze is thus lacking in blue, which is why sunsets appear reddish.

The dependence of scattering on $1/\lambda^4$ is valid only if the scattering objects are much smaller than the wavelength of the light. This is valid for oxygen and nitrogen molecules whose diameters are about 0.2 nm. Clouds, however, contain water droplets or crystals that are much larger than λ; they scatter all frequencies of light nearly uniformly. Hence clouds appear white (or grey, if shadowed).