UPH004 – Applied Physics

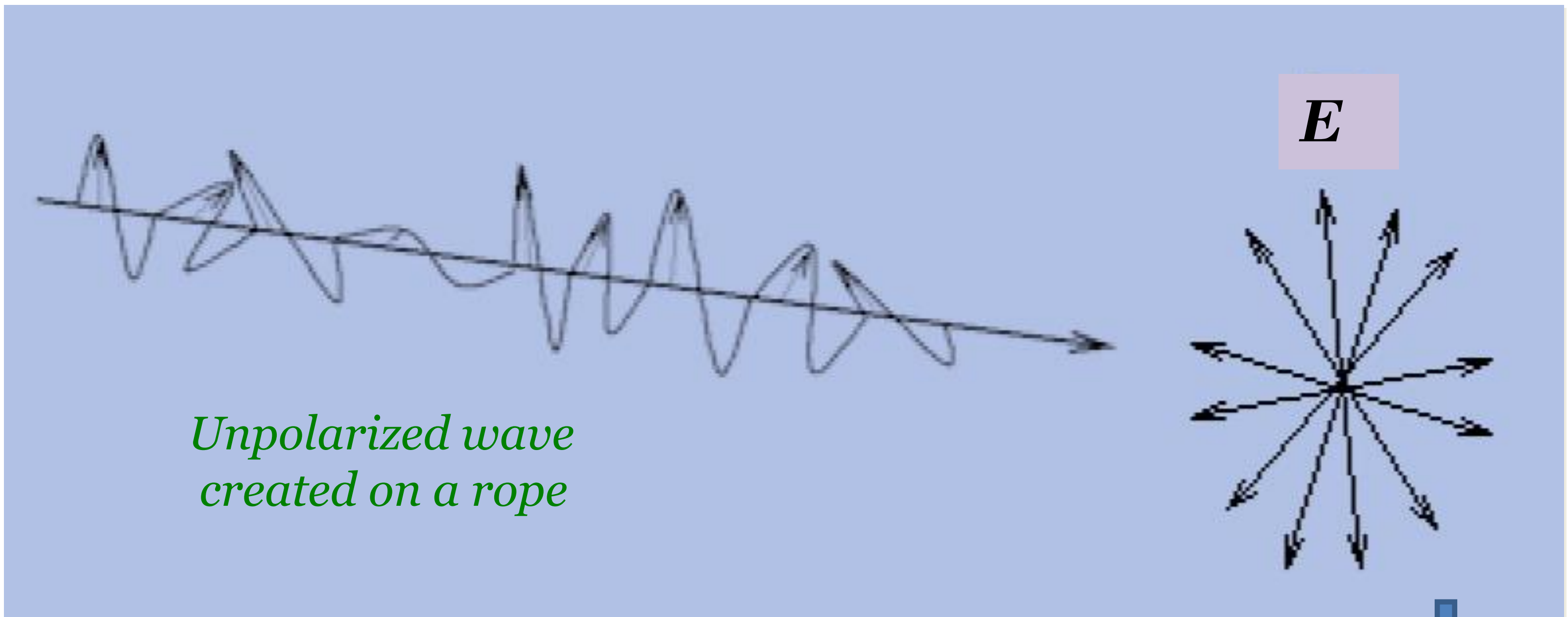
Polarization

(Semester: Jan – June 2023)

- **What is polarization?**
- **A few methods to polarize light**
- **Applications**

What if we give an impulse to one end of the rope in random direction after a short interval of time?

Unpolarized wave



Electric fields in the unpolarized light

Natural light, like most other common sources of visible light, is produced independently by a large number of atoms or molecules whose emissions are uncorrelated and generally of random polarizations.

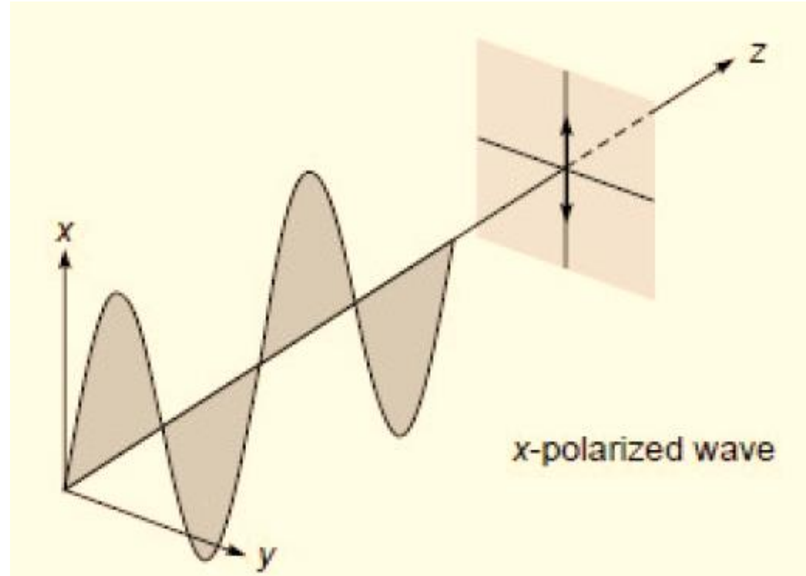
What type of waves can be polarized?

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

Linearly polarized wave

❖ *Wave on a rope with displacements of it's element sinusoidally varying along x axis.*

❖ *Or, electric field in the electromagnetic field fluctuating sinusoidally along x axis.*



❖ *Wave on a rope with displacements of it's element sinsuoidally varying along y axis.*

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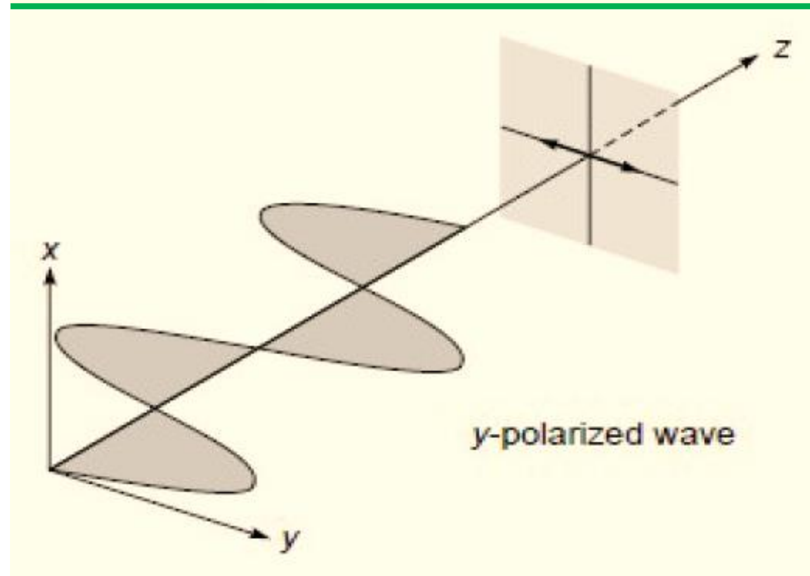
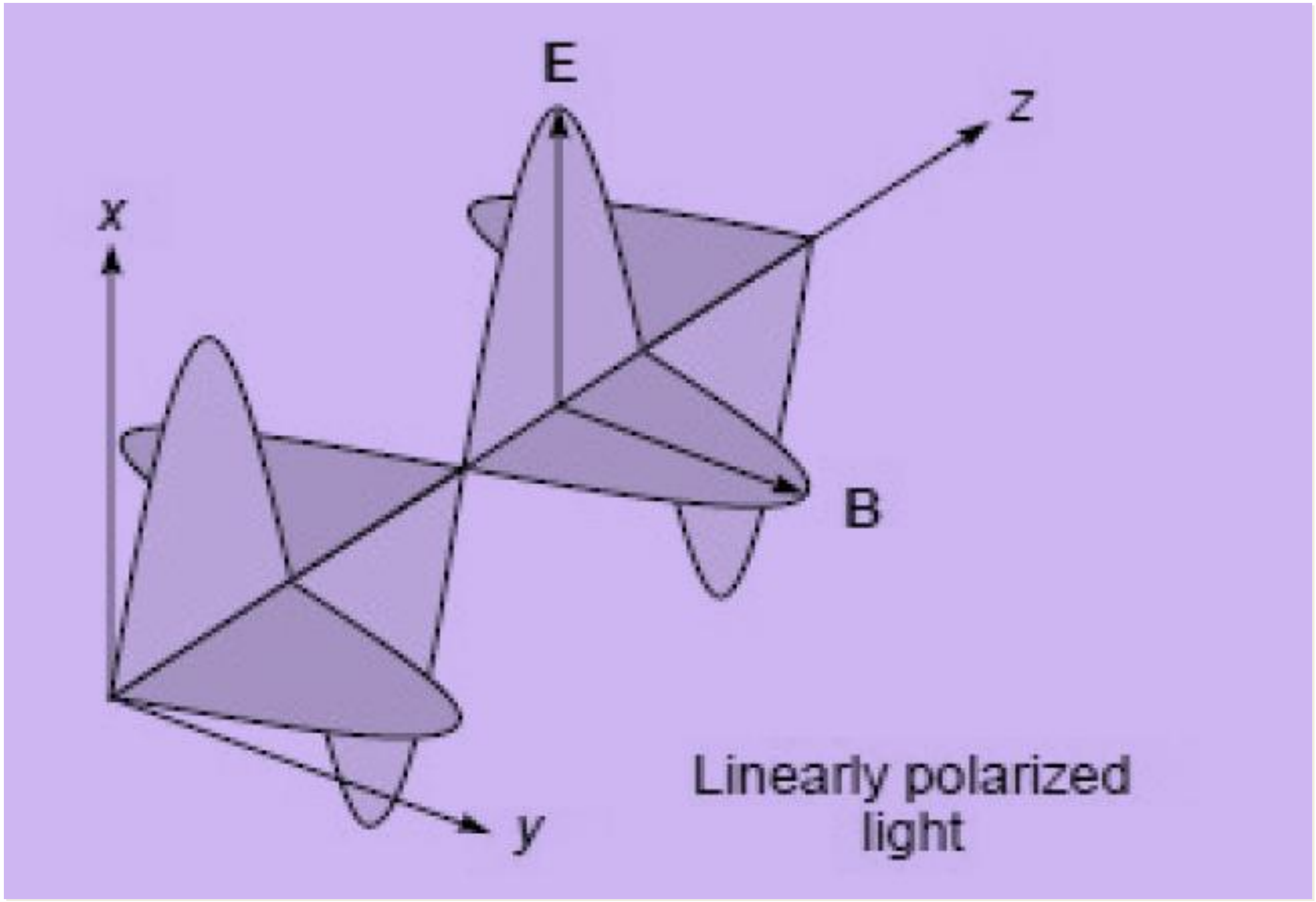
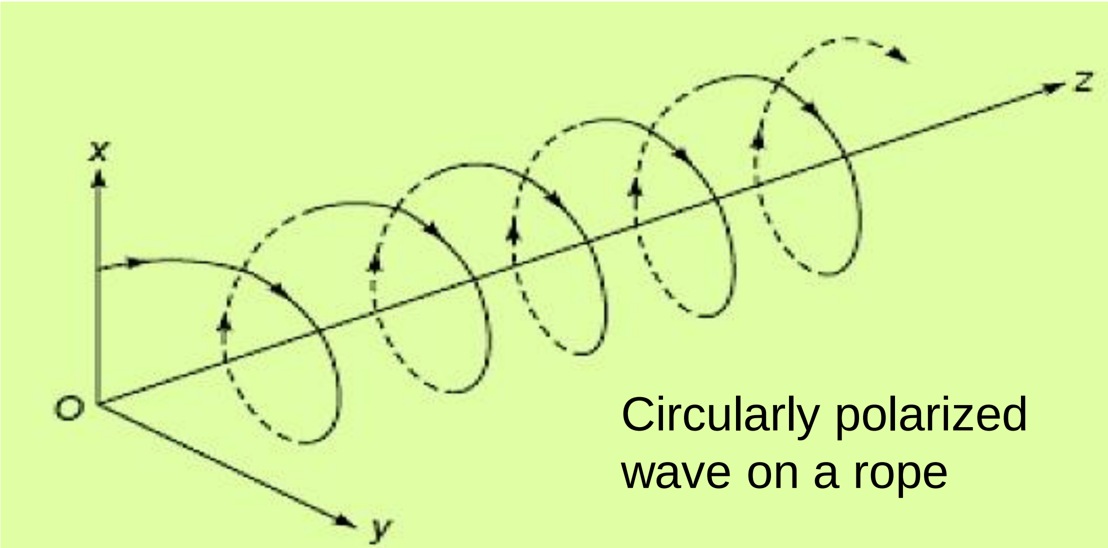


Linearly polarized light

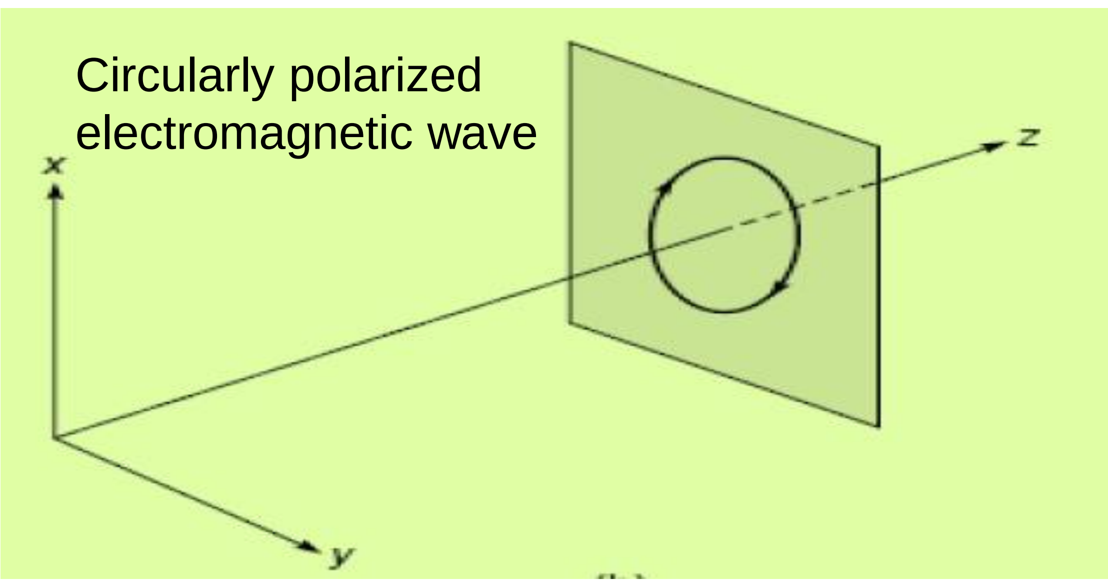


The direction of polarization of an electromagnetic wave is taken to be along the direction of oscillating electric field.

Circularly polarized wave



Circularly polarized wave on a rope



Circularly polarized electromagnetic wave

Suppose

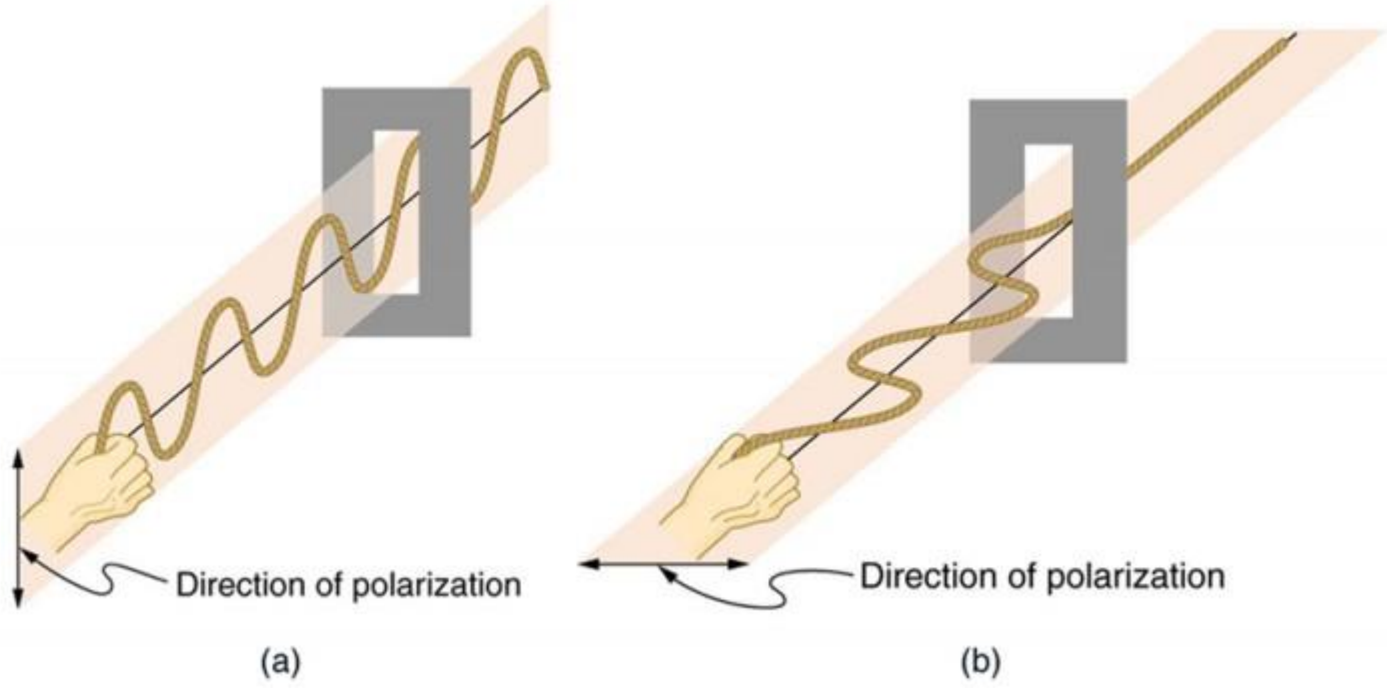
❖ The phase difference between two linearly polarize waves is $\pi/2$.

❖ and the displacements or electric fields associated with the two waves are perpendicular to each other.

Then, the two wave combine to give what is known as circularly polarized wave.

How to polarize a wave?

What if we introduce a slit in the path?

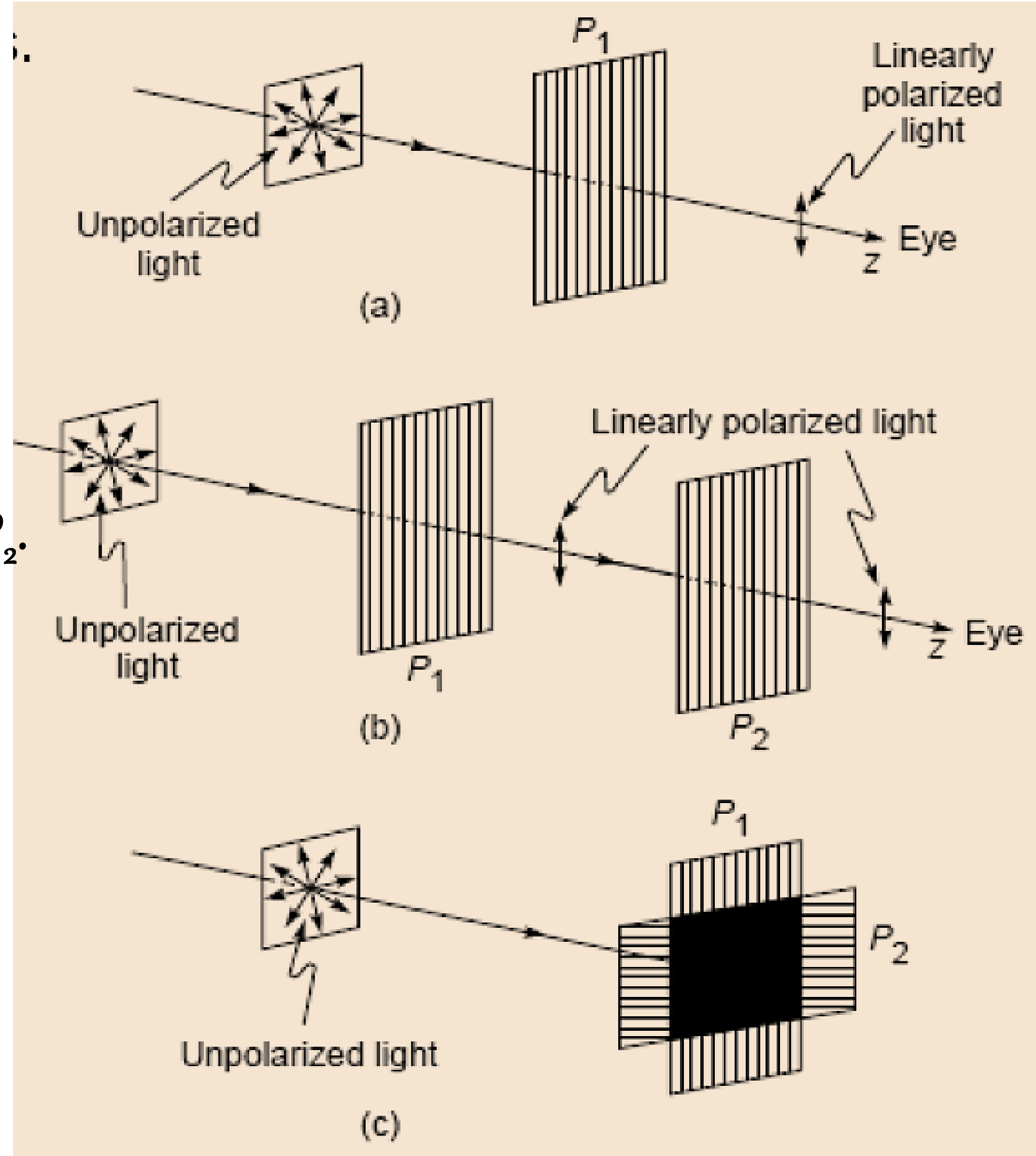


If a longitudinal wave were propagating through string, the amplitude of transmitted wave would have been completely unaffected.

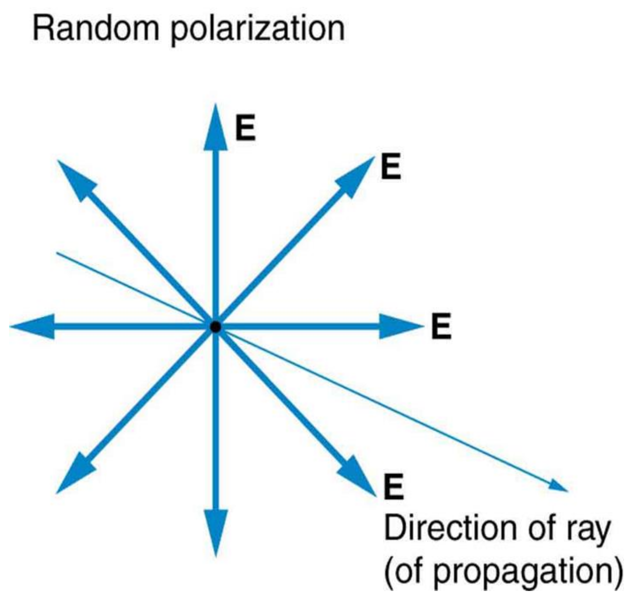
P_1 and P_2 are polaroids.

If P_1 and P_2 (transmission axis) are parallel to each other, light intensity will be maximum after P_2.

If P_1 and P_2 are perpendicular to each other, light intensity is minimum after P_2.

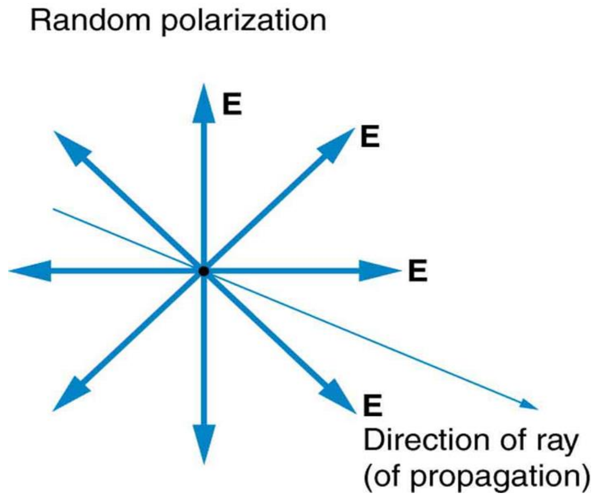


Representation of unpolarized light

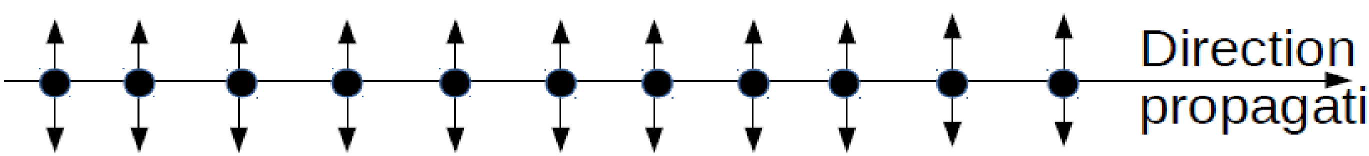


Important to note:
In unpolarized light, at any instant of time at one location there is a definite direction to the electric and magnetic fields, but the polarization changes very rapidly in time.

Representation of unpolarized light



If E is represented in x and y direction:



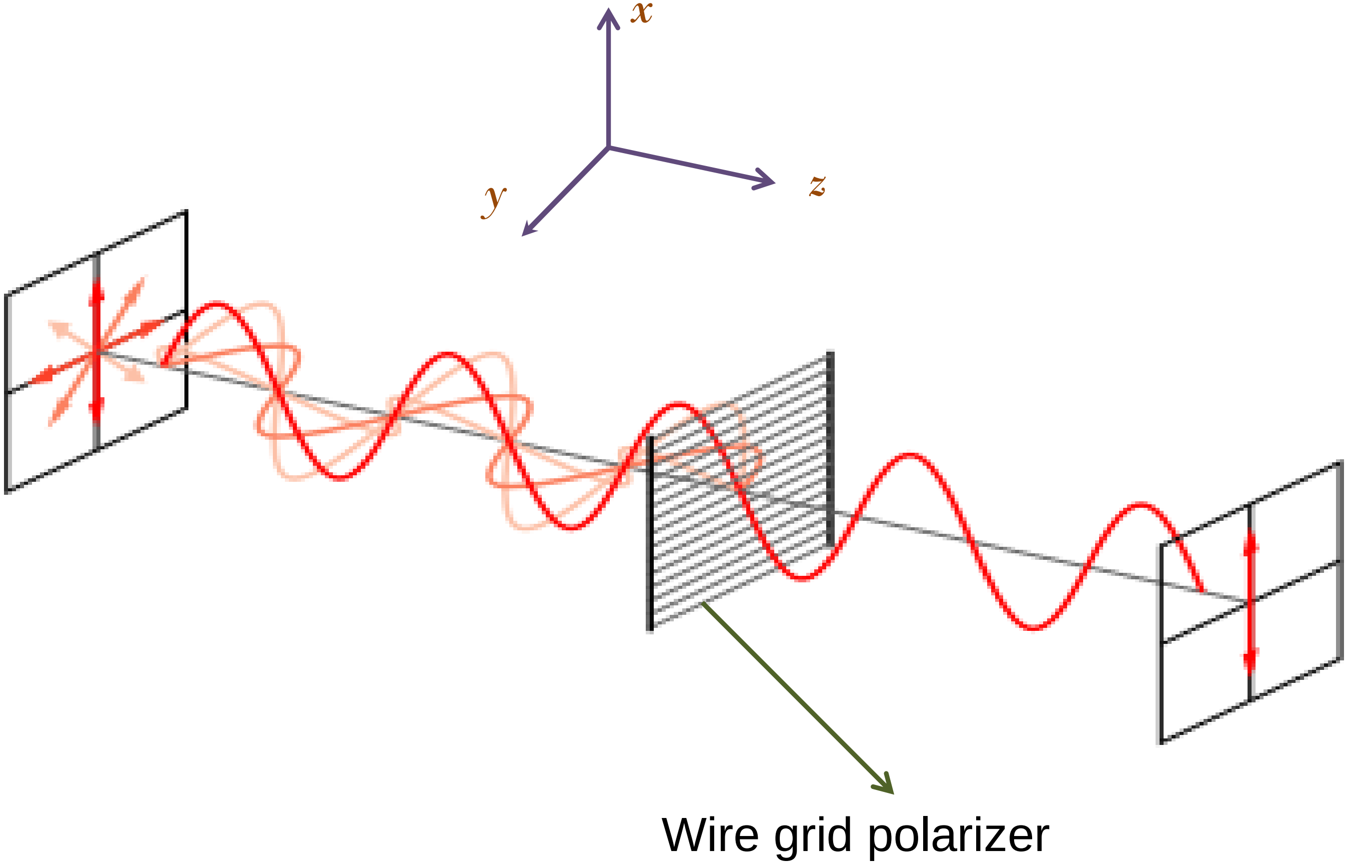
Represents component out of plane

Represents component in the plane

Production of Linearly Polarised light:

- The wire grid polarizer
- The Polaroid.
- Polarization by reflection.
- Polarization by double refraction.

The wire grid polarizer



The wire grid polarizer

- Very thin copper wires placed parallel to each other.
- When an unpolarized light is incident on it, component of light with electric field along the length of the wire is reflected and absorbed. This is because electrons in wire start moving in electric field and energy associated with electric field is lost in Joule heating of wires.
- The wires are very thin. The light component with electric field perpendicular to wires is unable to move the electrons because electrons don't have much space to move. The light is not reflected much. Therefore, the electric field passes through without much attenuation.
- The result is that outgoing wave is linearly polarized with electric vector in a direction perpendicular to the wires.

The wire grid polarizer

Further points to note:

- ✓ It will work (E will be almost completely attenuated) if the spacing between is $\leq\lambda$.
- ✓ Wire grid polarizer is easy to fabricate for a microwave (~1cm) because spacing needed between wires ~1cm.
- ✓ Visible light waves have small wavelength (5×10^{-5} cm), fabricating a polaziser with wire spacing $\leq 5 \times 10^{-5}$ cm is very difficult. A polaroid is used for this.

Polaroid

- Substance containing 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.

Polaroid and wire grid polarizer

- ✓ When a light beam is incident on a polaroid, the molecules (aligned parallel to one another) absorb the component of electric field which is parallel to the direction of alignment. This is again 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.

Polarization by reflection

There exists an angle at which, if unpolarized light is incident on glass or dielectric material, the reflected light is polarized. This particular angle of incidence is also known as **Brewster** angle.

The Brewster angle is given by

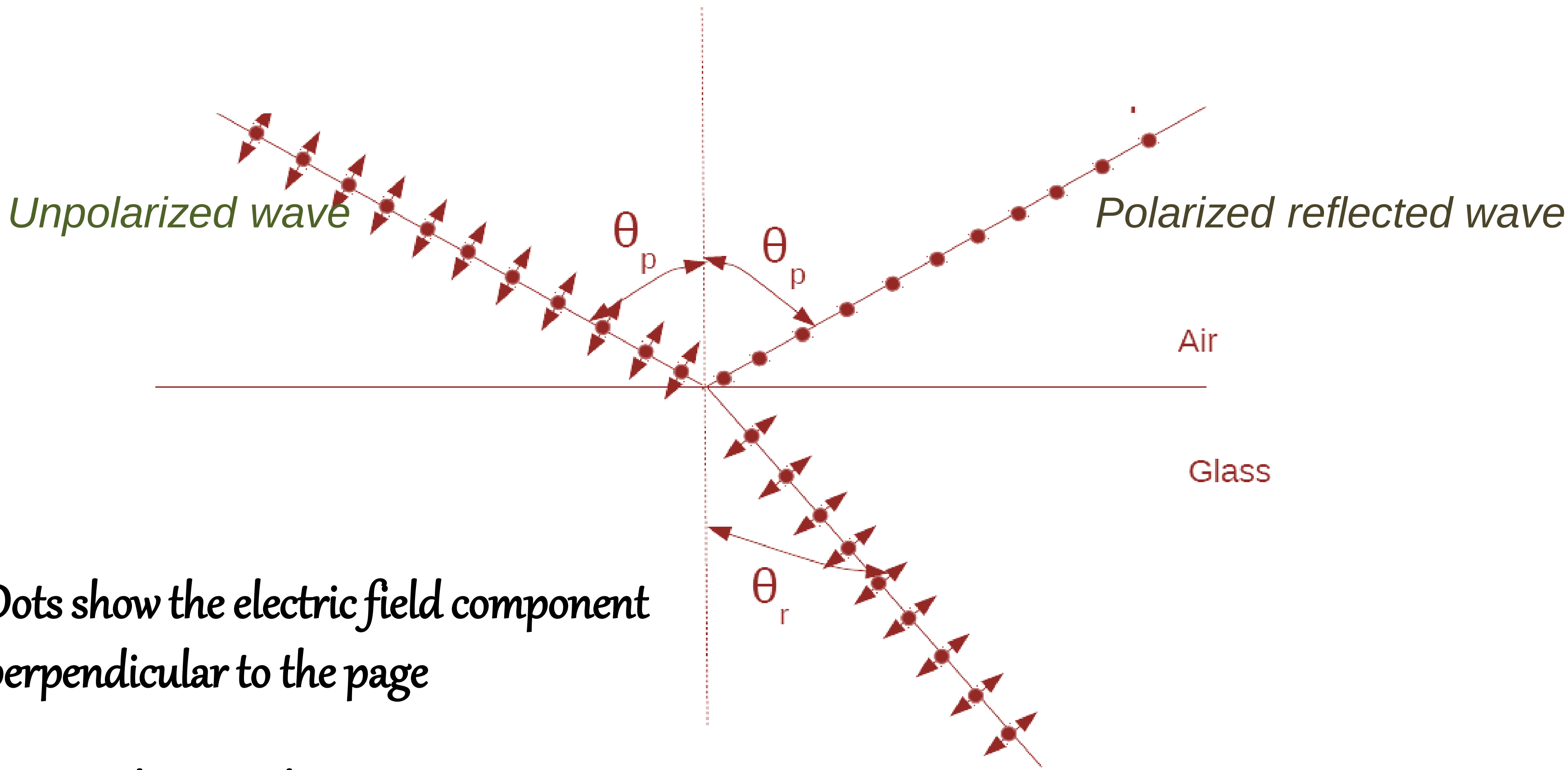
$$\theta = \theta_p = \tan^{-1}\left(\frac{n_2}{n_1}\right)$$

where n_1 is the refractive index of the initial medium through which the light propagates, and n_2 is the index of the other medium.

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

Polarization by reflection

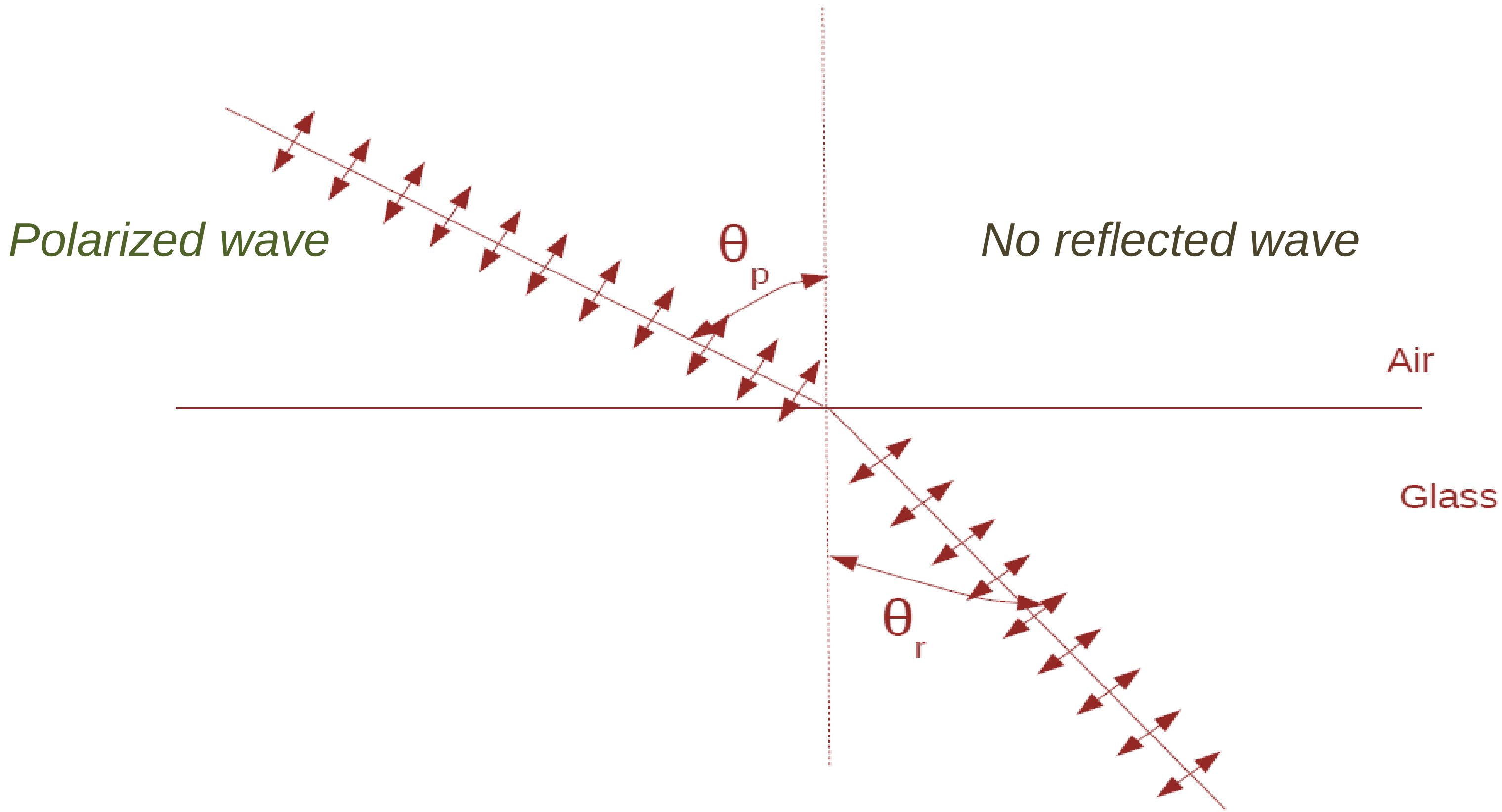
If an unpolarized light is incident at Brewster angle, then the reflected beam will be linearly polarized with its electric vector perpendicular to the plane of incidence.



- ❖ Dots show the electric field component perpendicular to the page
- ❖ Arrows show in plane components of electric field.

Polarization by reflection

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



Relating refracting angle and Brewster angle

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

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

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

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

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

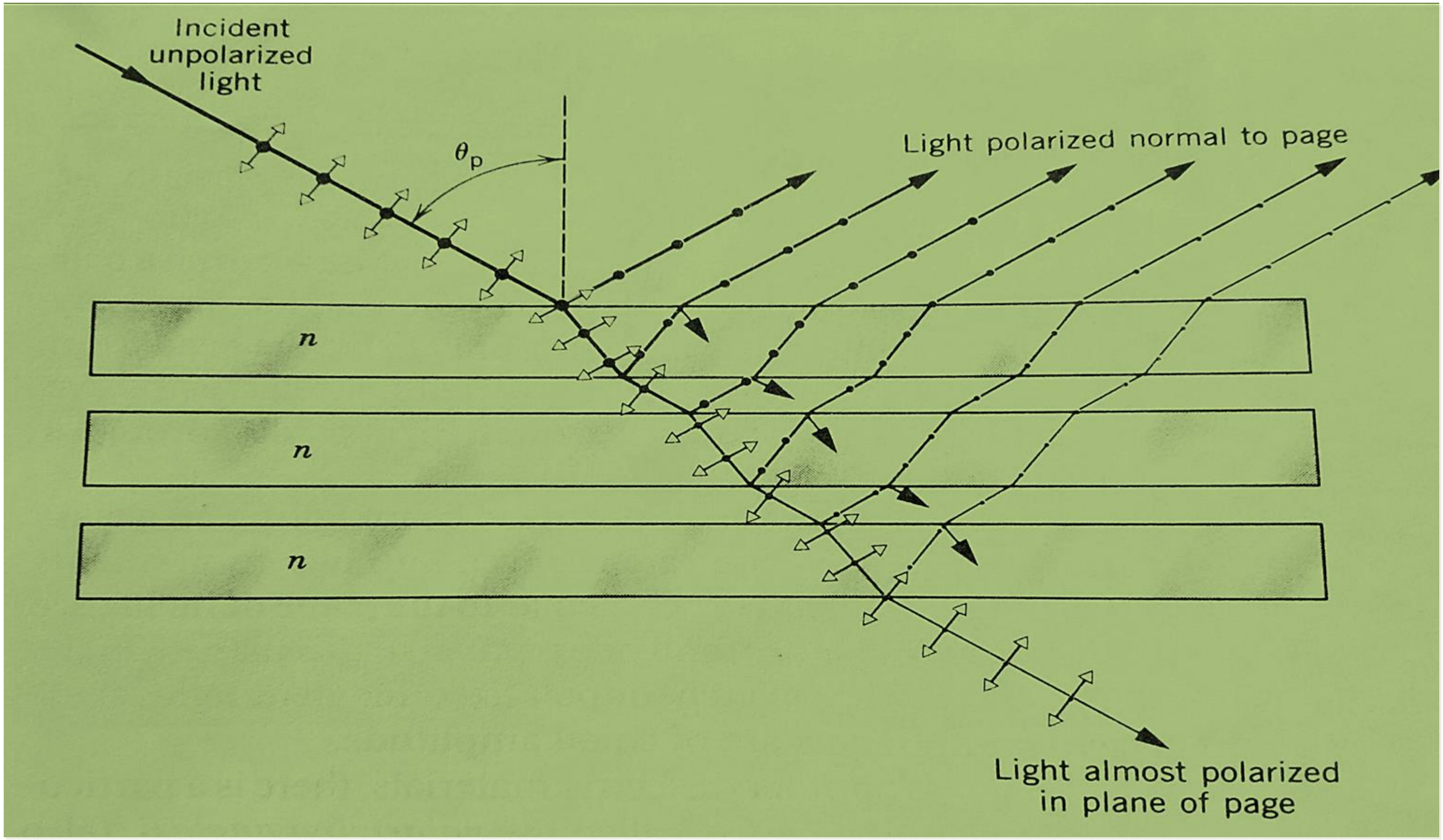
From both of these equations: $$\frac{\sin(\theta_p)}{\sin(\theta_r)} = \frac{\sin(\theta_p)}{\cos(\theta_p)}$$

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

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

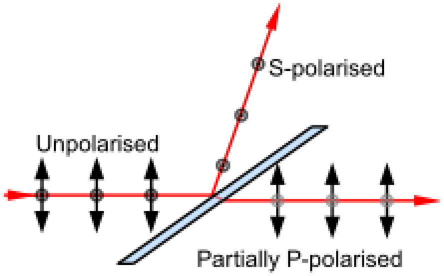
$$\Rightarrow \theta_r = 90^o - \theta_p \Rightarrow \theta_r + \theta_p = 90^o$$

Complete separation of polarized light by multiple reflection and refraction



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

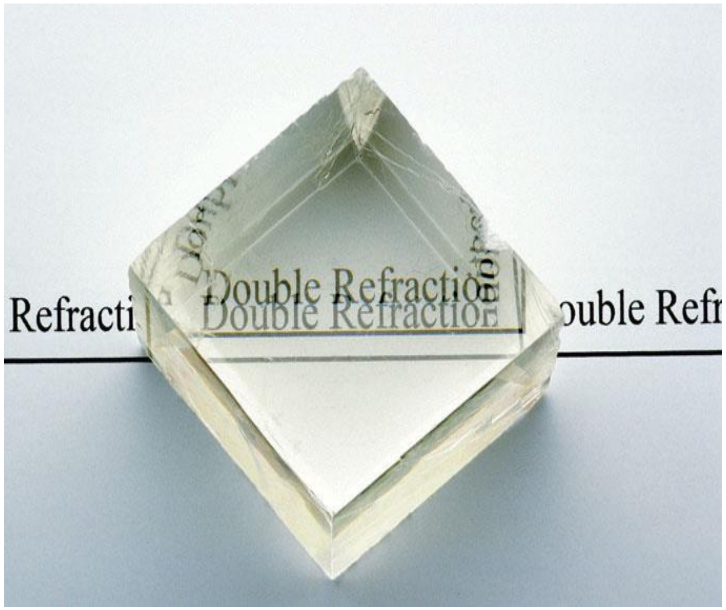
❖ Brewster's windows are used in gas lasers and in solid state lasers.In solid state lasers,the ends of the laser medium is cut at Brewster's angle to make a Brewster window.

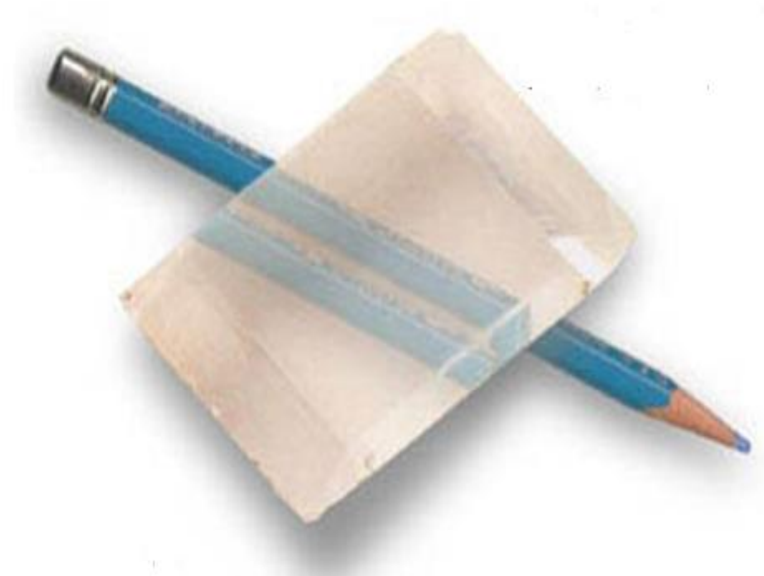


❖ Polarized sunglasses or lens use the principle of Brewster's angle to reduce the glare from the sun reflecting off horizontal surfaces such as water or road.

Double refraction(Birefrigence)

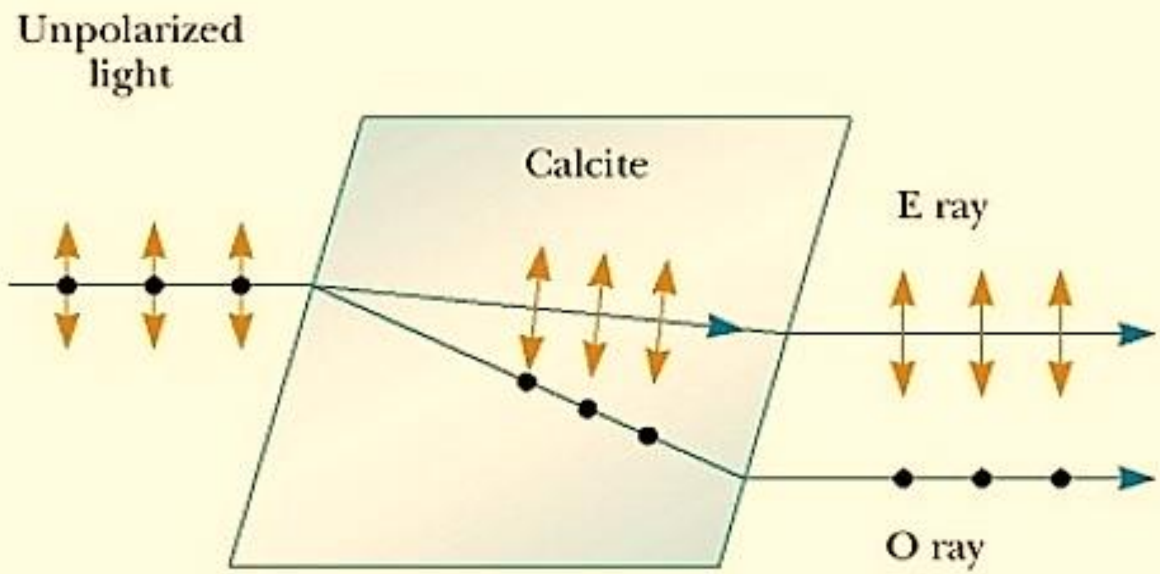
(Discovered by Rasmus Bartholin in1669)





Polarization by double refraction :

If beam of light is passed through certain crystal like calcite ($CaCO3$) or quartz ($SiO2$), it splits into two beams. These substances are called doubly refracting or birefringent.



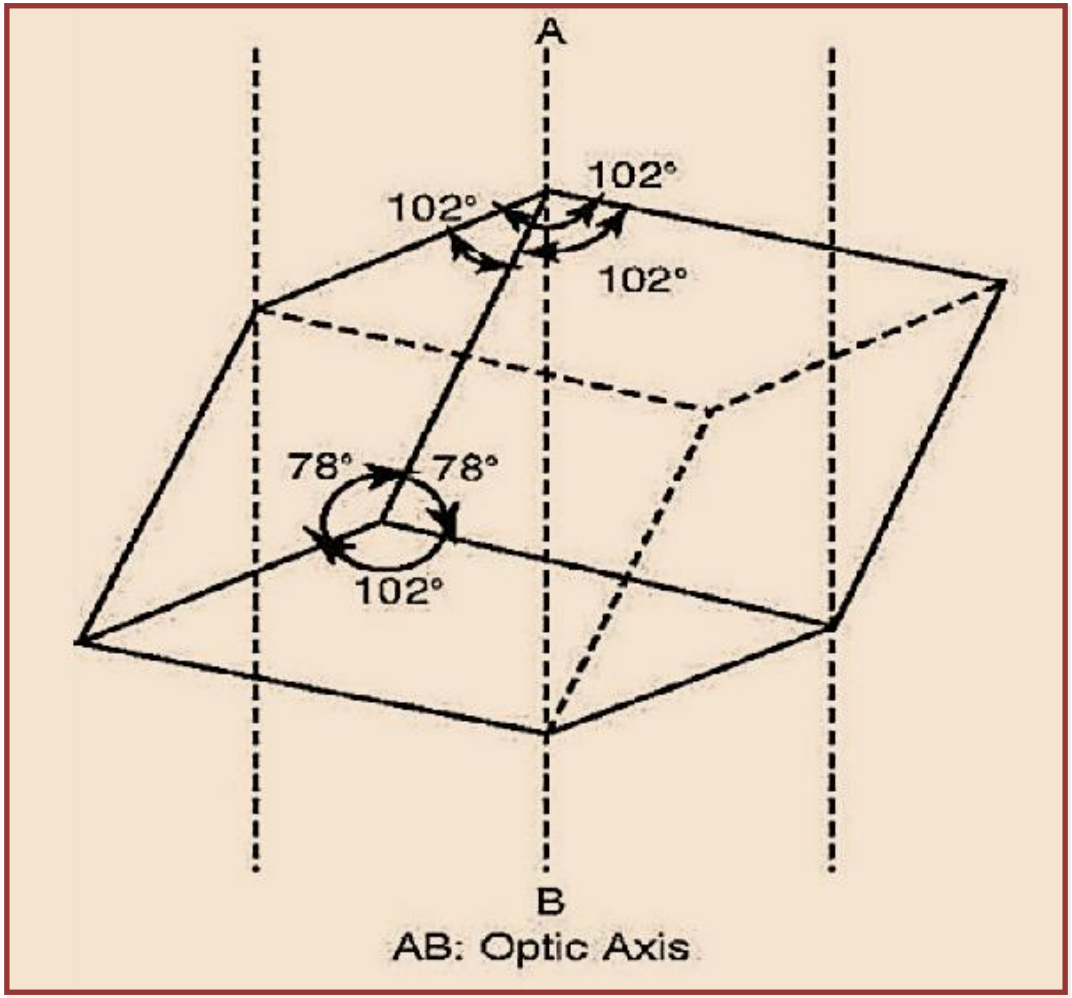
One of refracted beams obeys Snell's law and is called Ordinary ray (O-ray). The other beam doesn't obey Snell's law and is called Extraordinary ray (E-ray).

- *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.*

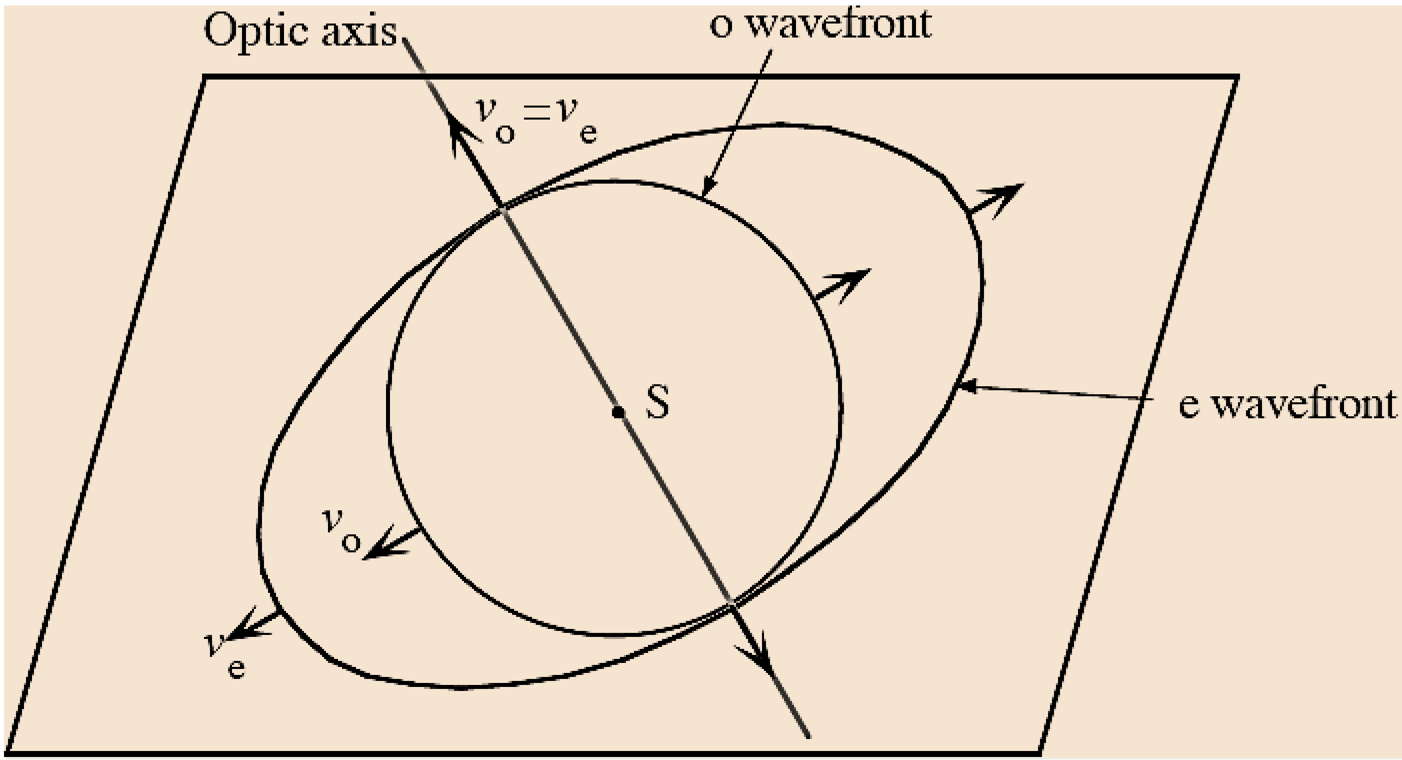
- *In the case of Calcite and Quartz crystal, there is one direction in which there is no double refraction. This direction is called* ***optic axis or principal axis.*** *There are also biaxial crystals, no double refraction occurs in two specific directions.*

- *O-rays and E-rays are polarized in a direction perpendicular to each other. E-rays are polarized in the plane containing direction of propagation and optic axis.*



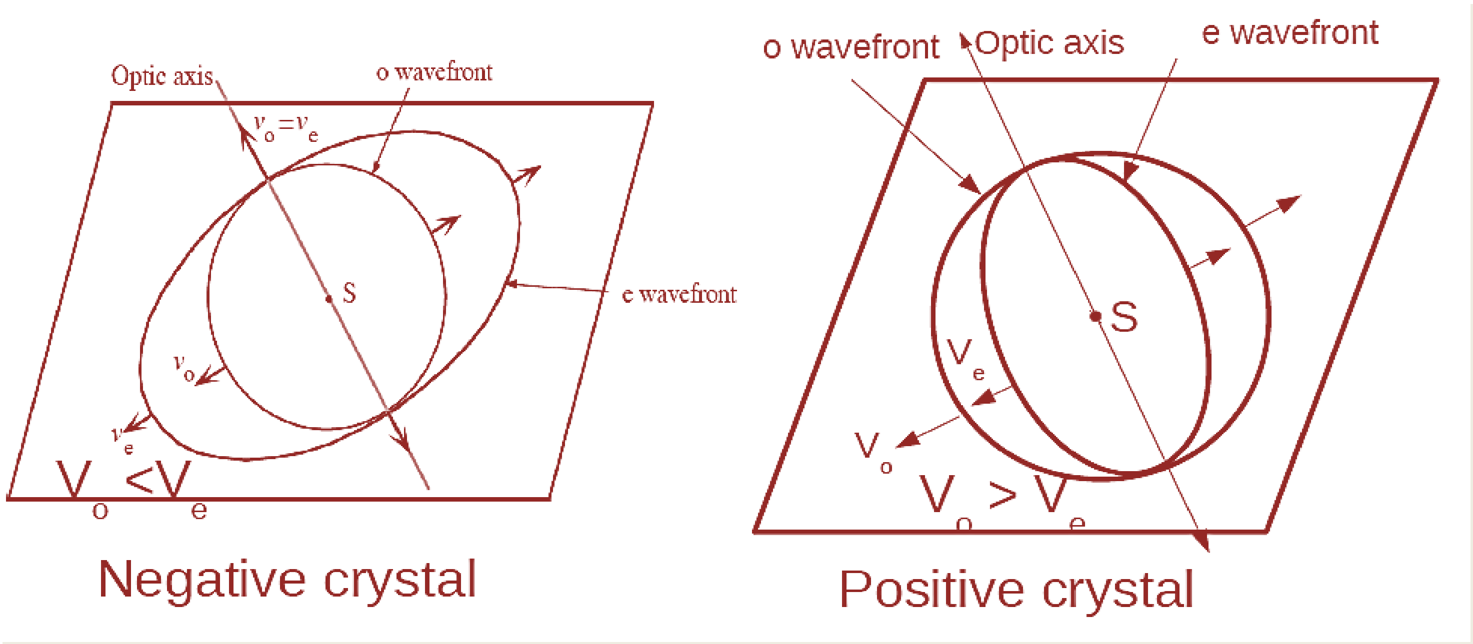
The optic axis of a calcite crystal denoted by dotted line AB. Any ray of ordinary unpolarized light incident along the optic axis or parallel to this axis does not split up into two rays.

Wavefront of O- and E-rays

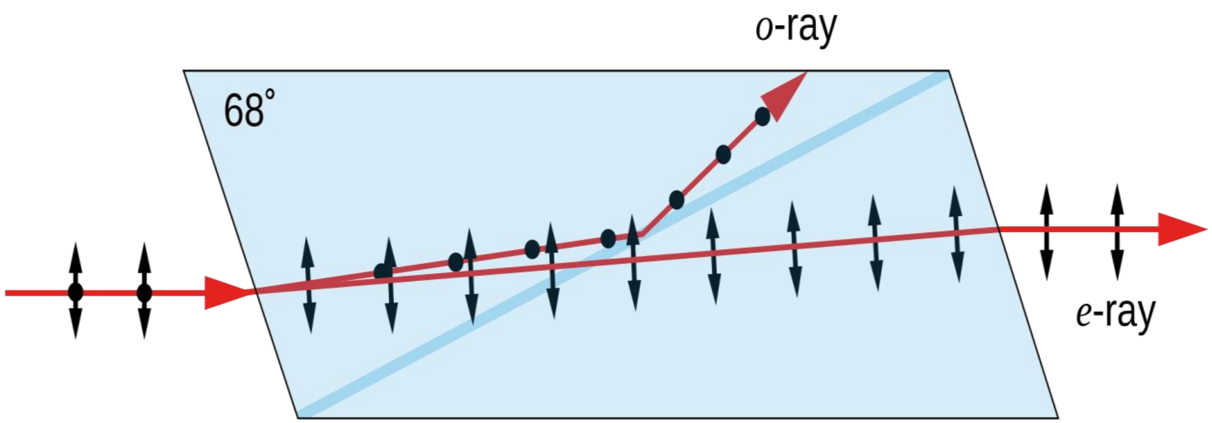


S is the point from where light is starting at same time in double refracting crystal.

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.



Nicol Prism

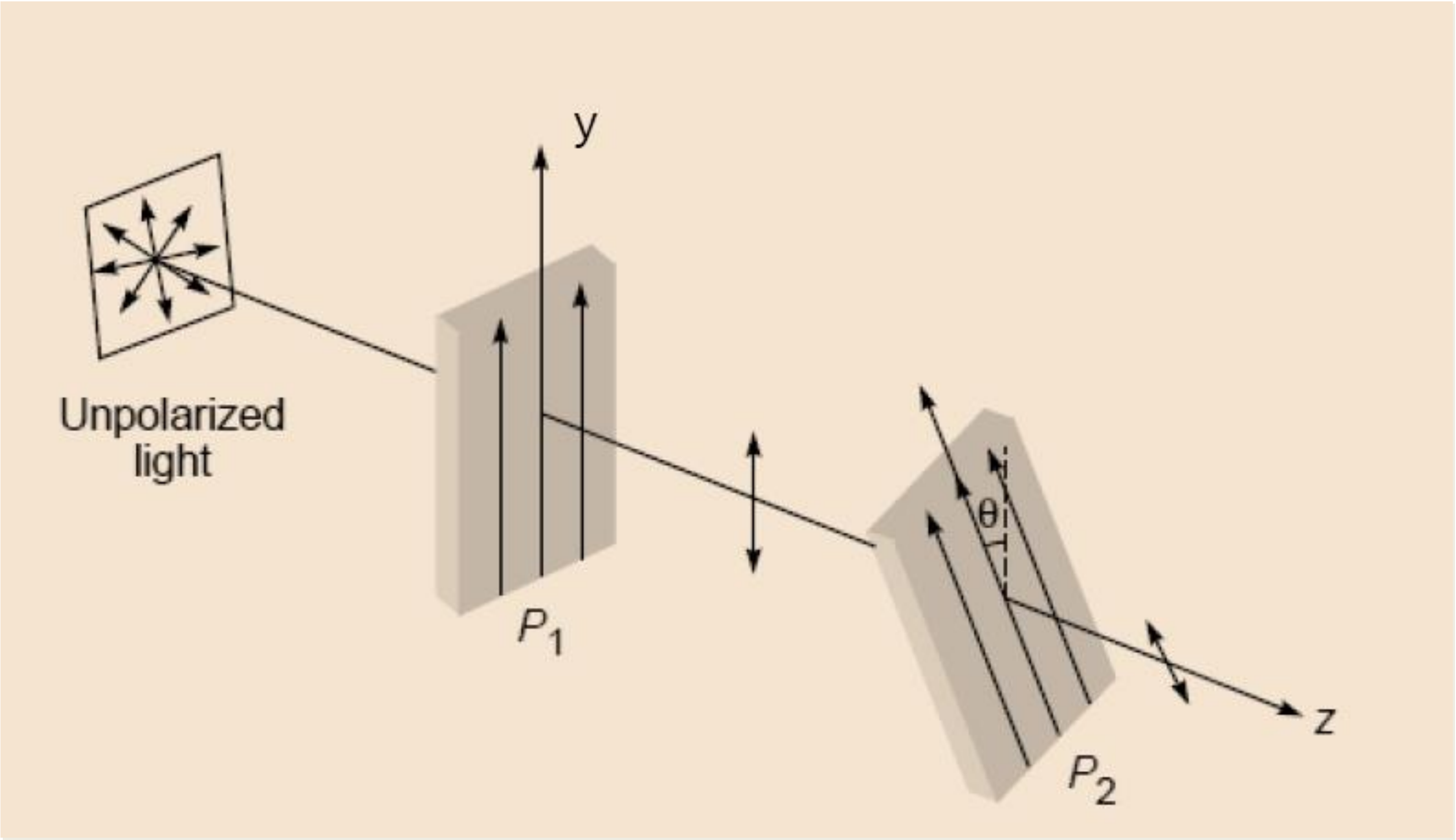


$n_E = 1.48$
$n_o = 1.65$

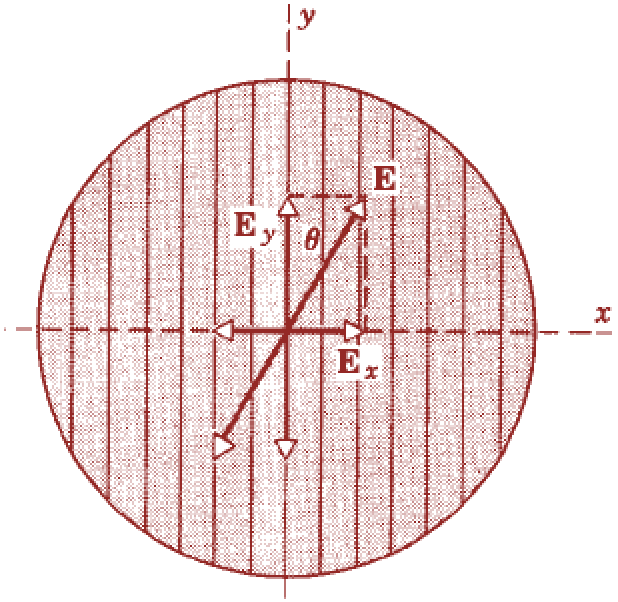
Polarized light

The Nicol prism is constructed from two prisms of calcite. The two prisms are attached with the help of Canada balsam. The ordinary ray can be caused to totally reflect off the prism boundary, leaving only the extraordinary ray.

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.



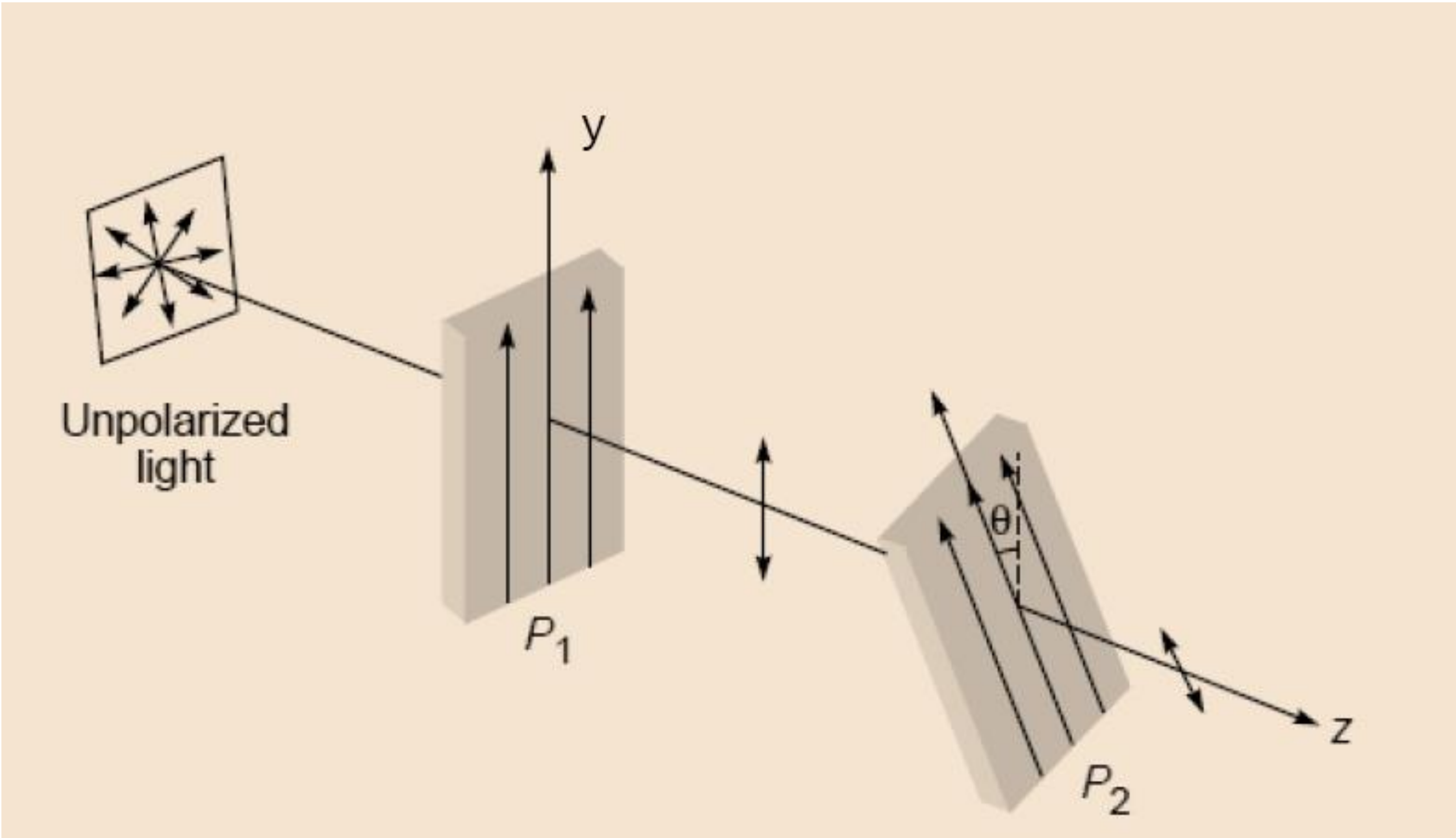
Consider the incidence of the y-polarized beam on the polaroid P_2 on the last slide, whose pass axis makes an angle θ with the y axis.

If the amplitude of the incident electric field is E_0, then the amplitude of the wave emerging from the polaroid P_2 will be $E_0\cos(\theta)$. Only E_y will be transmitted and E_x will be absorbed.

$E = E_0\cos\theta$, thus, $I = I_0 \cos^2(\theta)$.

The intensity of the emerging beam will be given by $I = I_0 \cos^2(\theta)$, which is known as Malus' law. I_0 represents the intensity of the emergent beam when the pass axis of P_2 is also along the y axis (i.e., when $\theta = 0$).

Suppose the intensity of unpolarized light is I_0, the intensity after light passes through P_2 is $I_0 \cos^2(\theta)/2$, why? Note a factor of 1/2 !!!.



Factor of ½ comes because the intensity is reduced by half after passing through P_1. Why?

Applications

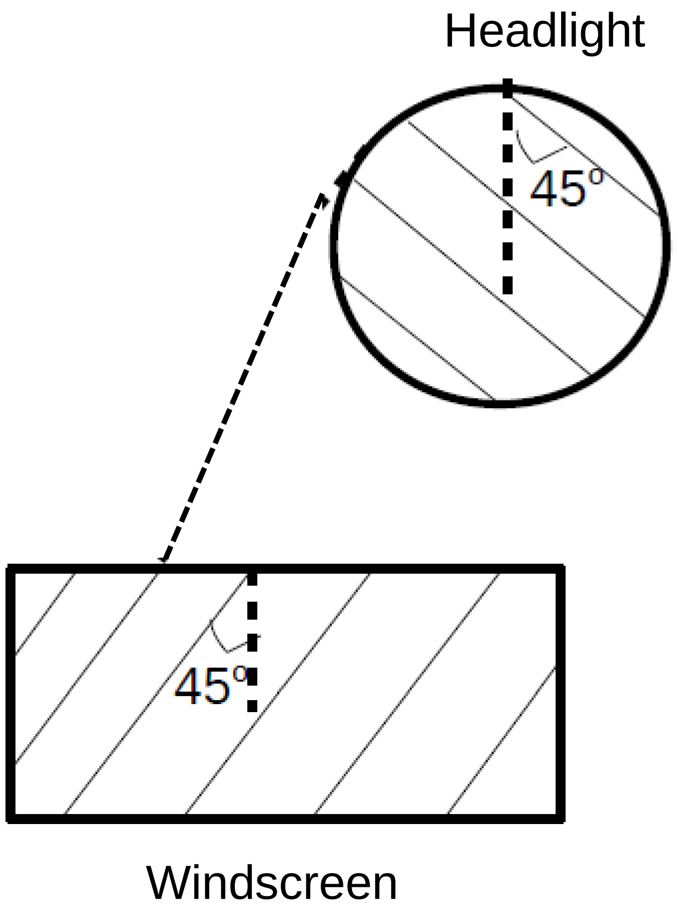
1. It is used in sun glasses to remove reflected light mostly utilized by fisherman, motorist, skiers, sportsman

2. Anti-glare automobile headlights, adjustable tint windows

3. To determine the chirality of various organic compounds

4. All radio transmitting and receiving antennas generate polarized signals

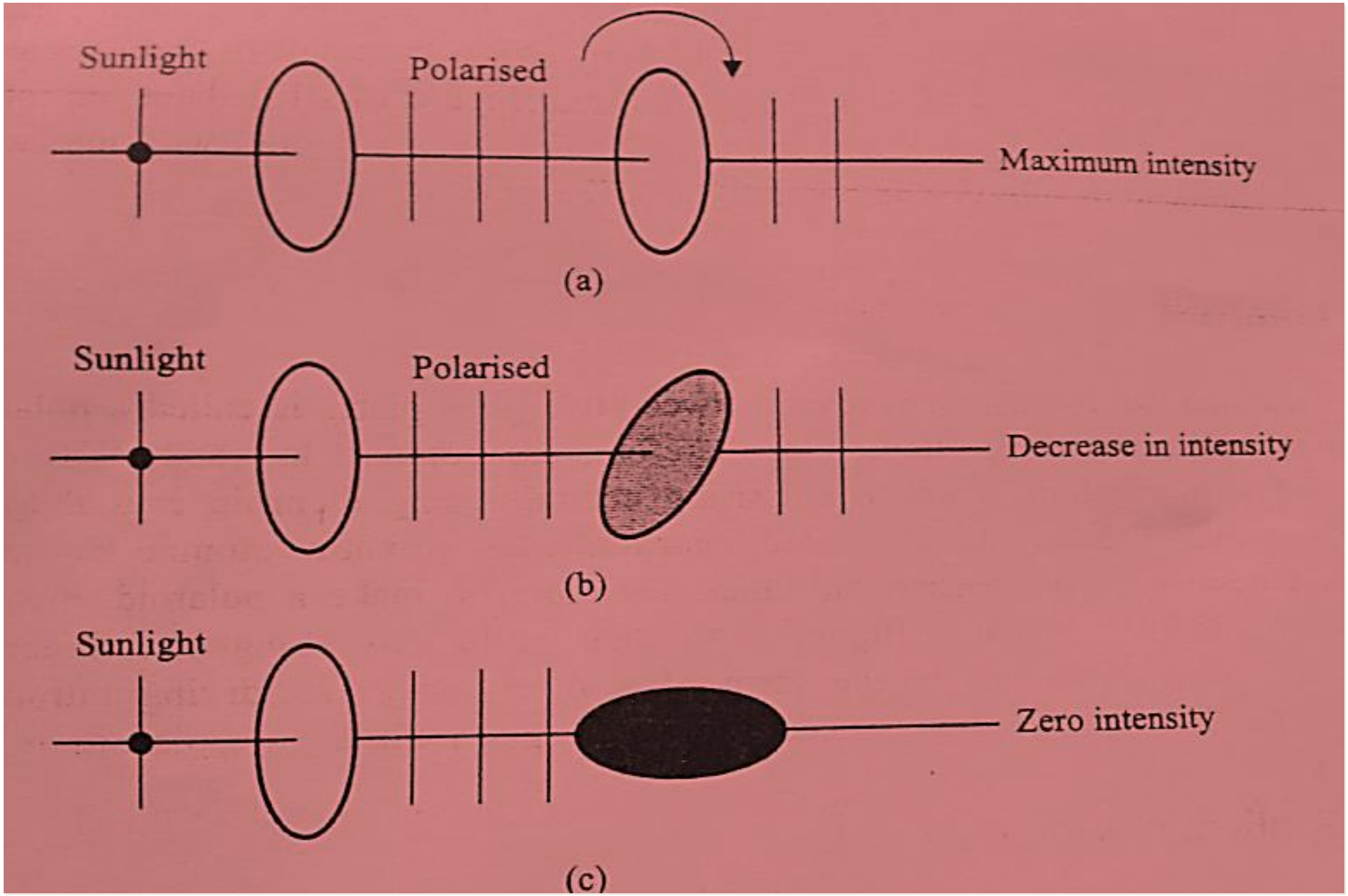
Anti-glare automobile headlights :



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.