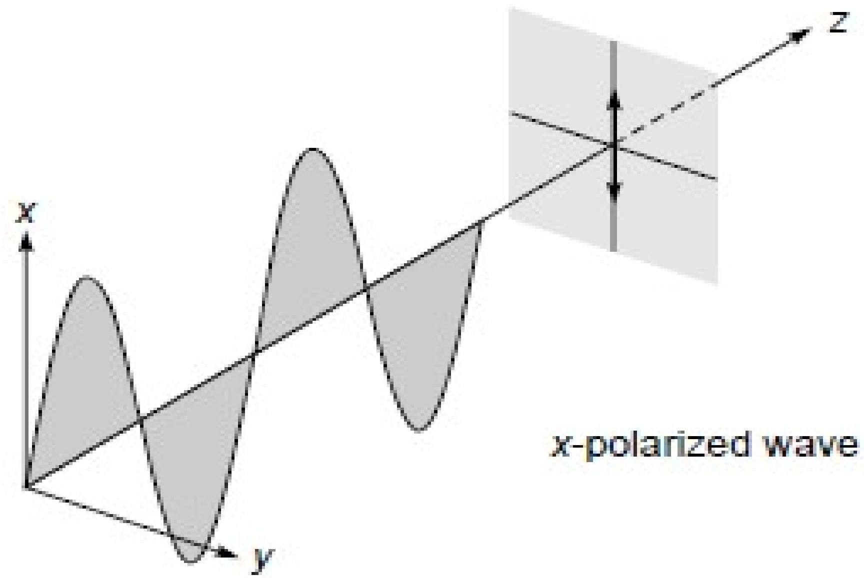
Polarisation

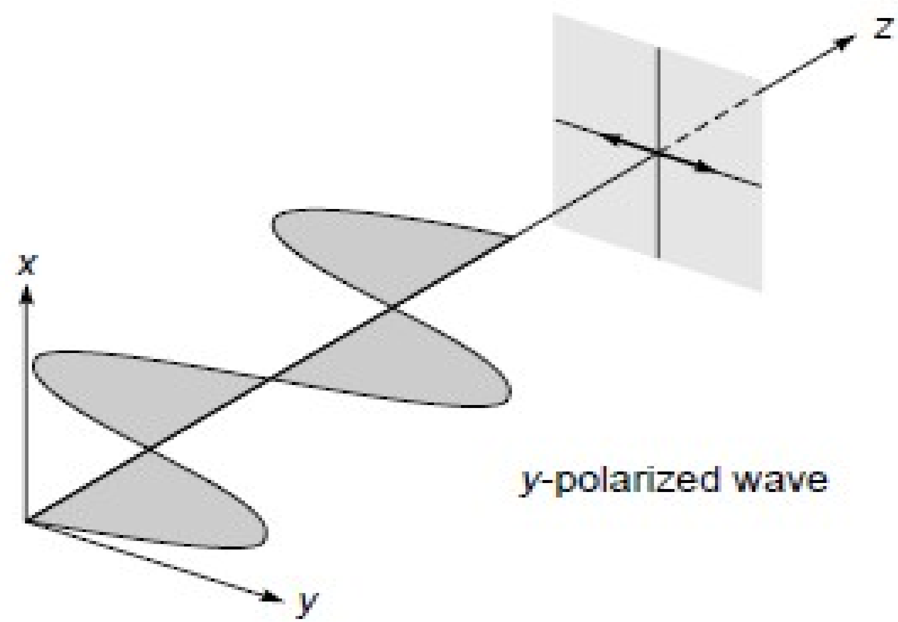
Only transverse waves can be polarised. Therefore, the fact that light waves can be polarised is a proof that EM waves are transverse in nature.

Imagine a rope and you are moving it in xz plane and then
in yz plane.

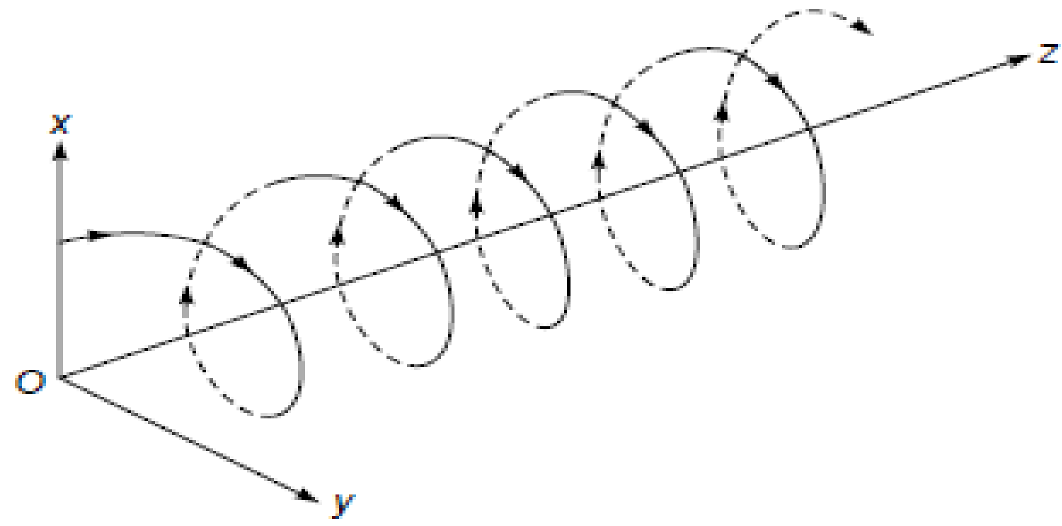
It can be related to plane polarised light in x- direction if Electric filed is oscillating in xz plane



(a)

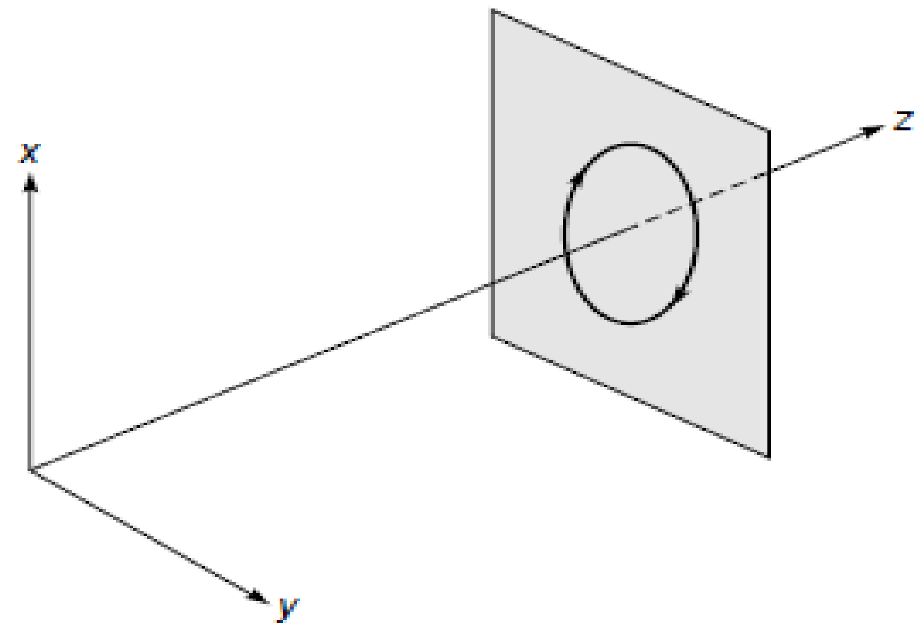


What if you start moving this rope in a circle.



(a)

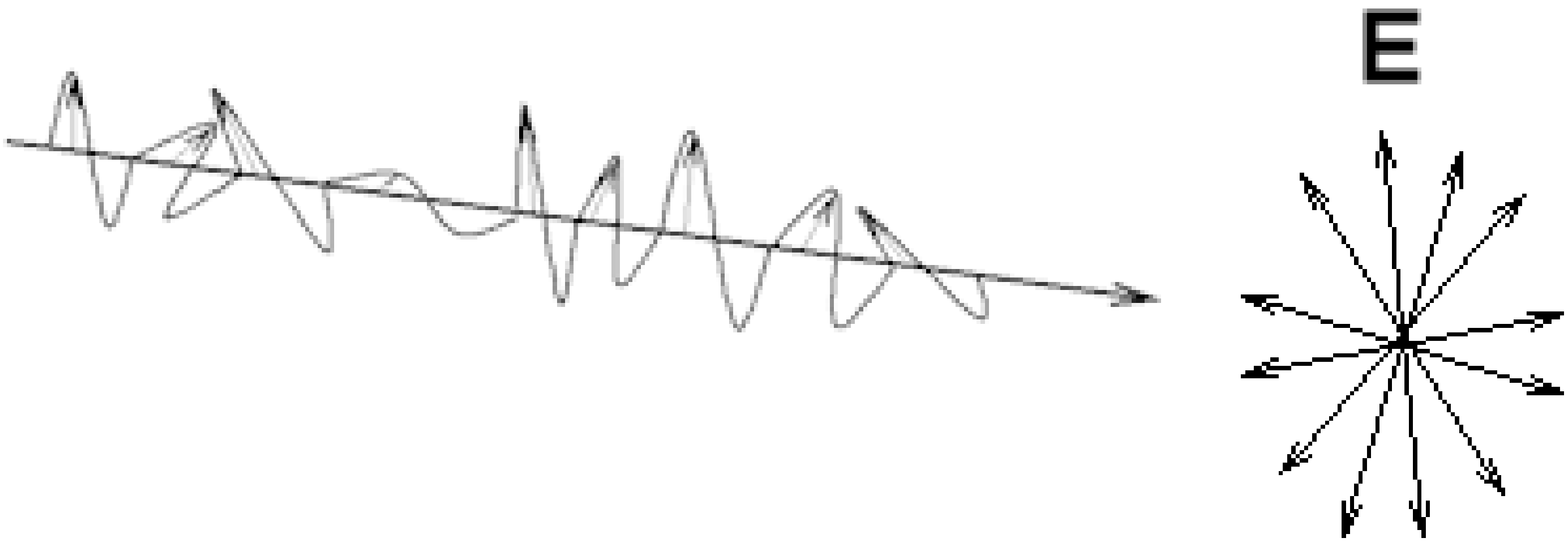
It can be related to circularly polarised light .



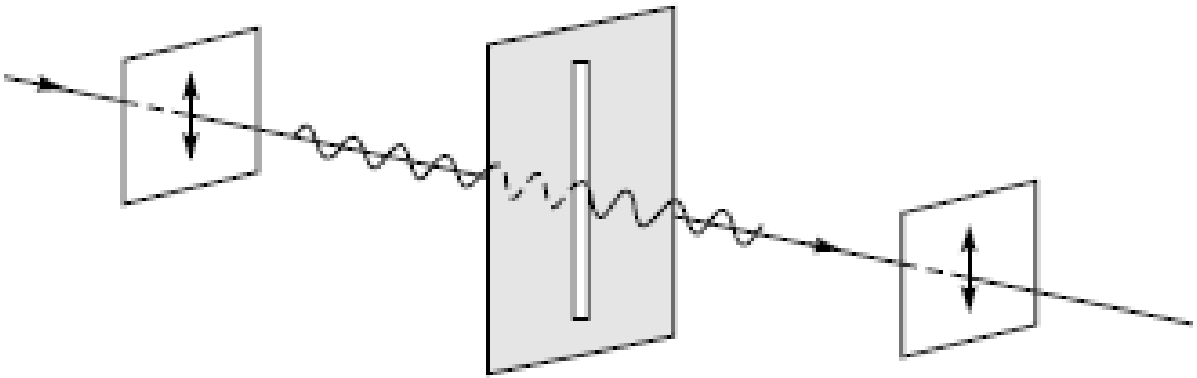
(b)

What if you start moving rope in random directions in short interval of time?

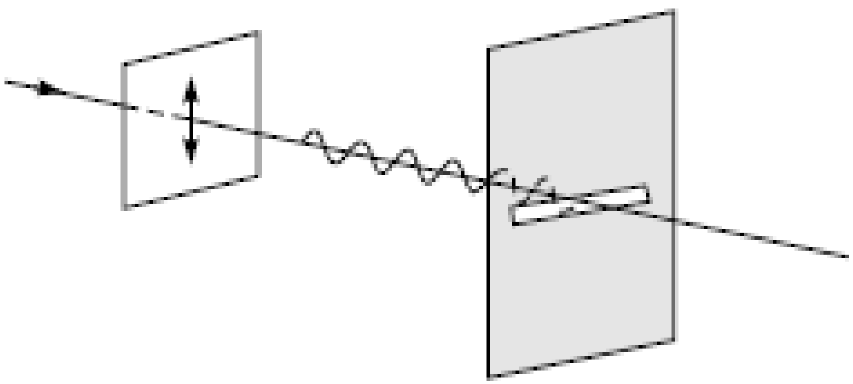
It can be related to unpolarised light.



What if you introduce a slit in the path?

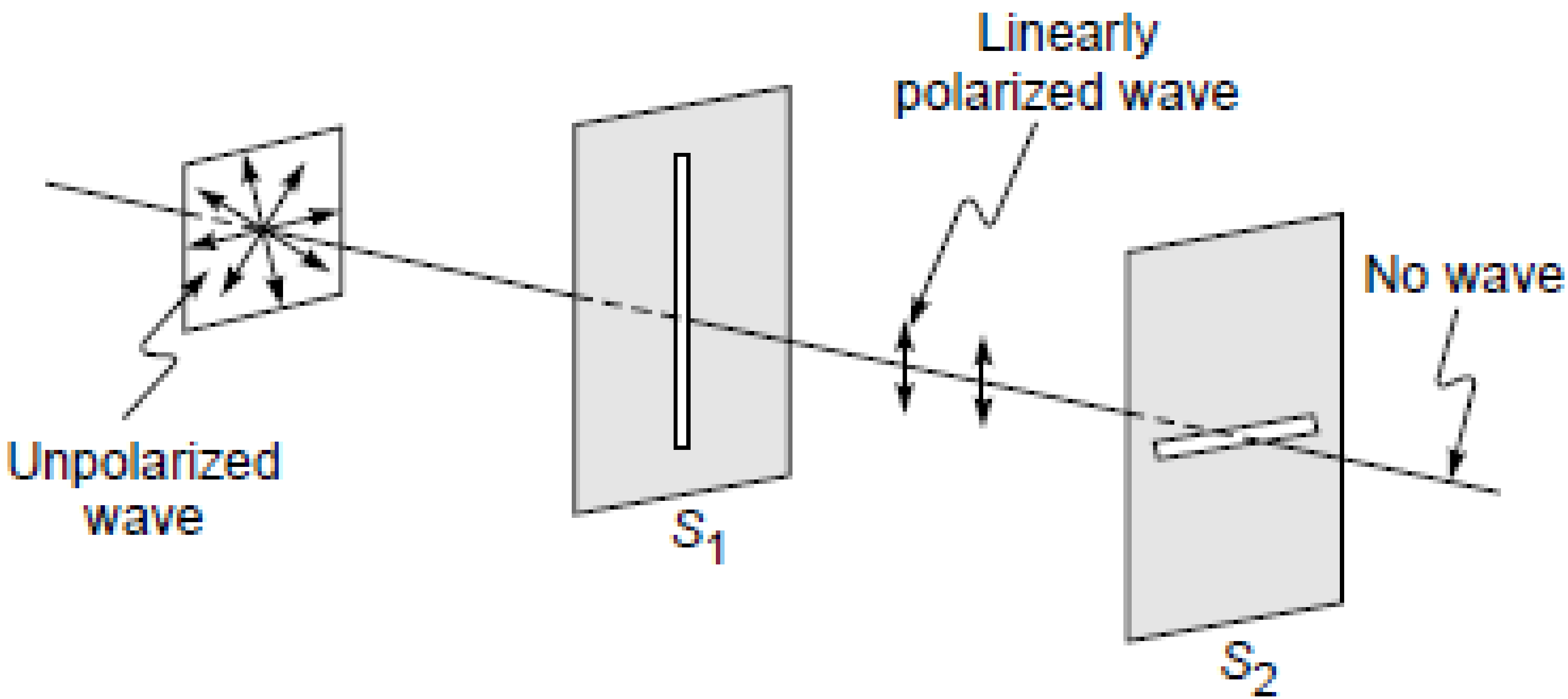


(a)

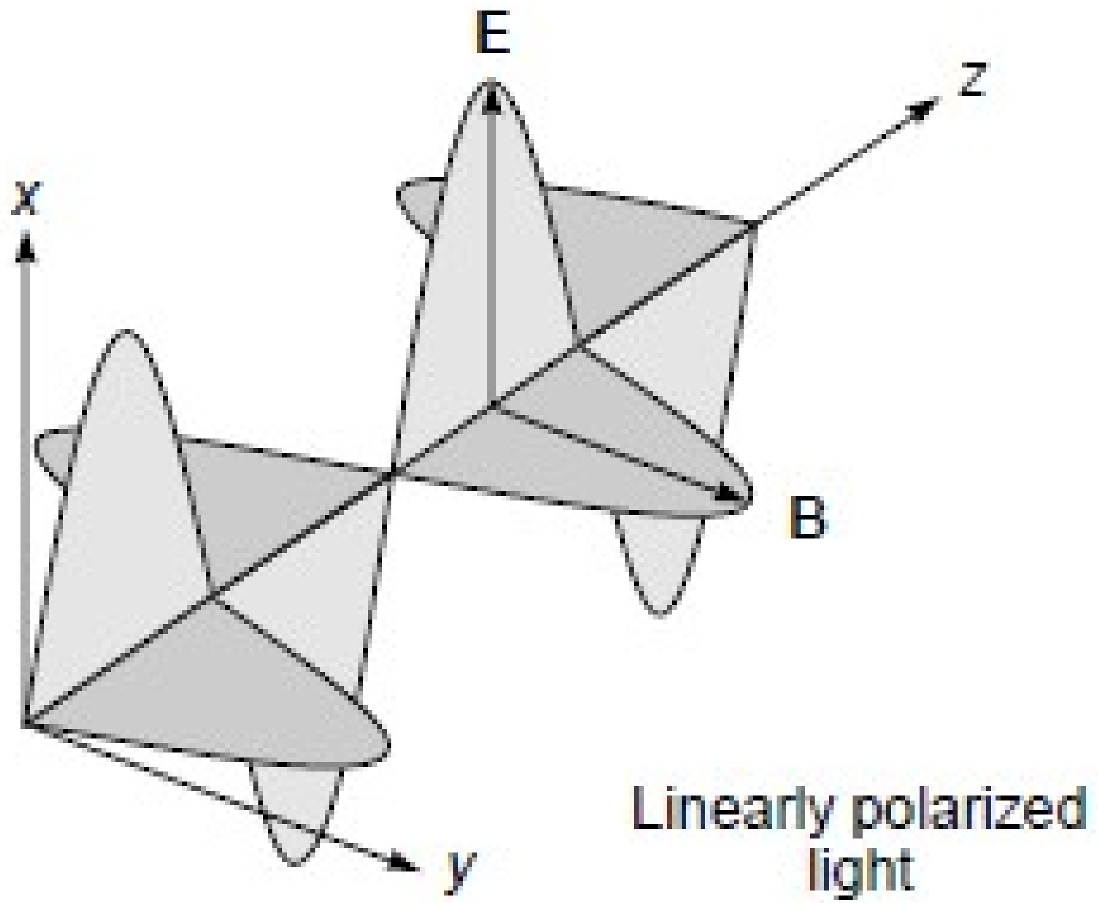


(b)

If a longitudinal wave were propagating in string, amplitude of transmitted wave would have been same for all orientations.

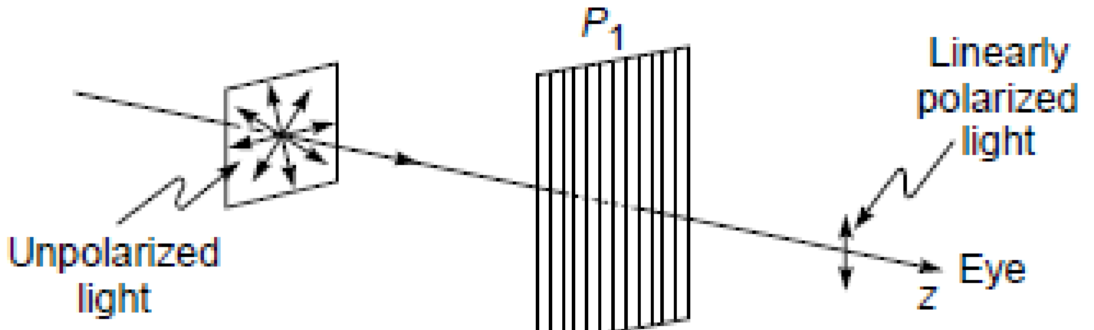

Linearly
polarized wave
No wave
Unpolarized
wave
S_1
S_2

Electromagnetic Waves :



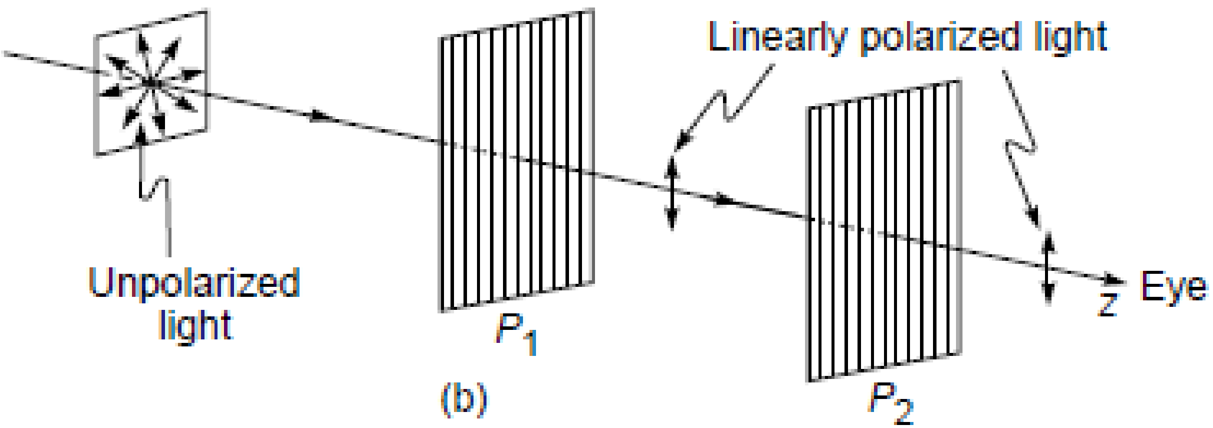
The direction of polarisation of an electromagnetic wave has traditionally been defined to lie along the direction of oscillation of the electric field.

P1 and P2 are polaroids.



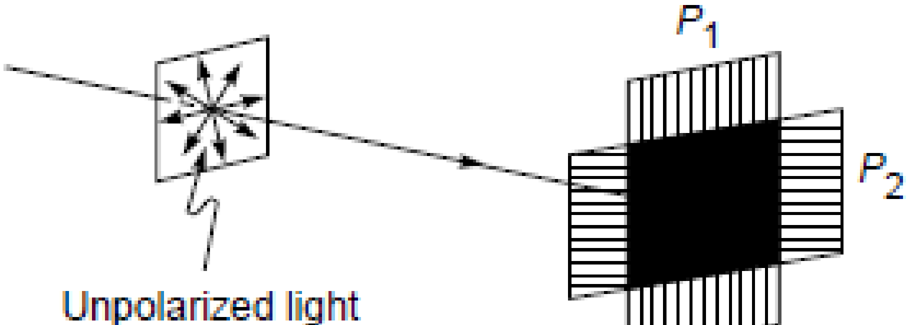
(a)

If P1 and P2 are parallel to each other, light intensity will be maximum
after P2.



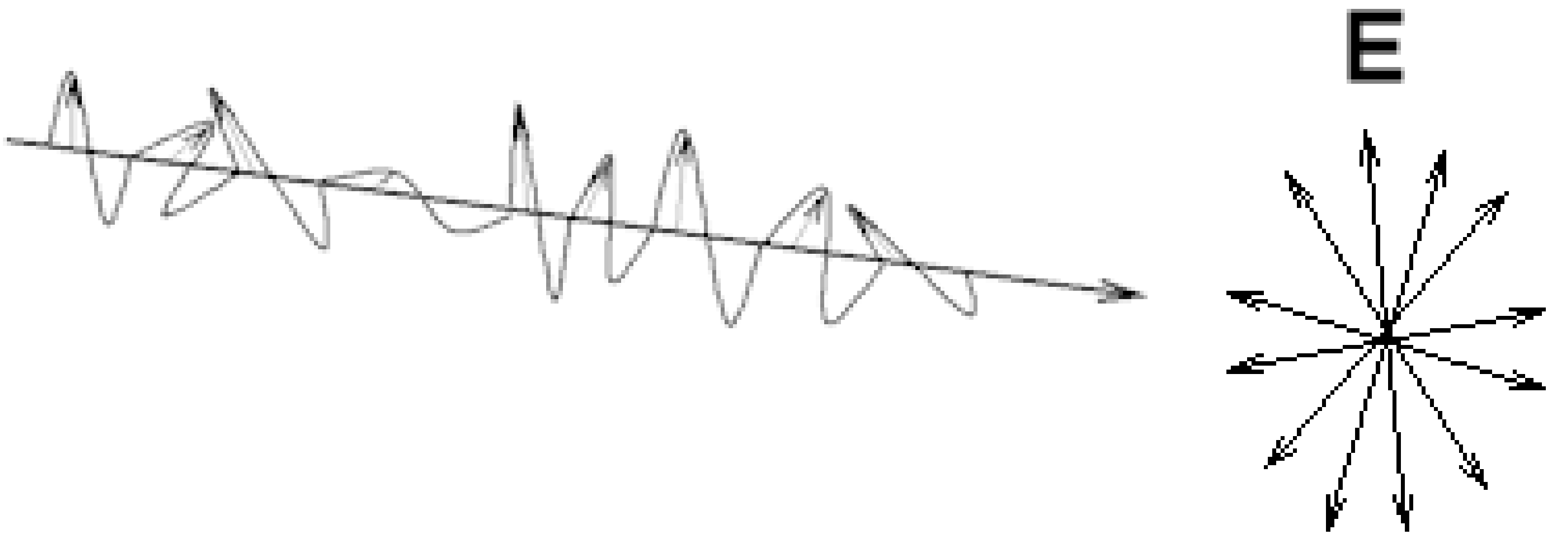
(b)

If P1 and P2 are perpendicular to each other, light intensity is minimum after P2.



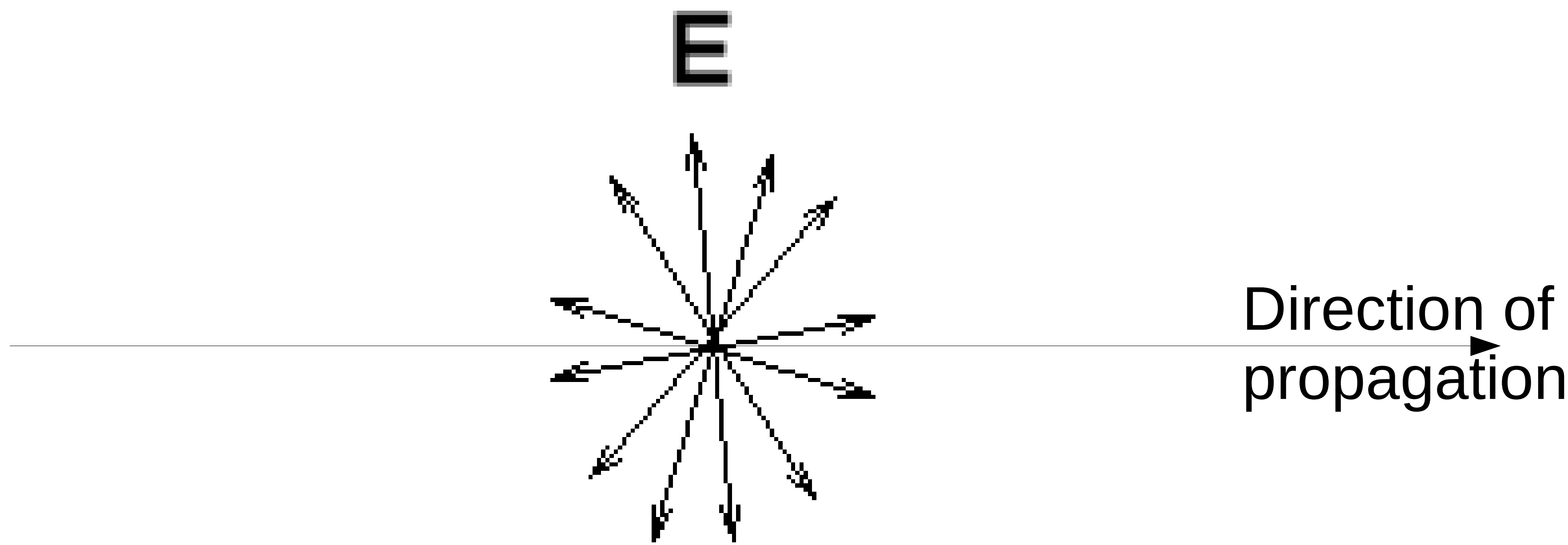
(c)

Representation of unpolarised light:

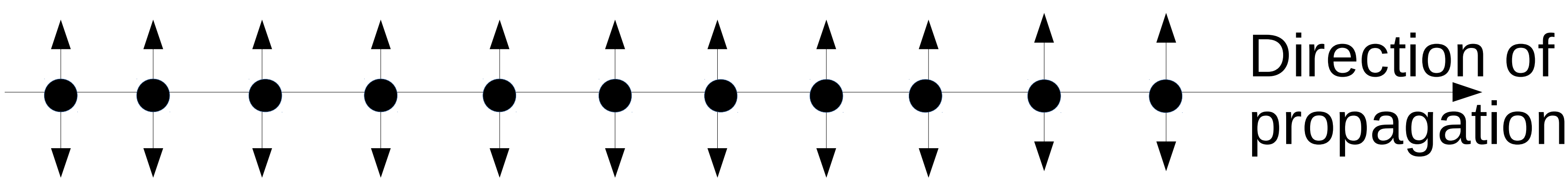


Electric field vector is decomposed into 2 perpendicular components. If direction of propagation of wave is z-direction, then Electric field vector is decomposed into x and y components.

For unpolarised light, the components have equal amplitudes, and the phase difference between them varies randomly.



If E is represented in x and y direction:



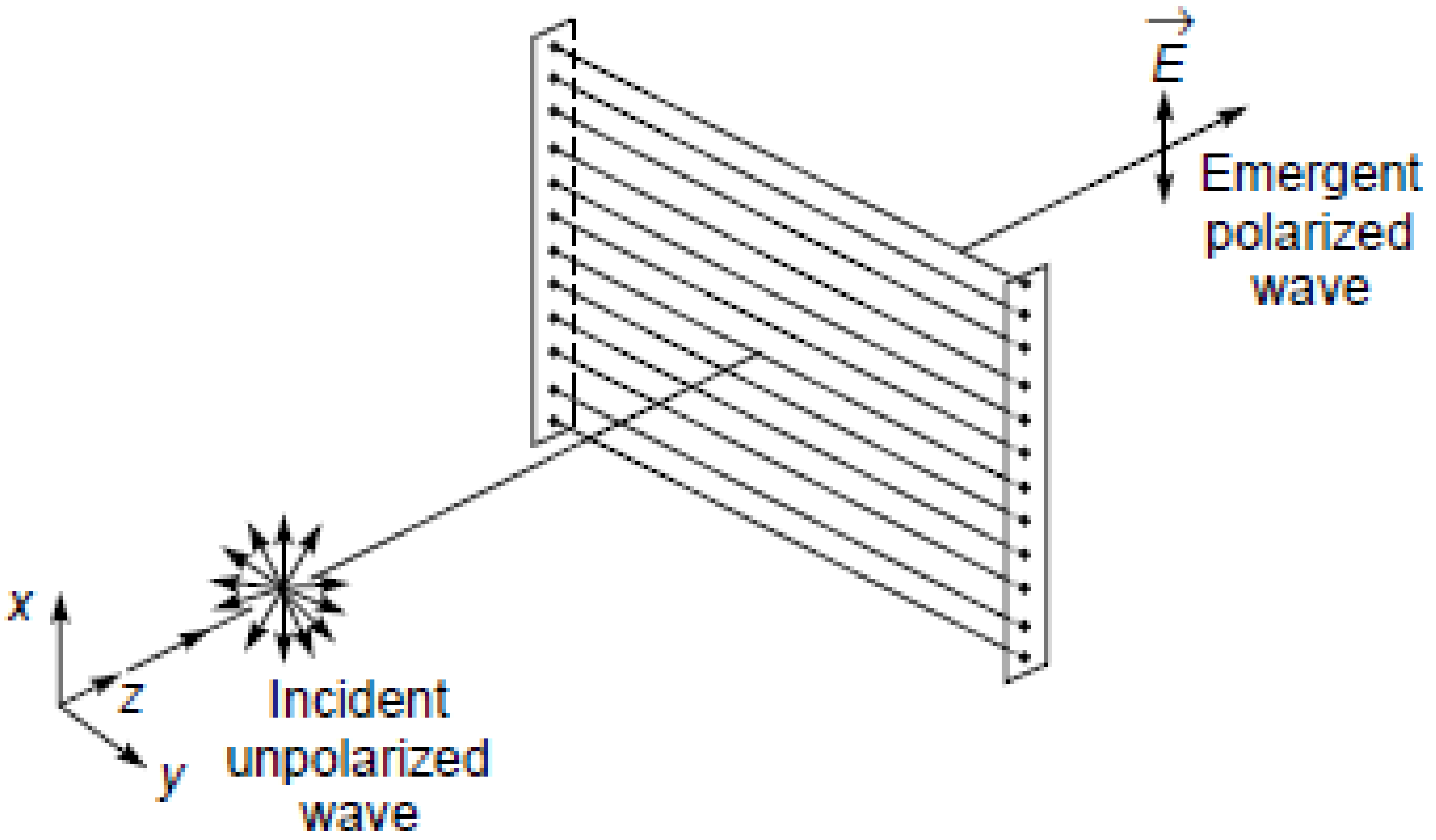
Represents component out of plane

Represents component in the plane

Production of Linearly Polarised light:

- The wire grid polariser
- The Polaroid.
- Polarisation by reflection.
- Polarisation by double refraction.

The wire grid polariser :



- Very thin Copper wires placed parallel to each other.

- When an unpolarised light is incident on it, component of electric vector along the length of the wire is absorbed. Because electrons in wire start moving in electric field and energy associated with electric field is lost in Joule heating of wires.

- Since wires are very thin electric field component along the x-axis passes through without much attenuation because electrons don't have much space to move.

- Therefore, outgoing wave is linearly polarised with electric vector in x-direction.

It will work (Ey will be almost completely attentuated) if the spacing between is $\leq\lambda$.

Therefore, this polariser is easy to fabricate for a 3cm microwave because spacing needed between wires $\leq$3 cm.

Visible light waves have small wavelength (5×10^{-5} cm), fabricating a polariser with wire spacing $\leq 5 \times 10^{-5}$ cm is very difficult. A **polaroid** is used for this.

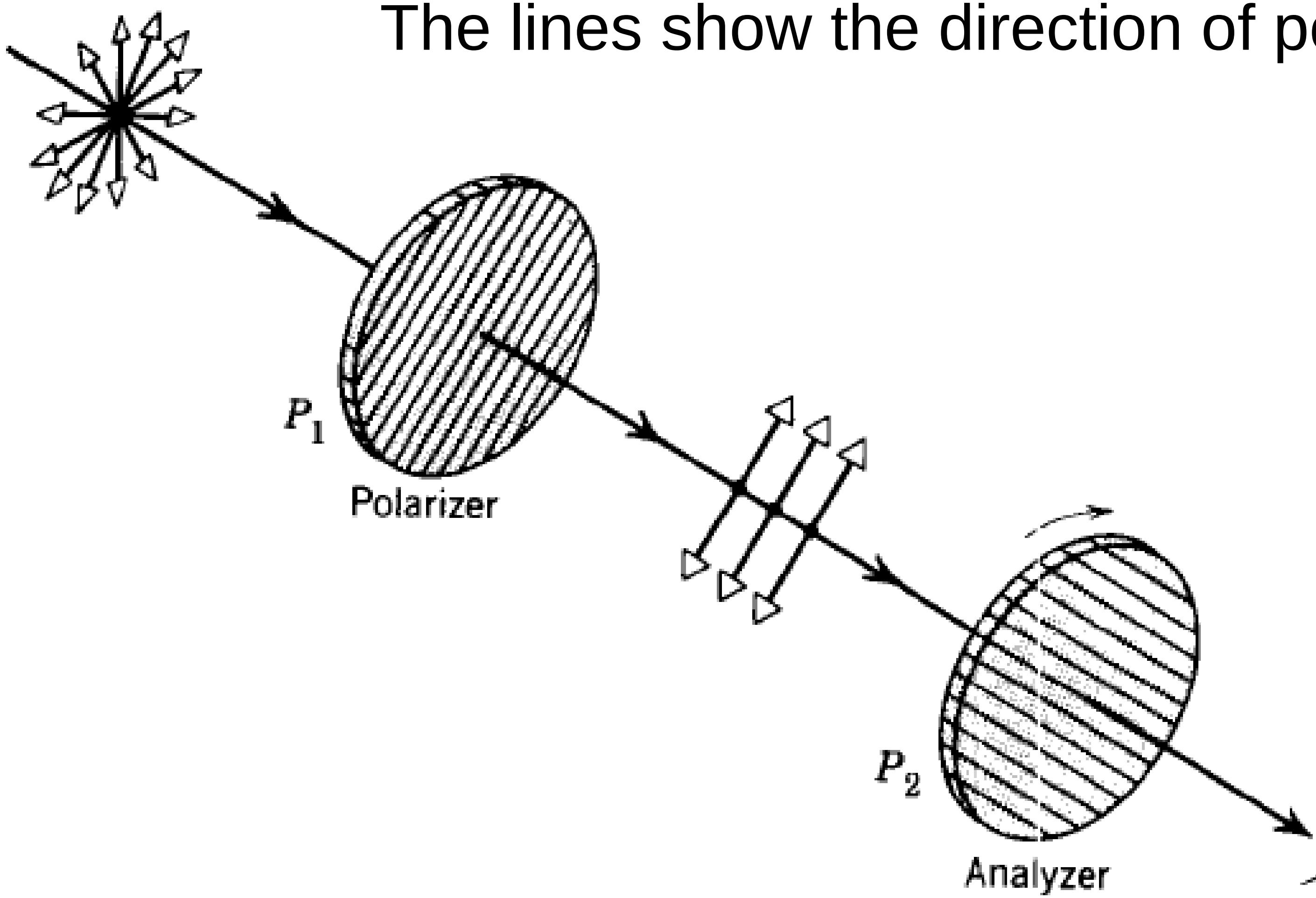
Polaroids:

- Instead of Cu wires, long chain polymer molecules that contain atoms (such as iodine) which provide high conductivity along the length of the chain.
- These long chain molecules are aligned so that they are almost parallel to one another.
- Because of the high conductivity provided by the iodine atoms, the electric field parallel to the molecules gets absorbed.
- A sheet containing such long chain polymer molecules (which are aligned parallel to one another) is known as a **Polaroid**.

When a light beam is incident on such a Polaroid, the molecules (aligned parallel to one another) absorb the component of electric field which is parallel to the direction of alignment because of the high conductivity provided by the iodine atoms; the component perpendicular to it passes through.

Thus the aligned conducting molecules act similar to the wires in the wire grid polarizer, and since the spacing between two adjacent long chain molecules is small compared to the optical wavelength, the Polaroid is usually very effective in producing linearly polarized light

The lines show the direction of polarisation.



If you start rotating the analyser, at 90^o and 270^o, the transmitted intensity will be minimum.

The transmitted intensity will be maximum when analyser is at angle of 0^o and 180^o.

Polarisation by Reflection:

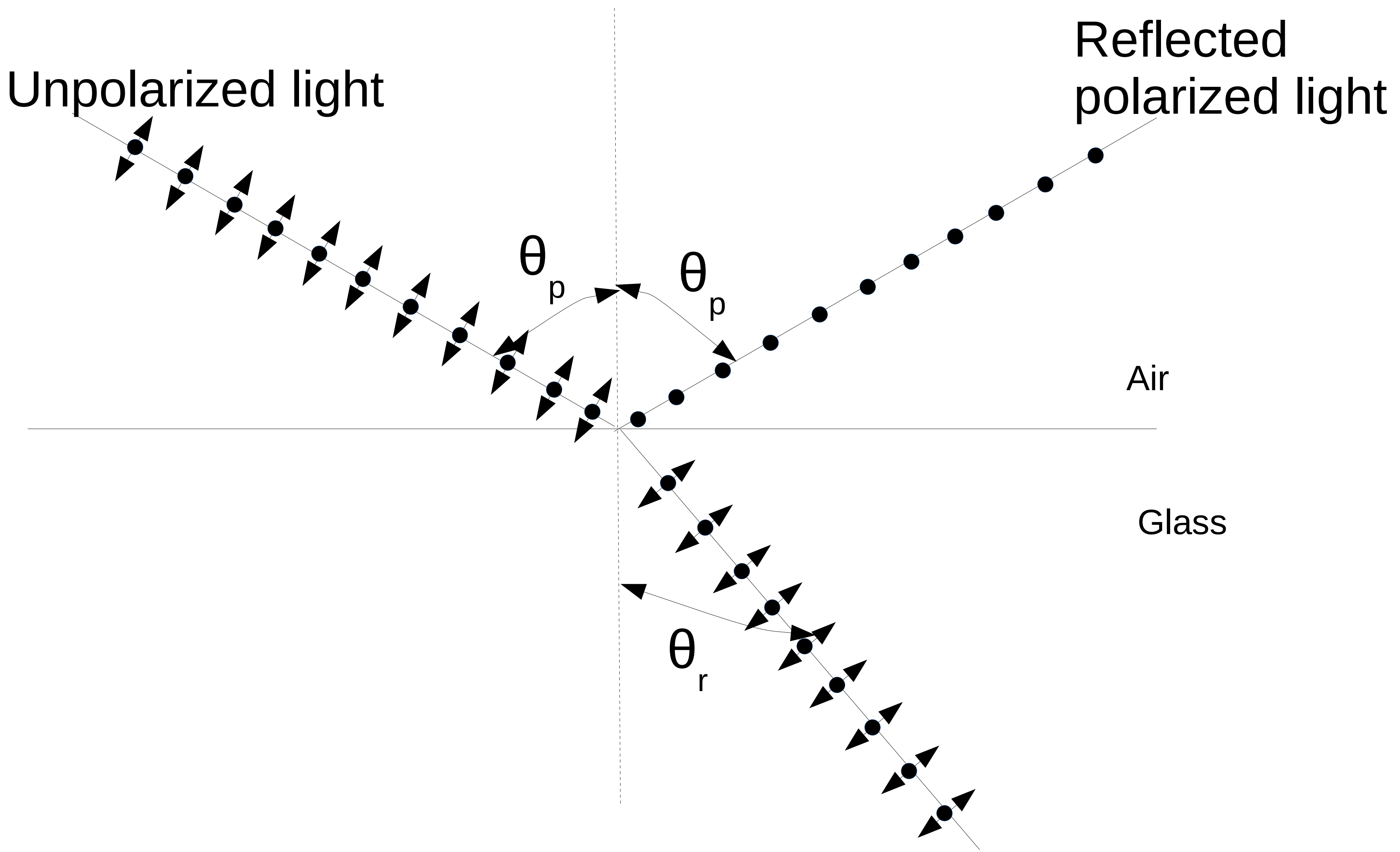
Brewster discovered that there is a particular angle of incidence at which, if unpolarised light is incident on glass or dielectric material, the reflected light is polarised.

This particular angle of incidence is also known as **Brewster** angle and is given by :

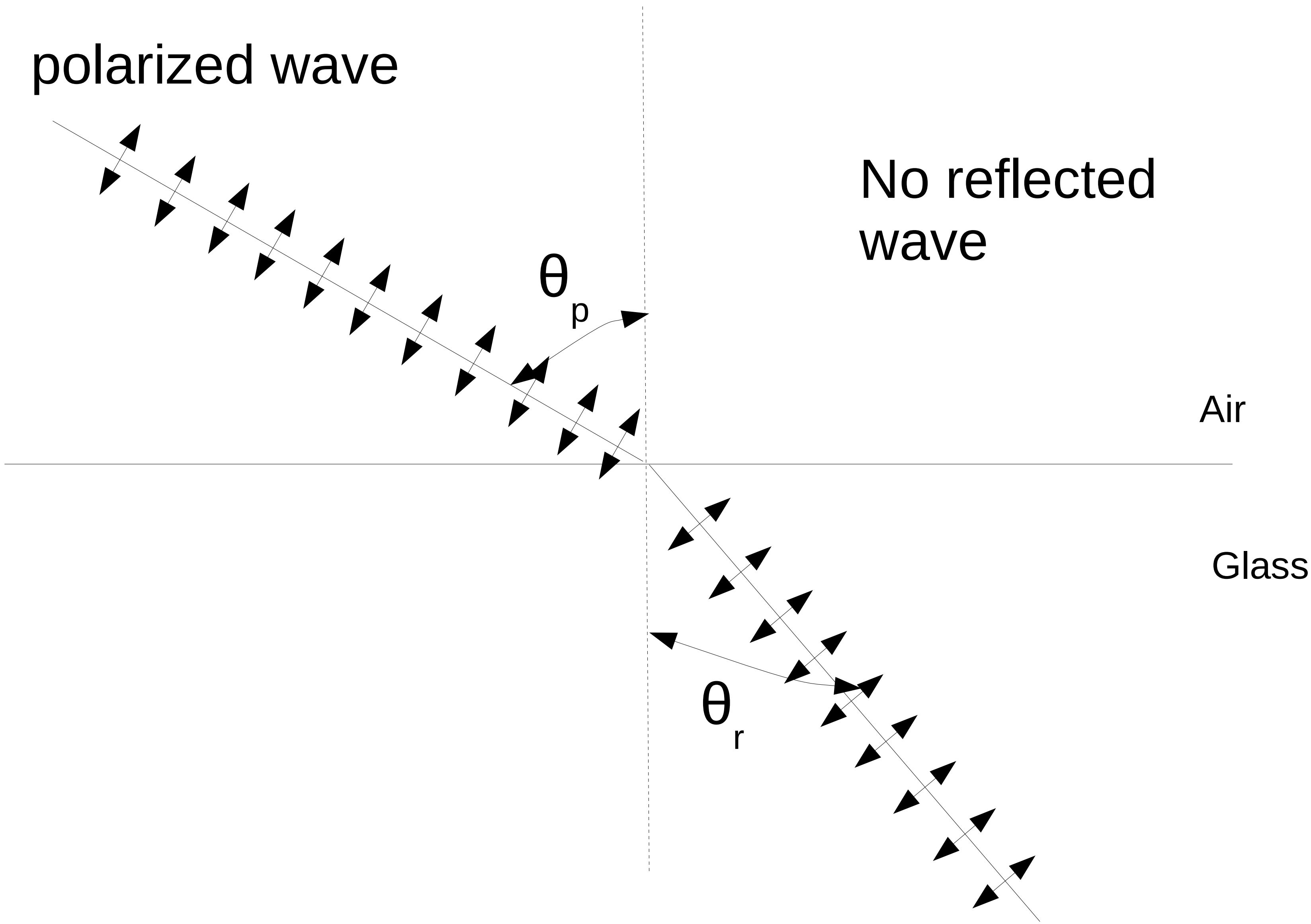
$$\theta=\theta_p=\tan^{-1}\left(\frac{n_2}{n_1}\right)$$

Using a polaroid, reflected light can be checked for polarisation. Intensity of reflected light should be zero twice in one complete rotation.

If an unpolarized light is incident at Brewster angle, then the reflected beam will be linearly polarized with its electric vector perpendicular to the plane of incidence.



If an wave polarised in plane of paper is incident at Brewster angle, then there will be no reflected beam!



Brewster angle is given by : $\theta_p = \tan^{-1}(\frac{n_2}{n_1})$

If wave is incident from air to glass, $n_1 = 1$. Therfore,

$$\theta_p = \tan^{-1}(n_2) \Rightarrow \tan(\theta_p) = n_2$$

$$\frac{\sin(\theta_p)}{\cos(\theta_p)} = n_2$$

Applying Snell's law : $\frac{\sin(\theta_p)}{\sin(\theta_r)} = n_2$

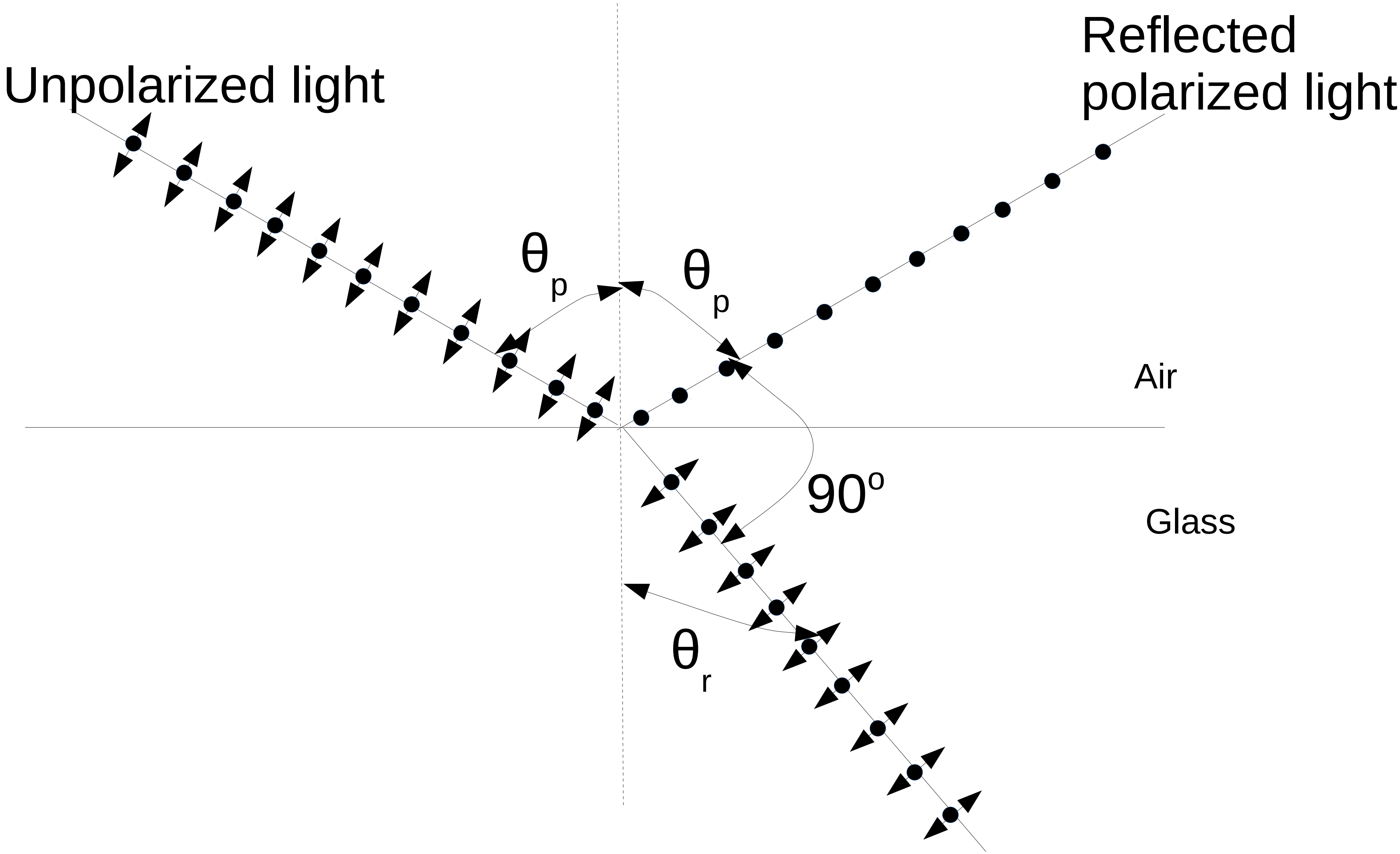
From both of these equations:

$$\frac{\sin(\theta_p)}{\sin(\theta_r)} = \frac{\sin(\theta_p)}{\cos(\theta_p)}$$

$$\Rightarrow \sin(\theta_r) = \cos(\theta_p)$$

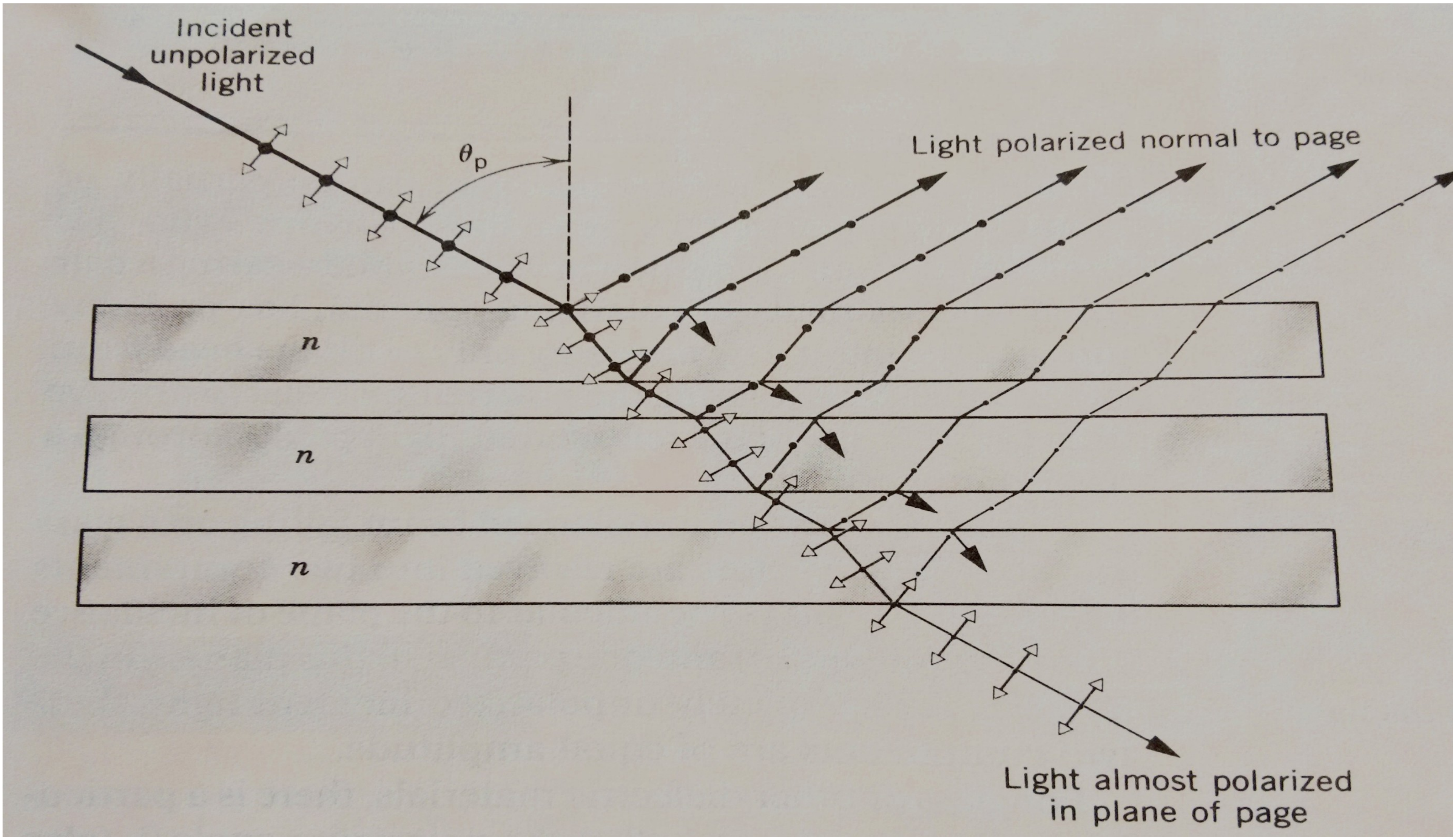
$$\Rightarrow \sin(\theta_r) = \sin(90^o - (\theta_p))$$

$$\Rightarrow \theta_r = 90^o - \theta_p \Rightarrow \theta_r + \theta_p = 90^o$$



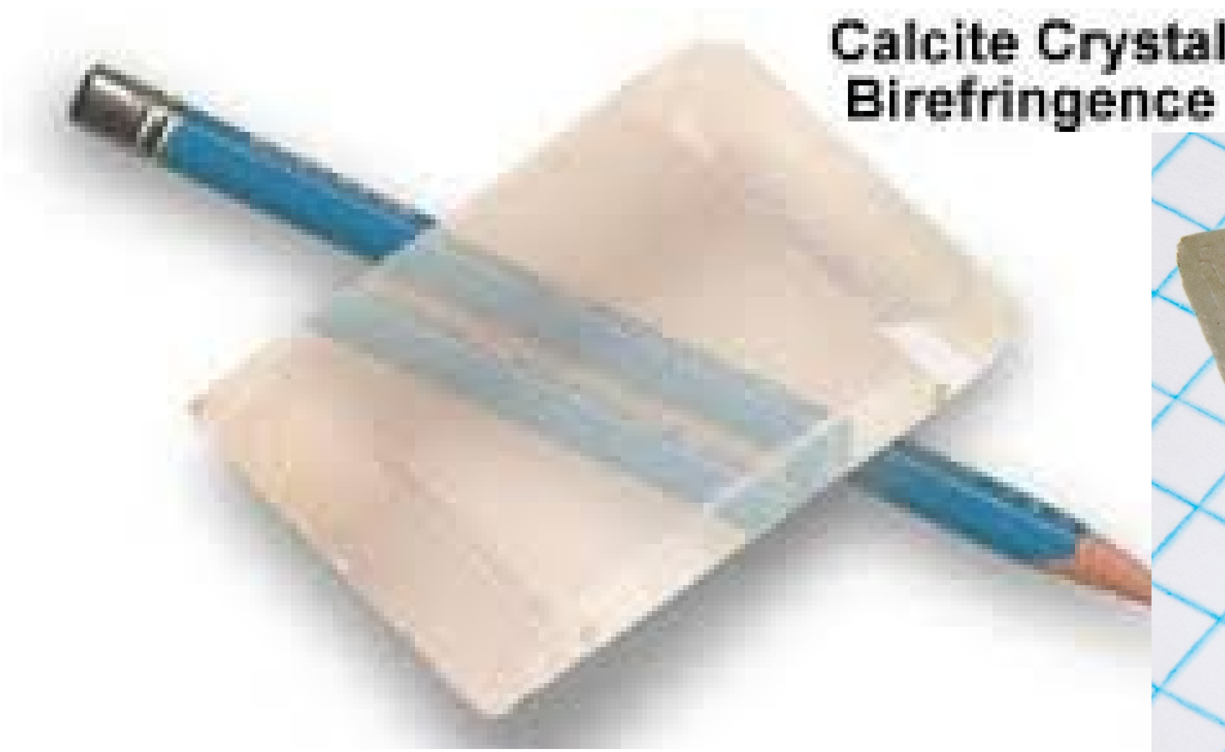
Unpolarized light
Reflected
polarized light
θp
θp
Air
90o
Glass
θr

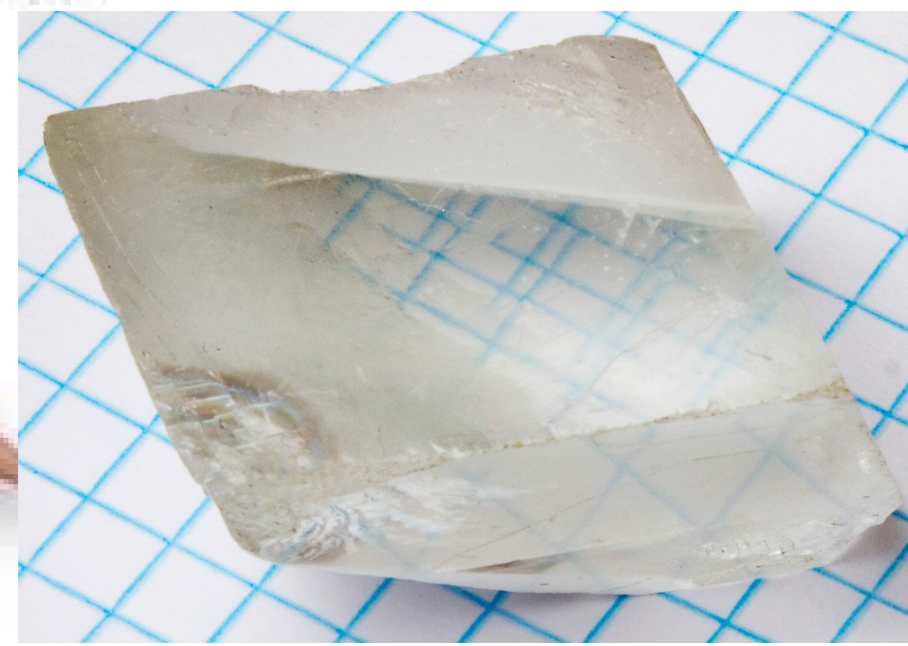
Intensity of reflected polarised light can be increased by using a pile of plates.

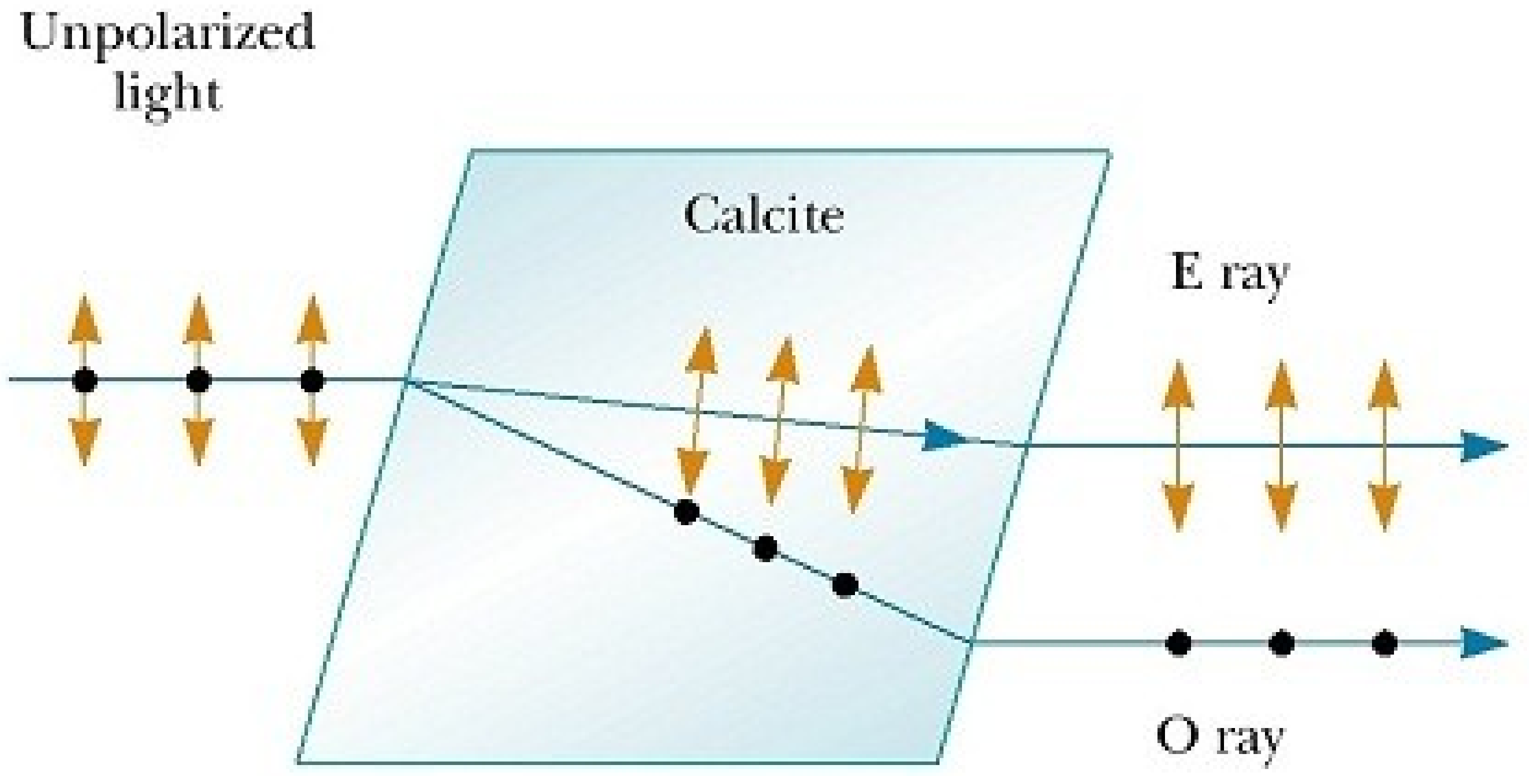


Polarisation by double refraction :

- If beam of light is passed through certain crystal like calcite ($CaCO_3$) or quartz (SiO_2), it splits into two beams. These substances are called **doubly refracting** or **birefringent**.







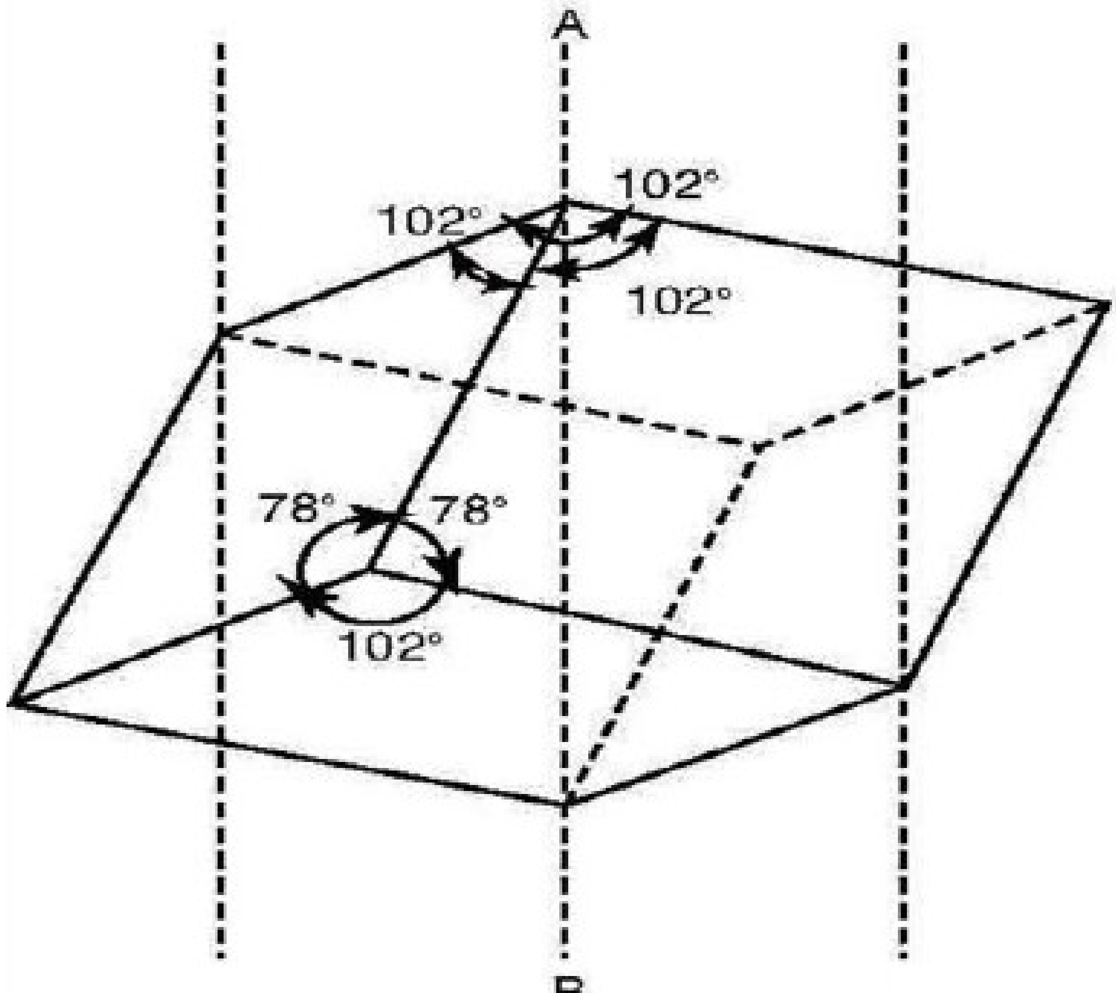
One of refracted beams obeys Snell's law and is called Ordinary ray (O-ray). The other beam doesn't obey Snell's law and is called Extraordinary ray (E-ray).

- The E-ray travels in the crystal with a speed that varies with direction and is described by ellipsoid. The O-ray travels in the crystal with a constant speed in all direction and is described by spheroid.

- The refractive index for O-rays is constant and is direction dependent for E-rays.

- In the case of Calcite and Quartz crystal, there is one direction in which there is no double refraction. This direction is called **optic axis or principal axis.** There are also biaxial crystals, no double refraction occurs in two specific directions.

- O-rays and E-rays are polarised in a direction perpendicular to each other. O-rays are polarised perpendicular to plane containing optical axis.



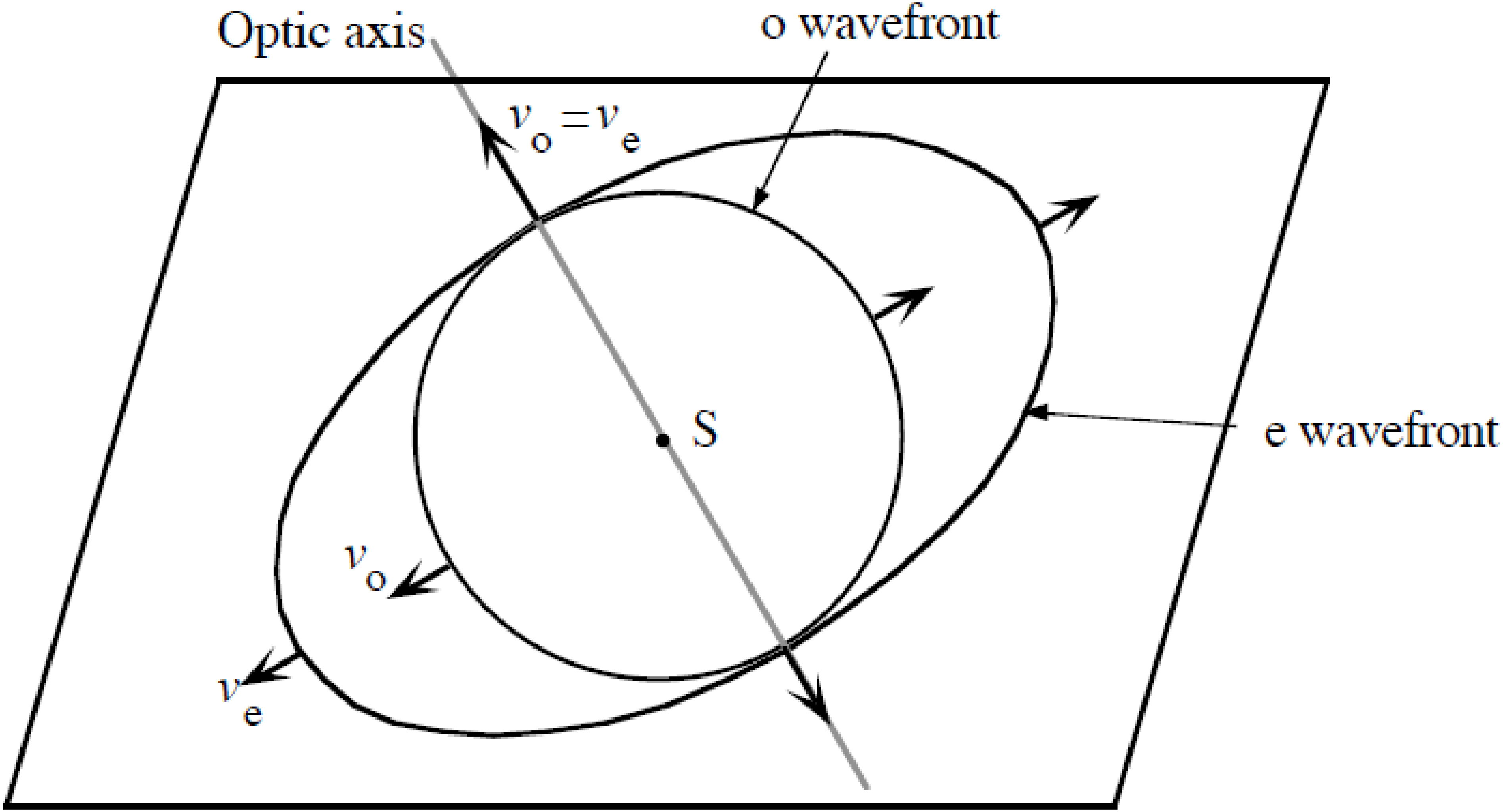
AB: Optic Axis

The **optic axis** of a calcite crystal denoted by dotted line AB. Any ray of ordinary unpolarised light incident along the optic axis or parallel to this axis does not split up into two rays.

The plane containing the optic axis and the perpendicular to the pair of opposite faces of the crystal is known as **principal section** for that pair of faces of the crystal.

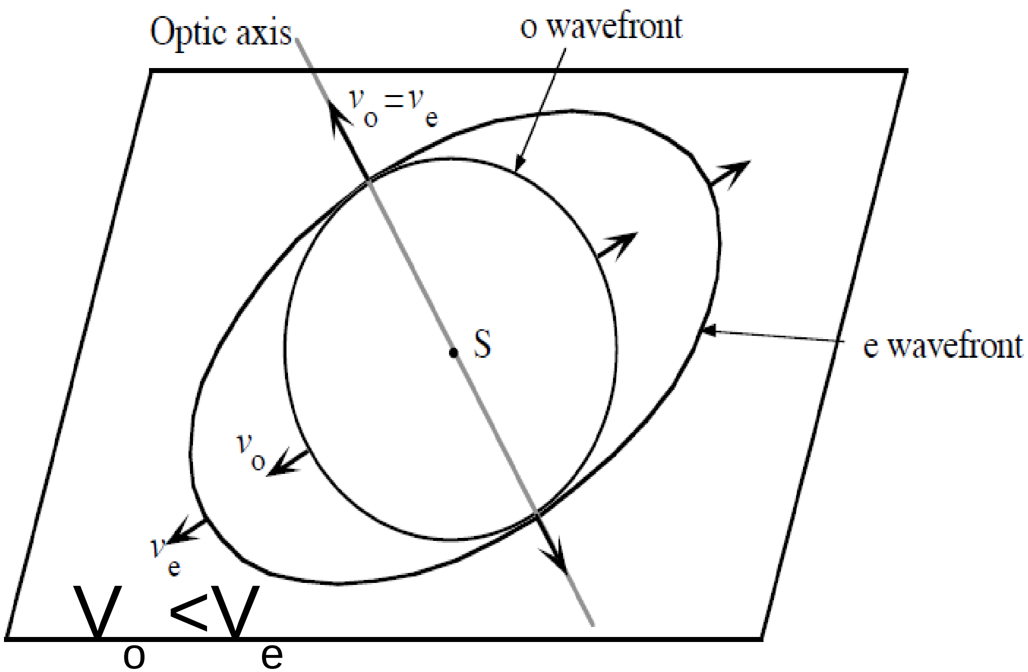
Since the crystal has six faces, for each pair of opposite faces of the crystal, there are three principal sections.

Wavefront of O- and E-rays :

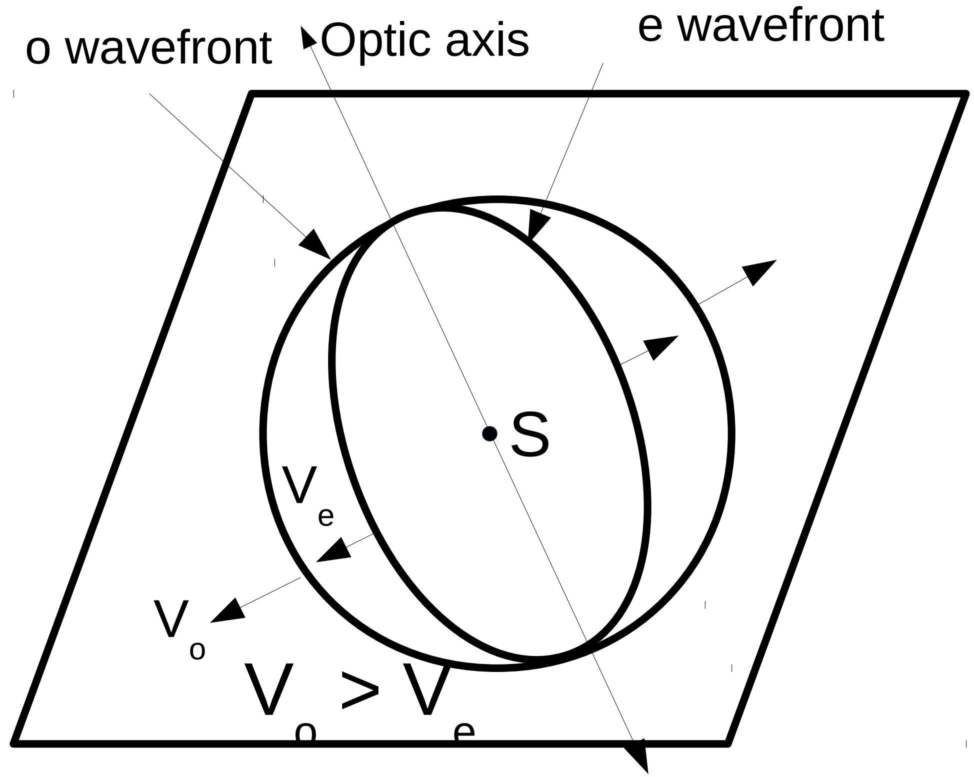


S is the point from where light is starting at same time in double refracting crystal.

For negative uniaxial crystals (like calcite) in which the velocity of O-ray is less than the velocity of E-ray, sphere lies inside the ellipsoid. However, for positive uniaxial crystals (like quartz) the ellipsoid lies inside the sphere since in this case the velocity of O-ray is greater than the velocity of E-ray.



Negative crystal



Positive crystal

Nicol Prism : Based on **double refraction**

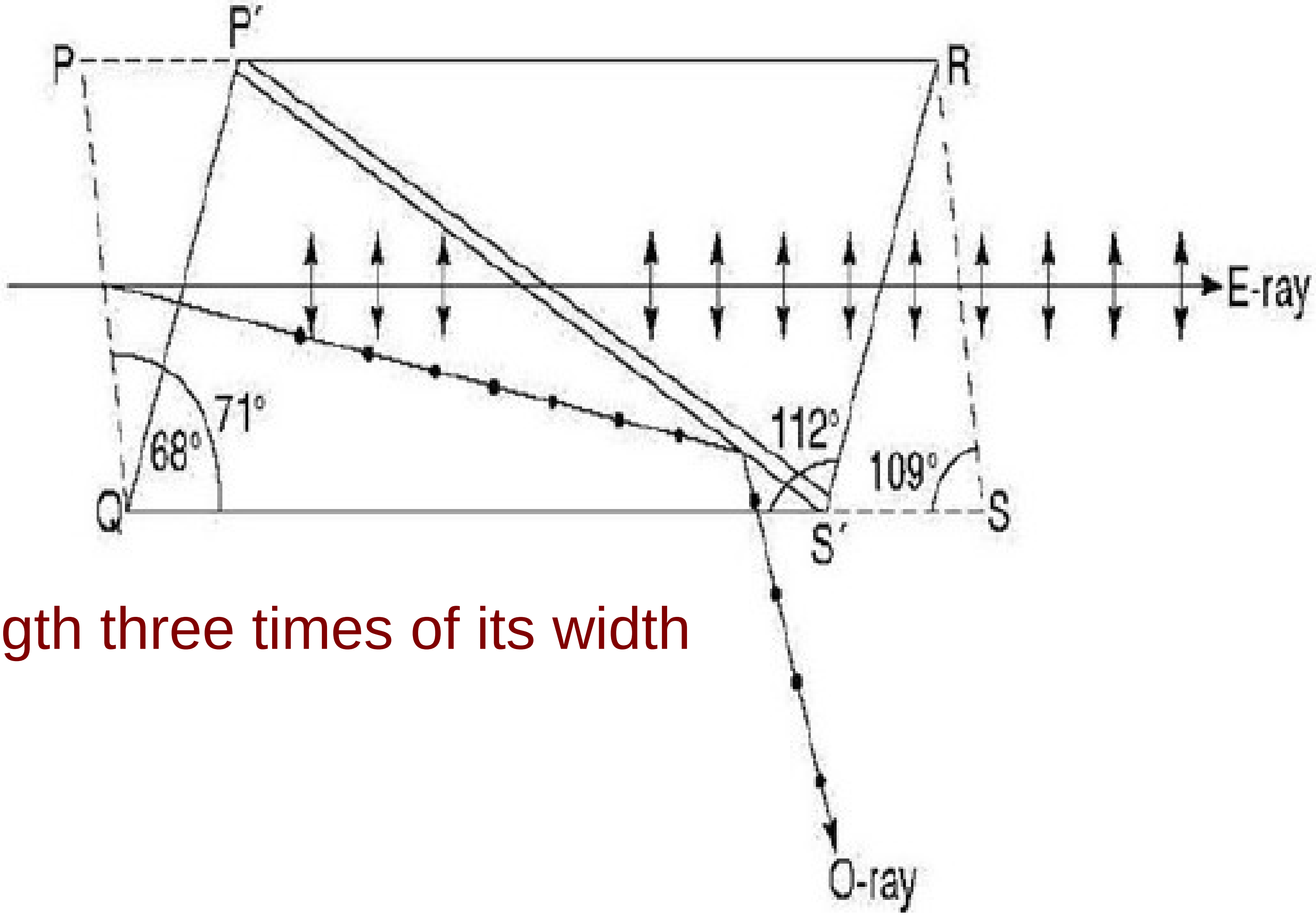
Nicol prism is an optical device which is used for producing and analyzing plane polarized light in practice.

Calcite crystal is cut along a diagonal and cemented back together with special cement called **Canada balsam**.

$\mu_o = 1.65836$, $\mu_{\text{canada balsam}} = 1.55$, $\mu_e = 1.48641$

Birefringence (B) = $|\mu_e - \mu_o|$

where μ_e and μ_o are the refractive indices experienced by the extraordinary and ordinary rays, respectively.



Length three times of its width

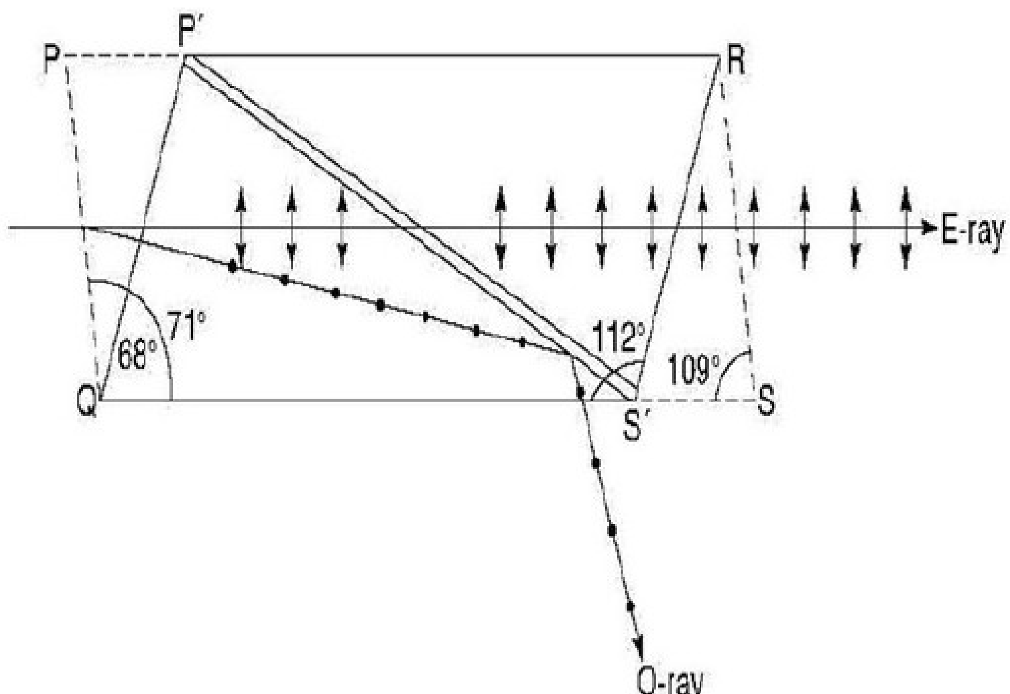
Its end faces PQ and RS are cut such that the angles in the principal section become 68° and 112° in place of 71° and 109° (naturally occurring crystal).

Working of Nicol Prism :

- When a beam of unpolarised light is incident on the face P′Q, it gets split into O-ray and E-ray.
- These two rays are plane polarised rays, whose vibrations are at right angles to each other. The refractive index of Canada balsam cement being 1.55 lies between those of ordinary and extraordinary (1.65836 and 1.4864, respectively).
- Canada Balsam layer acts as an optically rarer medium for the ordinary ray and it acts as an optically denser medium for the extraordinary ray.

- When ordinary ray of light travels in the calcite crystal and enters the Canada balsam cement layer, it passes from denser to rarer medium. Moreover, the angle of incidence is greater than the critical angle, the incident ray is totally internally reflected from the crystal and only extraordinary ray is transmitted through the prism.

- Therefore, fully plane polarised wave is generated with the help of Nicol prism.



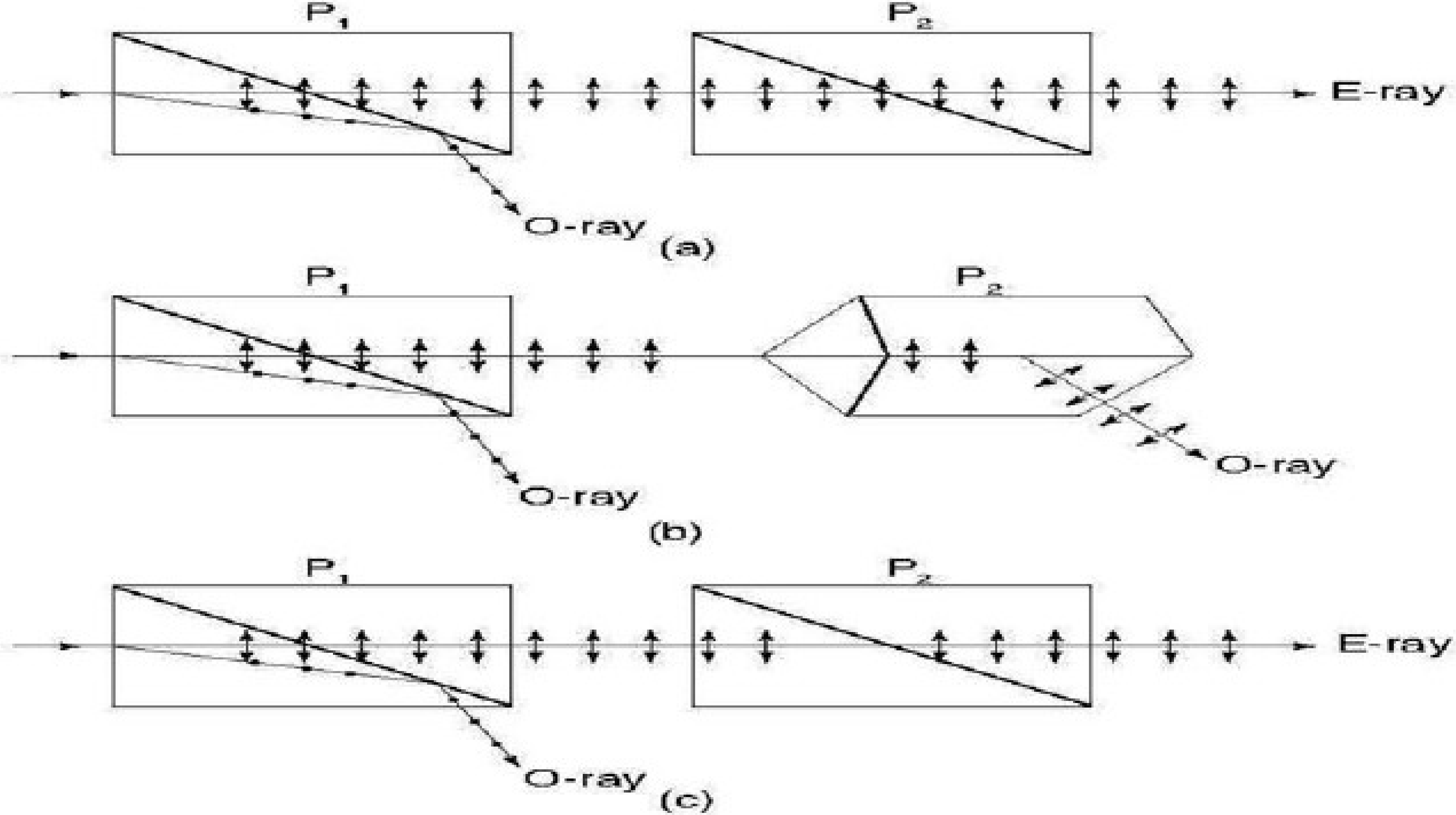
Nicol Prism as a Polariser and an Analyser :

- In order to produce and analyse the plane polarised light, two nicol prisms are arranged.

- When a beam of unpolarised light is incident on the nicol prism, emergent beam from the prism is obtained as plane polarised, and which has vibrations parallel to the principal Section.

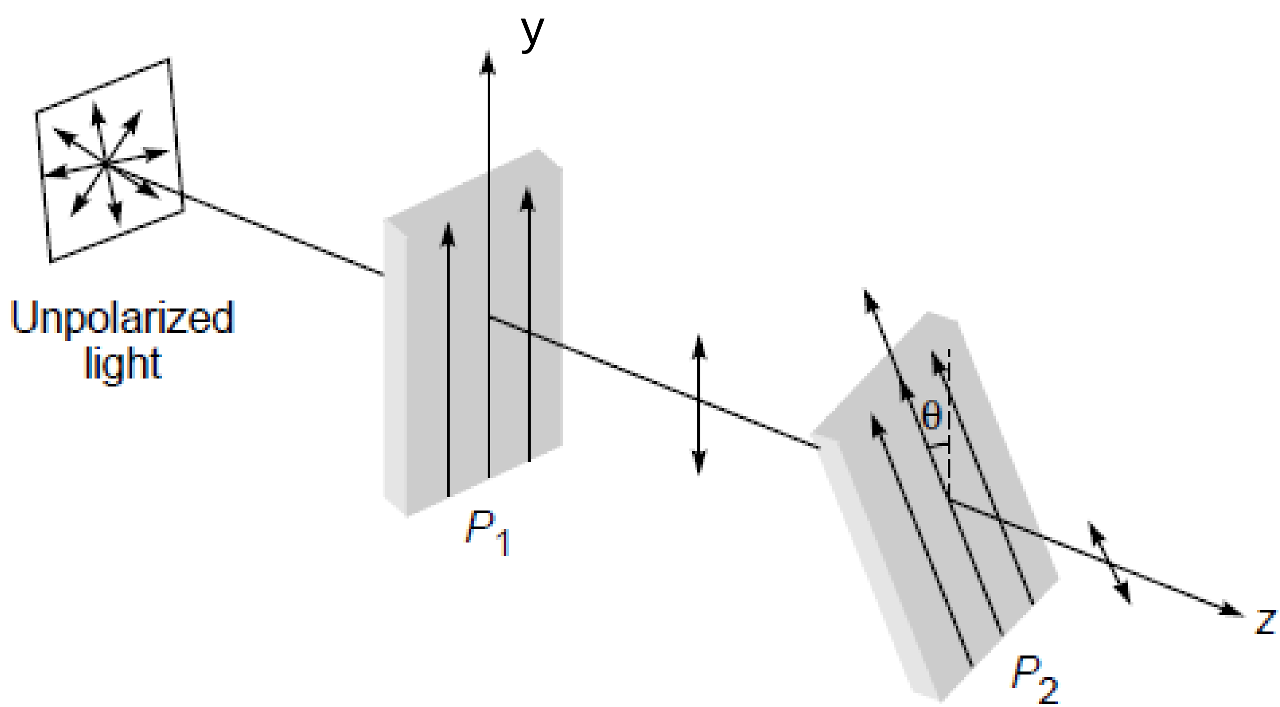
- This prism is therefore known as polariser. If this polarised beam falls on another parallel nicol prism P2, whose principal section is parallel to that of P1, then the incident beam will behave as E-ray inside the nicol prism P2 and gets completely transmitted through it.

- This way the intensity of emergent light will be maximum.


P1
P2
E-ray
O-ray
(a)
P1
P2
O-ray
O-ray
(b)
P1
P2
E-ray
O-ray
(c)

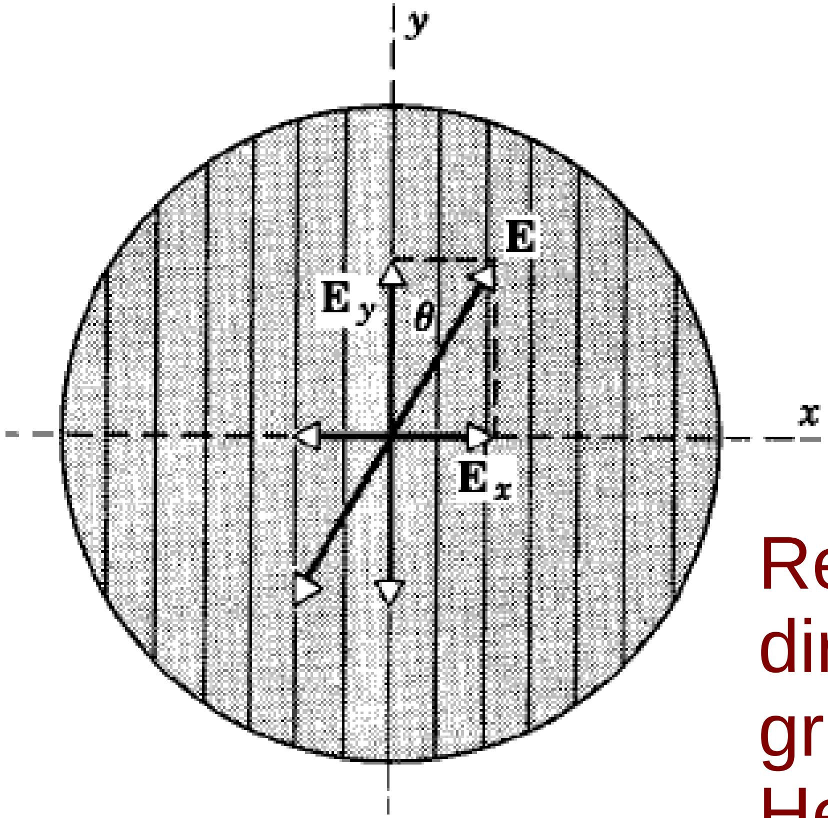
- Now the nicol prism P2 is rotated about its axis, then we note that the intensity of emerging light decreases and becomes zero at 90° rotation of the second prism (Fig. b).
- In this position, the vibrations of E-ray become perpendicular to the principal section of the analyser (nicol prism P2).
- Hence, this ray behaves as O-ray for prism P2 and it is totally internally reflected by Canada balsam layer. This fact can be used for detecting the plane polarised light and the nicol prism P2 acts as an analyser.
- If the nicol prism P2 is further rotated about its axis, the intensity of the light emerging from it increases and becomes maximum for the position when principal section of P2 is again parallel to that of P1 (Fig. c). Hence, the nicol prisms P1 and P2 acts as polariser and analyser, respectively.

Malus' law :



polarizer P_1 which has a pass axis parallel to the y axis; i.e., if an unpolarized beam propagating in the z direction is incident on the polarizer, then the electric vector associated with the emergent wave will oscillate along the y axis.

Consider the incidence of the y-polarized beam on the Polaroid P_2 whose pass axis makes an angle θ with the y axis. If the amplitude of the incident electric field is E , then the amplitude of the wave emerging from the Polaroid P_2 will be E cos(θ),



Only E_y will be transmitted, E_x will be absrobed.

$E_y = E_0 \cos\theta$

Remember lines here show direction of polarisation not wire grid or chain molecules direction. Here, wire grid or chain molecules are aligned along x-axis.

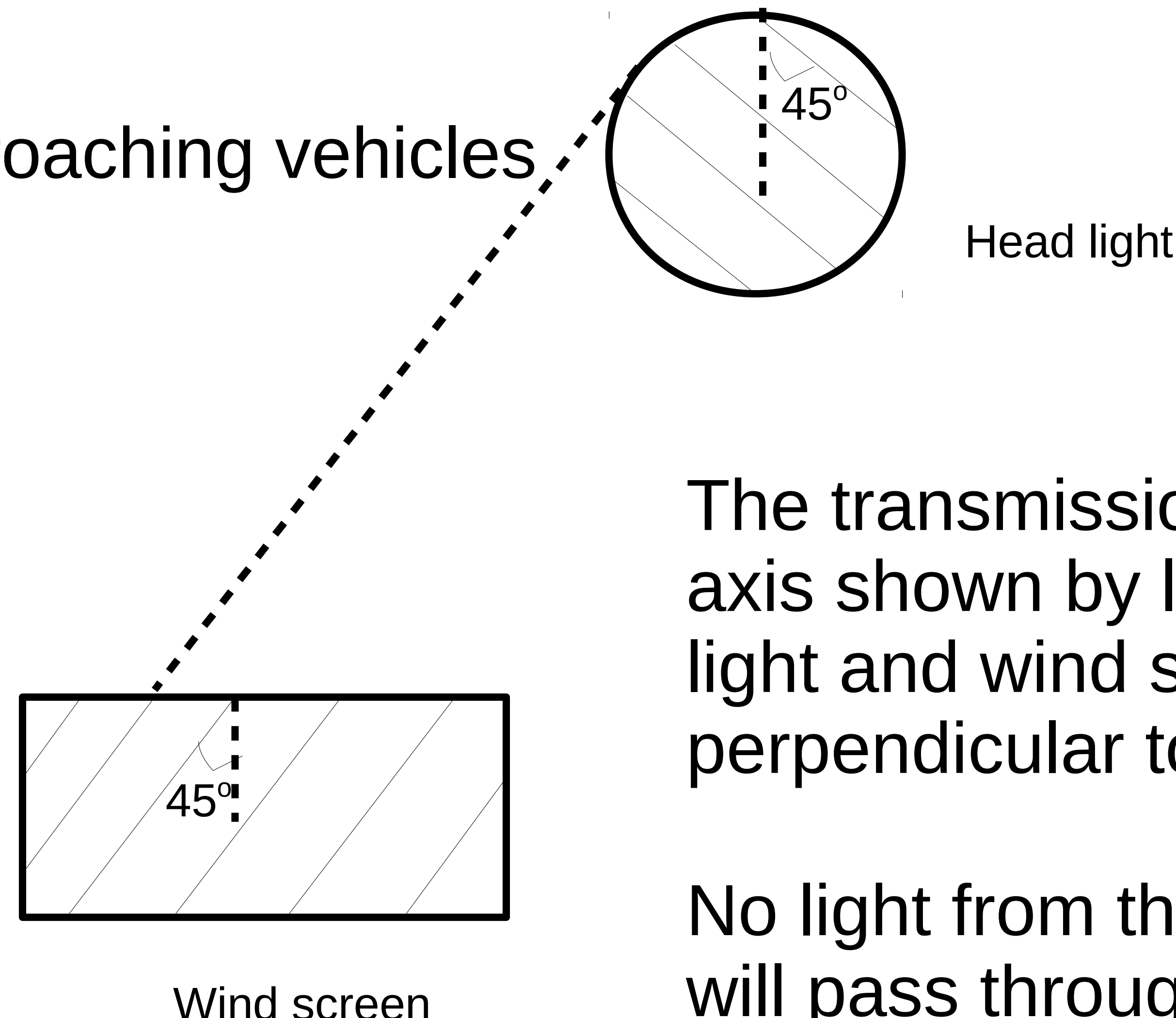
The intensity of the emerging beam will be given by

$I = I_0 \cos^2(\theta)$ **Malus' law**

where I_0 represents the intensity of the emergent beam when the pass axis of P_2 is also along the x axis (i.e., when $\theta = 0$).

Anti-glare automobile headlights :

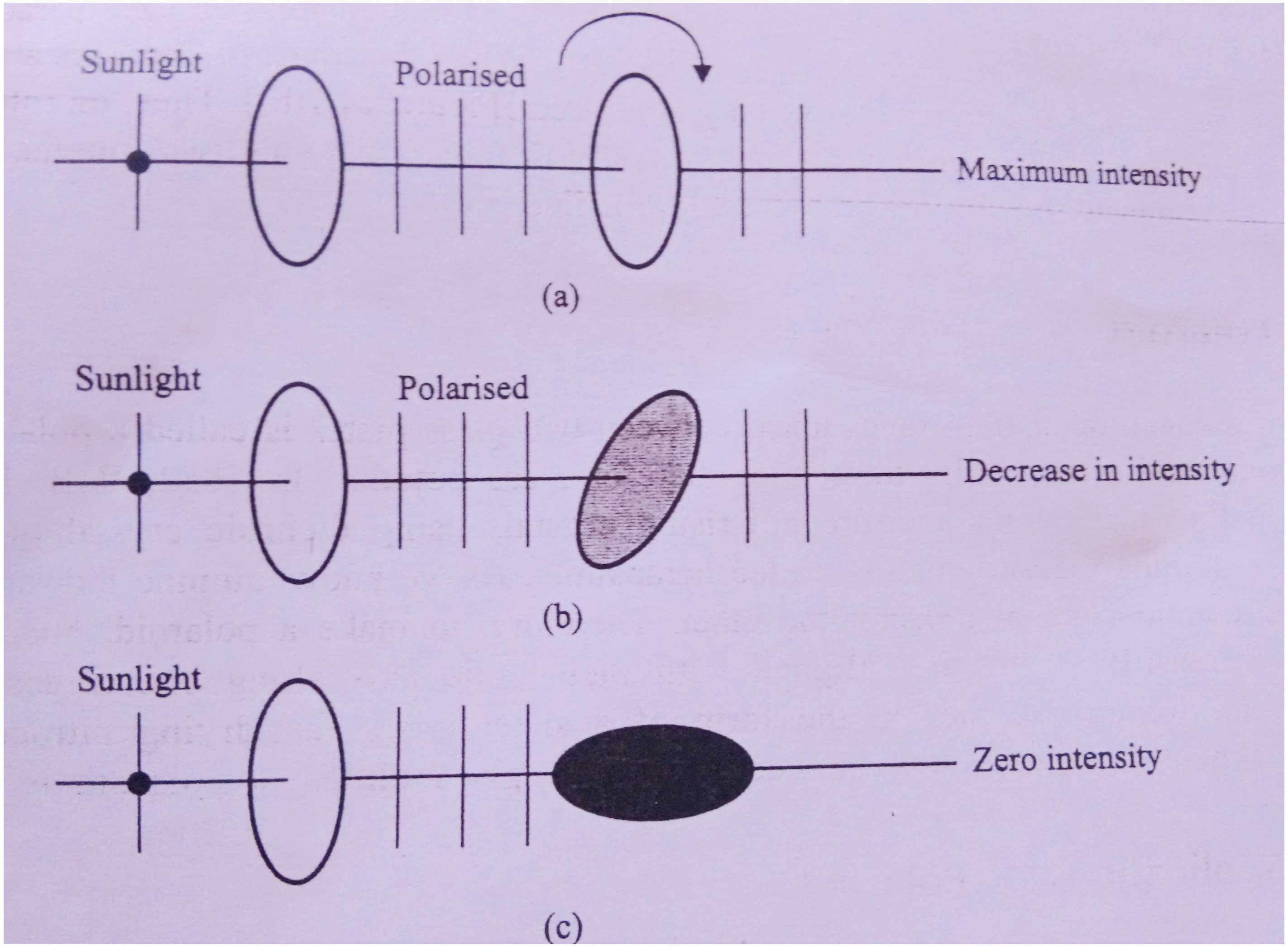
Two approaching vehicles



The transmission or pass axis shown by lines in head light and wind screen are perpendicular to each other.

No light from the head light will pass through the Wind screen.

Adjustable tint windows :



By adjusting relative orientation of 2 polaroids, the light intensity is adjusted in tint windows.