Polarization

- Polarization of waves, Polarization of light, Representation of PPL,UPL & partially polarized light

- Production of PPL by
  i) Reflection
  ii) Refraction(pile of plates)
  iii) Selective absorption (dichroism)
  iv) Double refraction
- Law of Malus
- Huygen’s theory of double refraction
- Retardation plates, QWP, HWP, optical activity, specific rotation
- Applications

Important terms

- **Unpolarized light:**

A light wave that is vibrating in all possible directions perpendicular to the direction of propogation is called unpolarised light

- **Polarized light:**

A light wave that is vibrating in only one direction is called polarized light

- **Polarization:**

The process of transforming unpolarised light into polarized light is called Polarization

- **Longitudinal waves:**

Vibration of particles back and forth in the direction of propagation of the wave

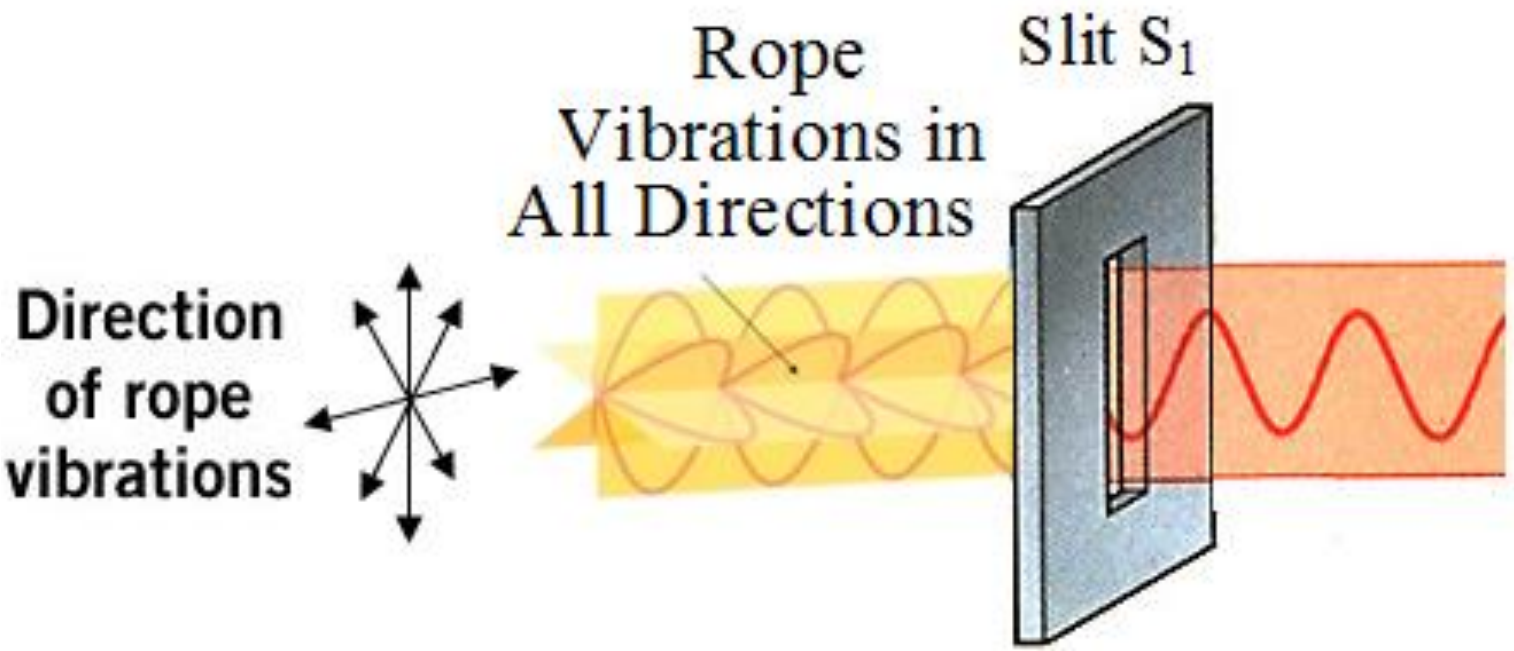
- **Transverse waves:**

Vibration of particles up and down perpendicular to the direction of propagation of the wave

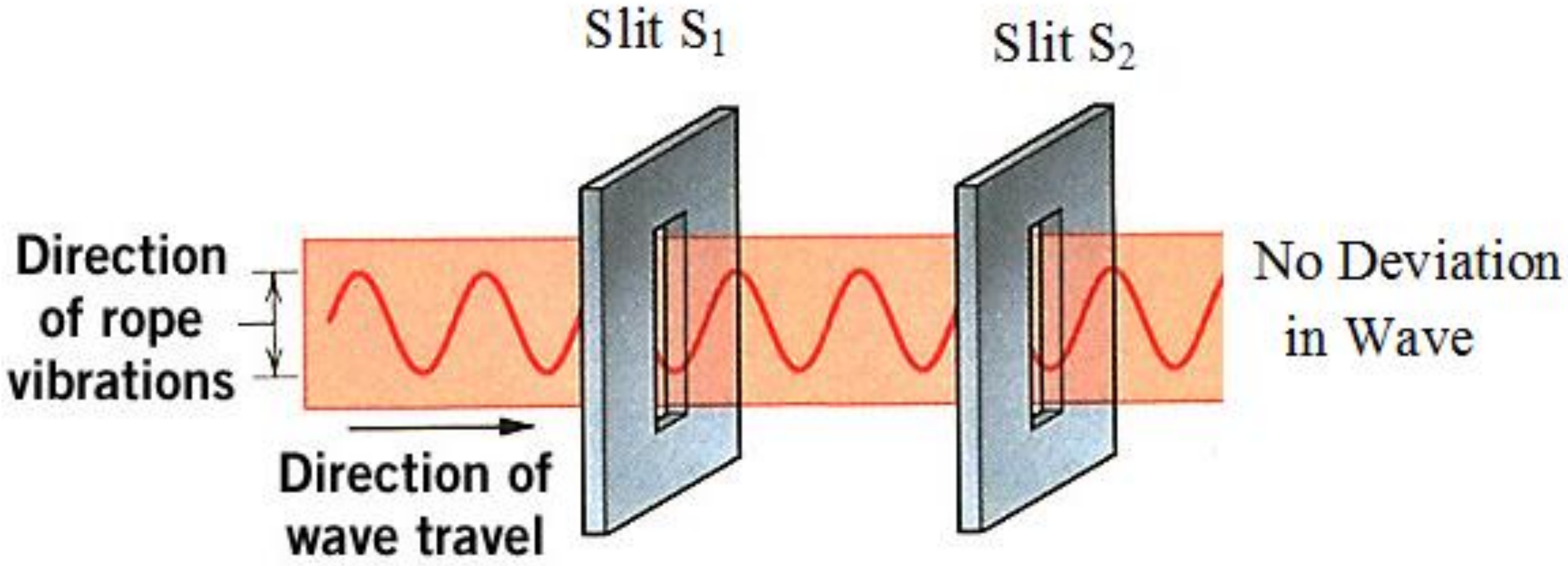
How Unpolarised light is converted into Polarized light?

Mechanical Experiment

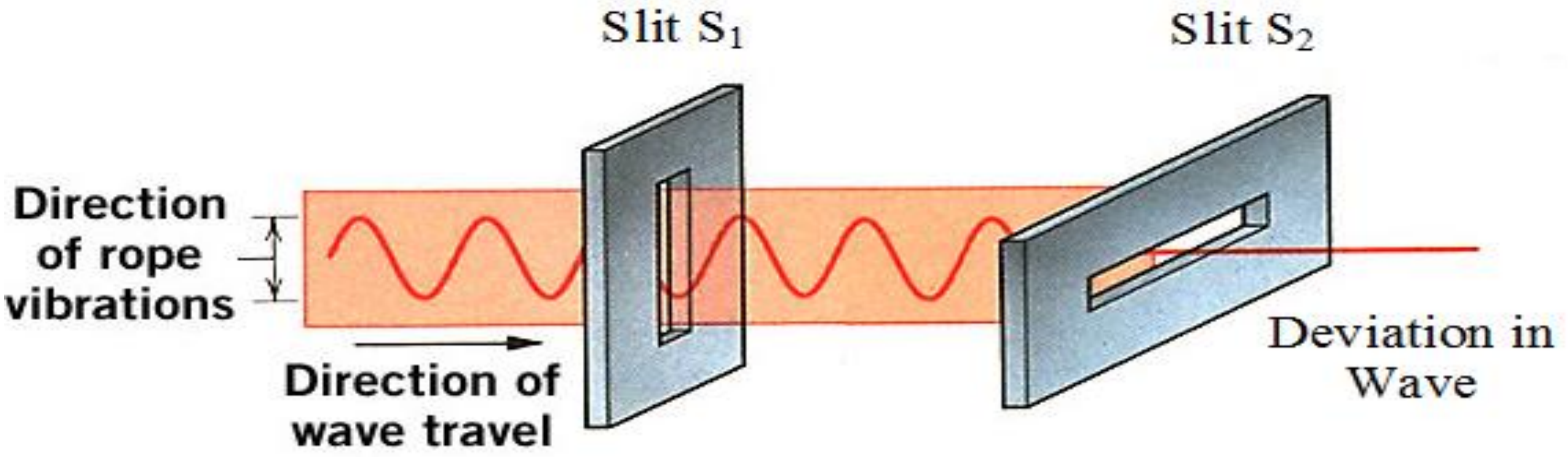
- If only S_1 is present and the rope is jerked such that it vibrates in all directions, then only parallel vibrations will be allowed through S_1.



- **Slit S_1 and S_2 are parallel: transmitted intensity is maximum**



- **Slit S_1 and S_2 are perpendicular: transmitted intensity is zero**

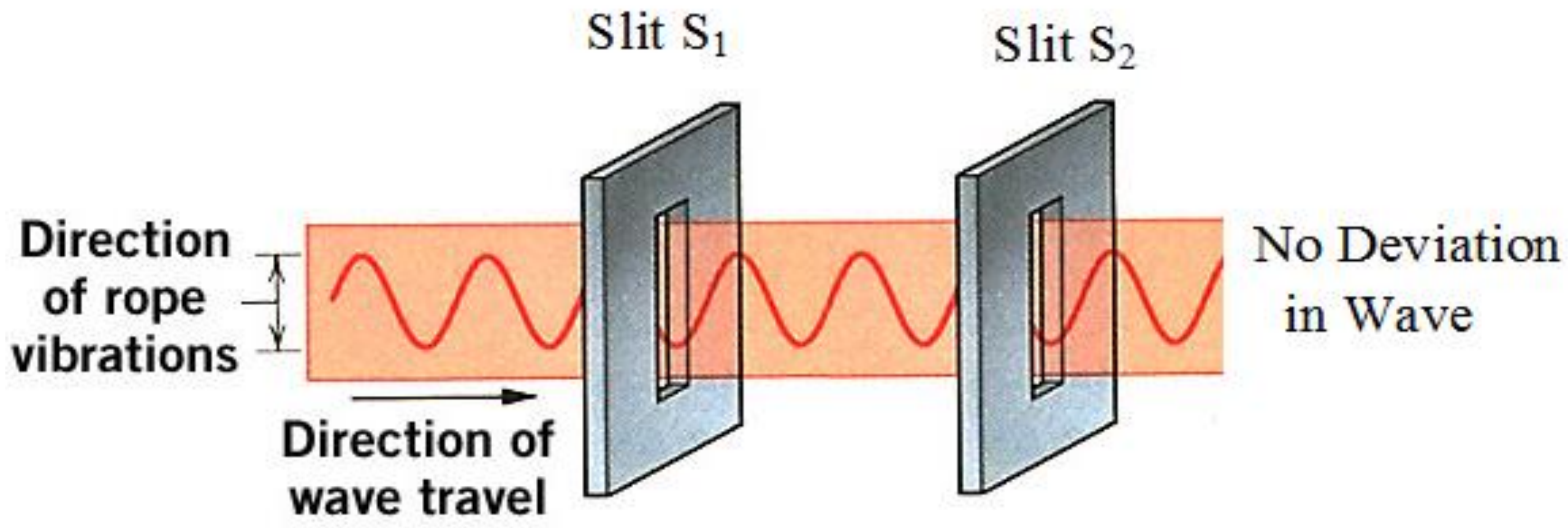


- Slit S_1 : **Polarizer**

selects single direction of vibration from random vibrations

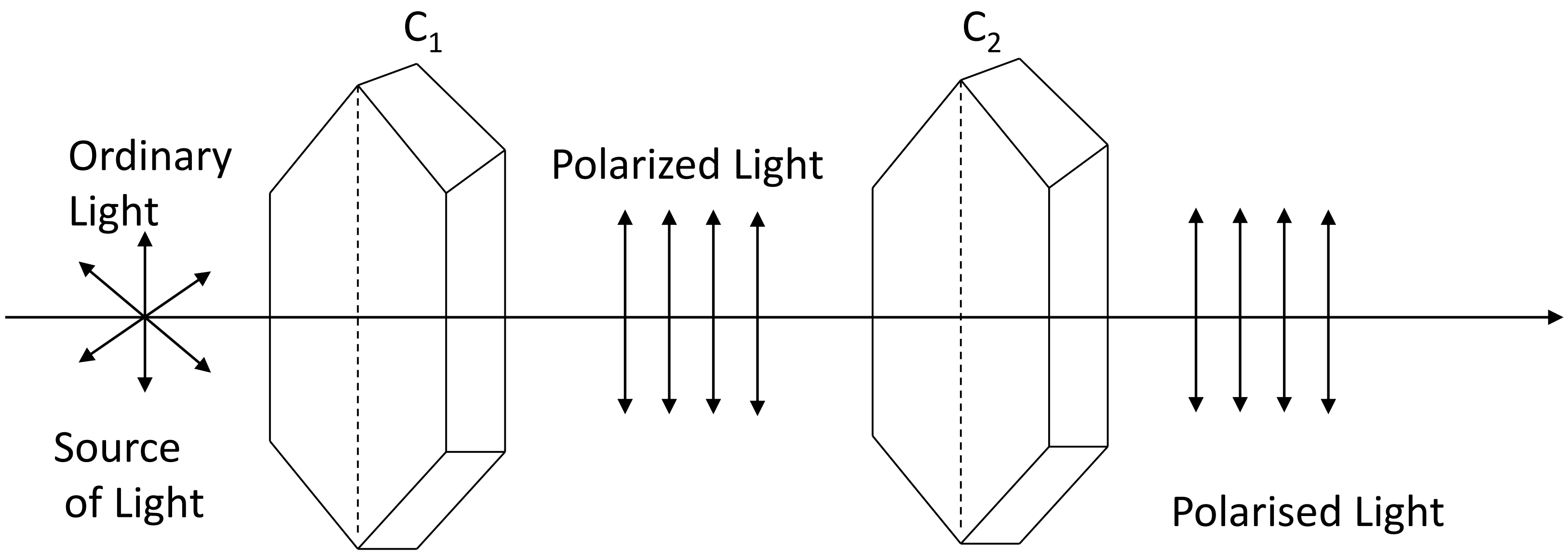
- Slit S_2: **Analyzer**

Identifies plane of vibration or it permits only that component wave which is polarized in particular plane



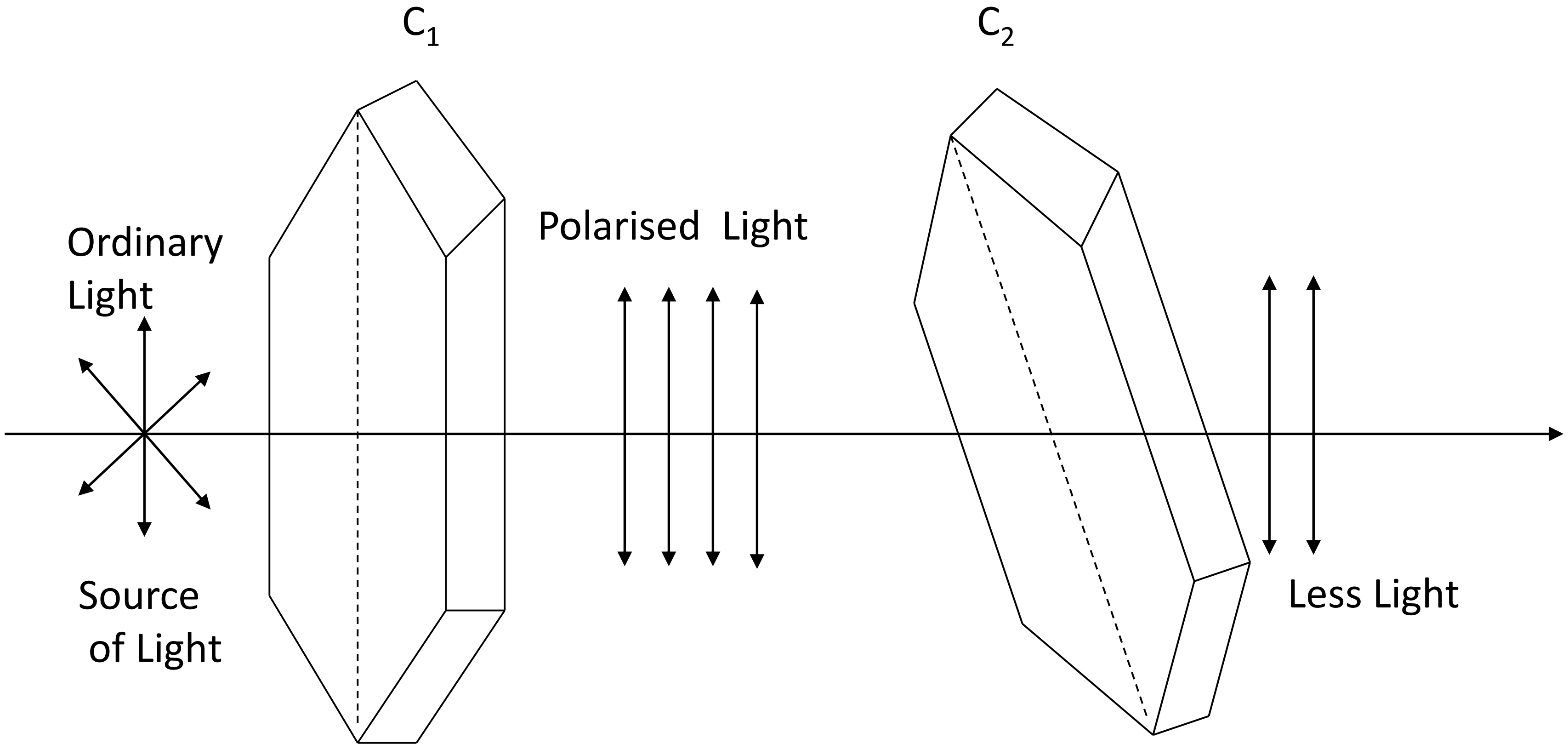
Optical Experiment

Ordinary light: vibrations in all possible directions

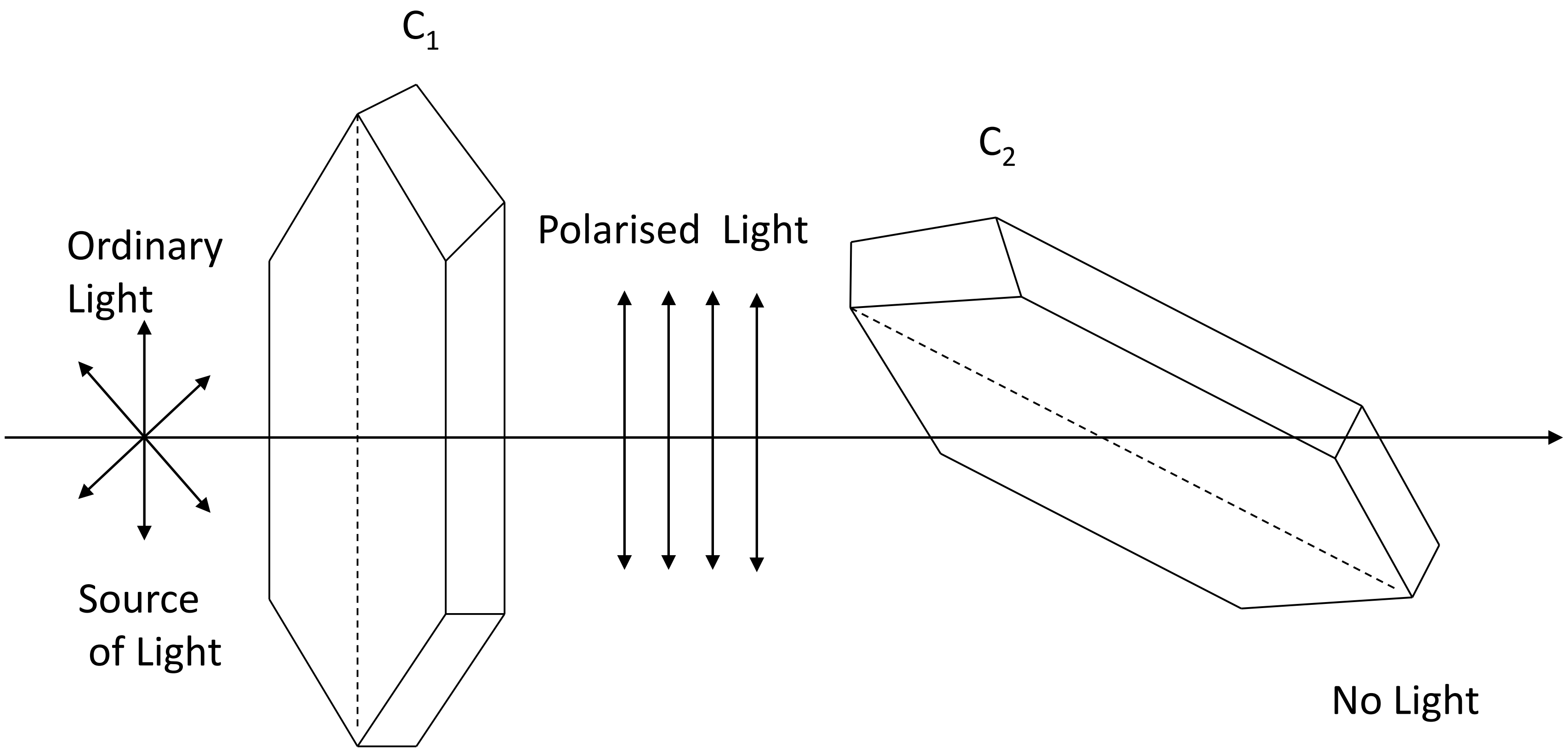


Tourmaline Crystal **Tourmaline Crystal**

- **If the crystal C_2 is rotated slightly, less light will pass through it.**



- **at right angles, no light will pass**



Conclusion of experiments

It is clear that, light waves are transverse. If they were longitudinal, then the rotation of analyzer would not have produced any change in the intensity of light

Why transverse wave can be polarized ?

- The vibration are perpendicular to the direction of energy travel.
- Longitudinal waves can not polarized: vibrations are in the same direction of energy travel (do not have oscillations)

- .**Plane of vibration:**

  The plane containing the direction of vibration and direction of propagation of light.

  The vibrating electric vector E and direction of wave propagation create a plane called plane of vibration.

- **Plane of Polarization:**

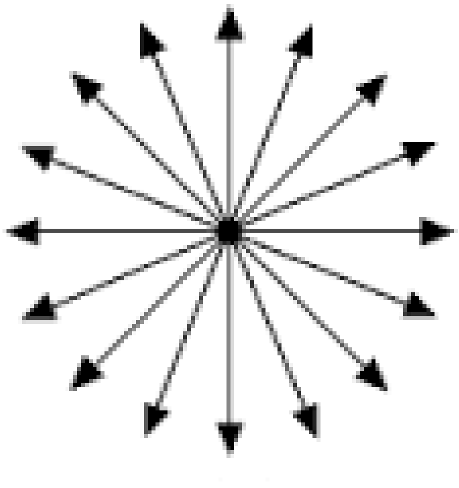
  The plane containing the direction of propagation of light but containing no vibrations. It is a plane perpendicular to the plane of vibration.

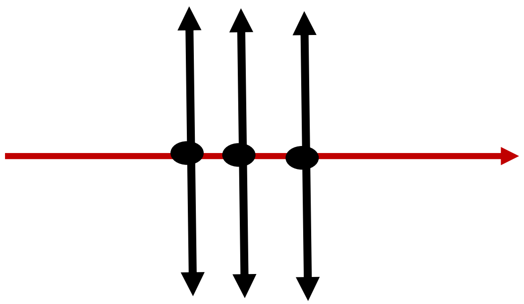
Types of polarization and their representation

1. Unpolarised light
2. Plane polarized light
3. Partially polarized light
4. Circularly polarized light
5. Elliptical polarized light

1. Unpolarized light

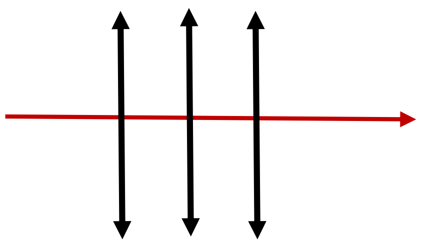
Natural light is generally unpolarized, all planes of propagation being equally probable



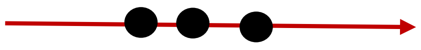


2. Linearly polarized light or Plane polarized

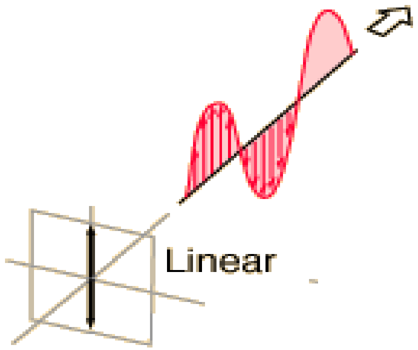
The light having vibrations only along one plane perpendicular to direction of propagation of light



Parallel Vibration

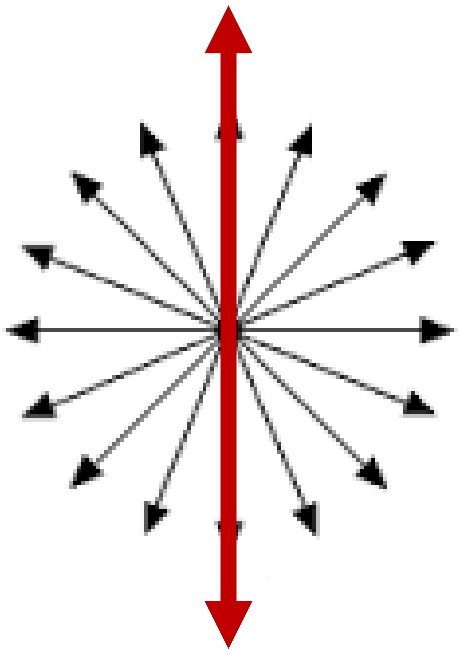


Perpendicular Vibration



3. Partially Polarized Light

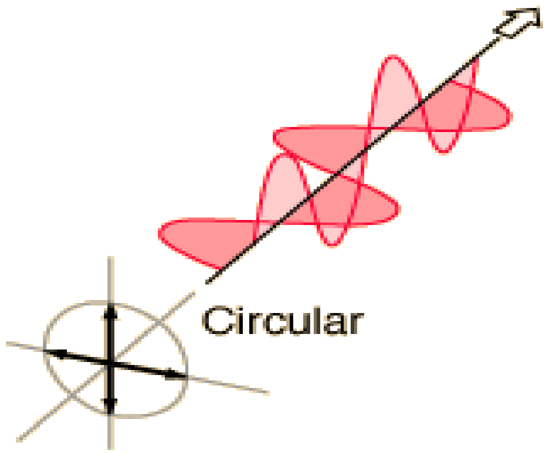
It is mixture of unpolarized and polarized light. Vibrations are dominant in plane polarized light over other directions



4. Circularly polarized light

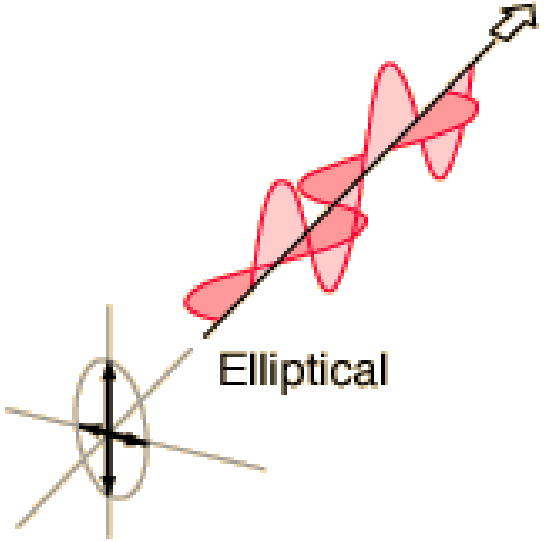
- If light is composed of two plane waves of equal amplitude by differing in phase by 90°.

- The electric field of the wave has a constant magnitude but its direction rotates with time at a steady rate in a plane perpendicular to the direction of the wave



5. Elliptically polarized light

If two plane waves of different amplitude with phase difference of 90°, or if the relative phase is other than 90°



Whether the intensity of Polarised light is same as Unpolarised light ?

If unpolarised light is polarised fully, its intensity will become half

- **I_m : intensity of polarized light after passing through polarizer**
- Intensity will be zero if polarizer and analyzer are perpendicular
- **I_θ : when analyzer will be in particular direction**

$$I_\theta = I_m \cos^2\theta$$

Malus Law

Law of Malus (state and prove)

Statement :

When unpolarized light is incident on the polarizer , the ratio of intensity of light transmitted by analyzer to the intensity transmitted by polarizer is equal to square of the cosine of the angle between the axes of polarizer and analyzer.

$$\frac{I_\theta}{I_m} = \cos^2\theta$$

Proof:

- If intensity of transmitted light is not changing: Unpolarized light
- If intensity of light is changing: Polarized light
- Malus law: by how much amount the intensity of polarized light is decreasing

- **What should be the angle of rotation for which the intensity of polarised light will become half?**

Given: $I_\theta / I_m = \frac{1}{2}$

$\mathbf{\cos^2\theta = \frac{1}{2}}$

$\mathbf{\cos\theta = (\frac{1}{2})^{1/2}}$

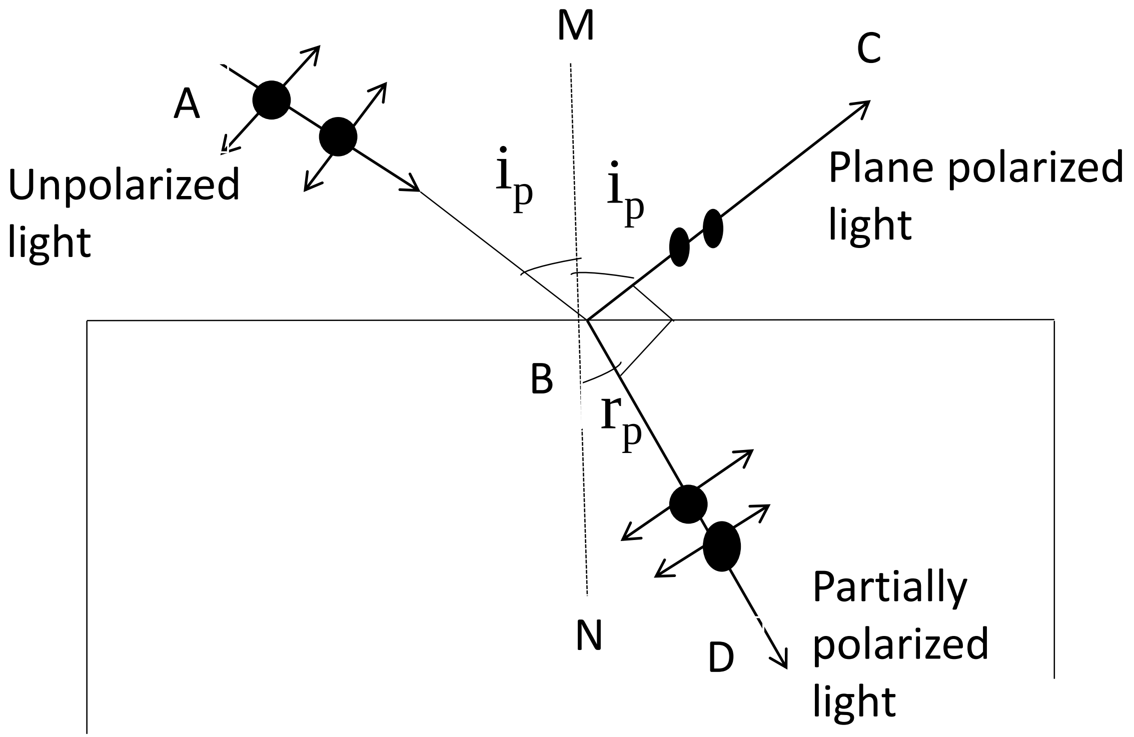
$\mathbf{\theta = 45^0}$

Methods for Producing Polarized Light

1. Reflection (Brewster’s law)
2. Refraction (Piles of Plates)
3. Double Refraction (Birefringence): Calcite crystal
4. Selective Absorption (Dichroism)
5. Scattering

Polarization by reflection and Brewster's law

- Polarization of light by reflection: Malus in 1808
- Partially reflected and refracted light: at any random angle
- Vibrations of incident light: parallel and perpendicular to reflecting surface
- Vibrations are perpendicular to the plane of incidence: **Reflected more**
- Vibrations are parallel to the plane of incidence: **Refracted**
- Plane polarized light : at polarization angle (57.5^0 for glass surface)
- Reflected and refracted rays : 90^0



Polarizing Angle:

The angle of incidence on the reflecting surface at which reflected light is completely polarized

Brewster's law

When unpolarised light is incident on reflecting surface, the maximum polarization of the reflected ray occurs only when the reflected and refracted rays are perpendicular to each other at **polarizing angle or Brewster's angle**.

$$i_p + 90^0 + r_p = 180^0$$

$$r_p = 90 - i_p$$

$$\mu = \frac{\sin i_p}{\sin r_p}$$ **Snell's law**

$$\mu = \frac{\sin i_p}{\sin(90 - ip)}$$

$$\mu = \frac{\sin i_p}{\cos ip}$$

$$\boxed{\mu = \tan i_p}$$

Brewster's equation

Refraction (Pile of Plates)

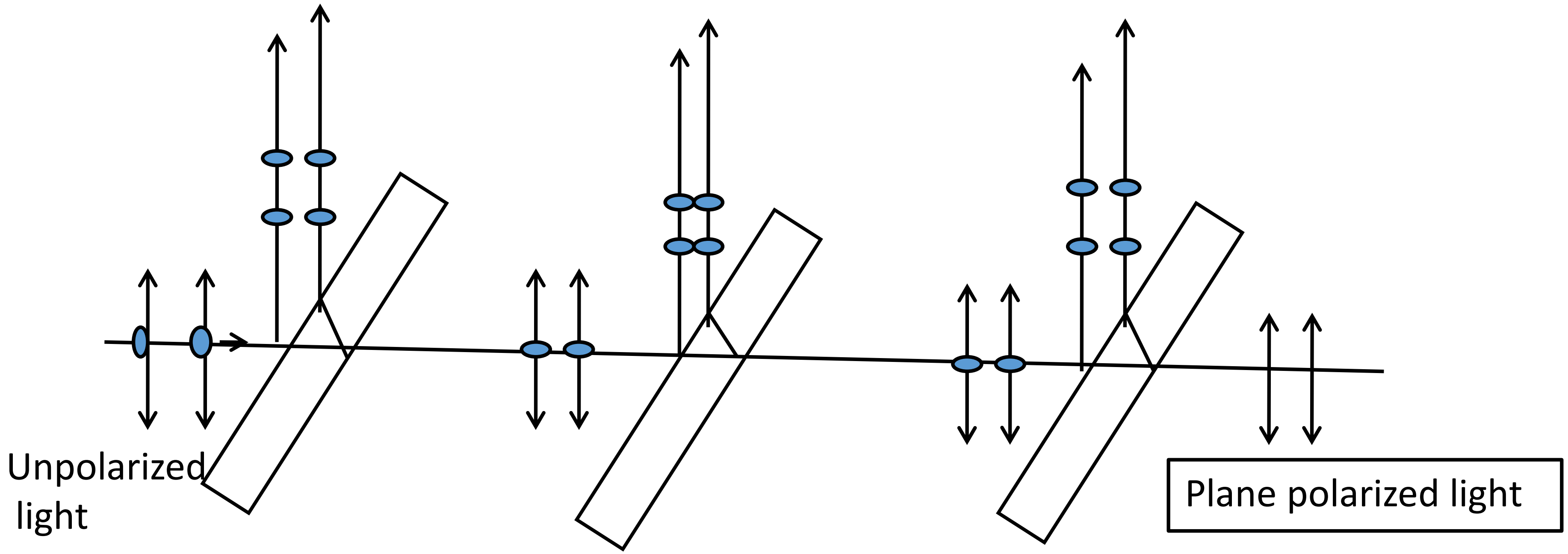
- Unpolarized light incident on surface
- Reflected light : completely or fully polarized (only at polarizing angle)
- Refracted light: partially polarized

- **How to get fully polarized light for refraction?**

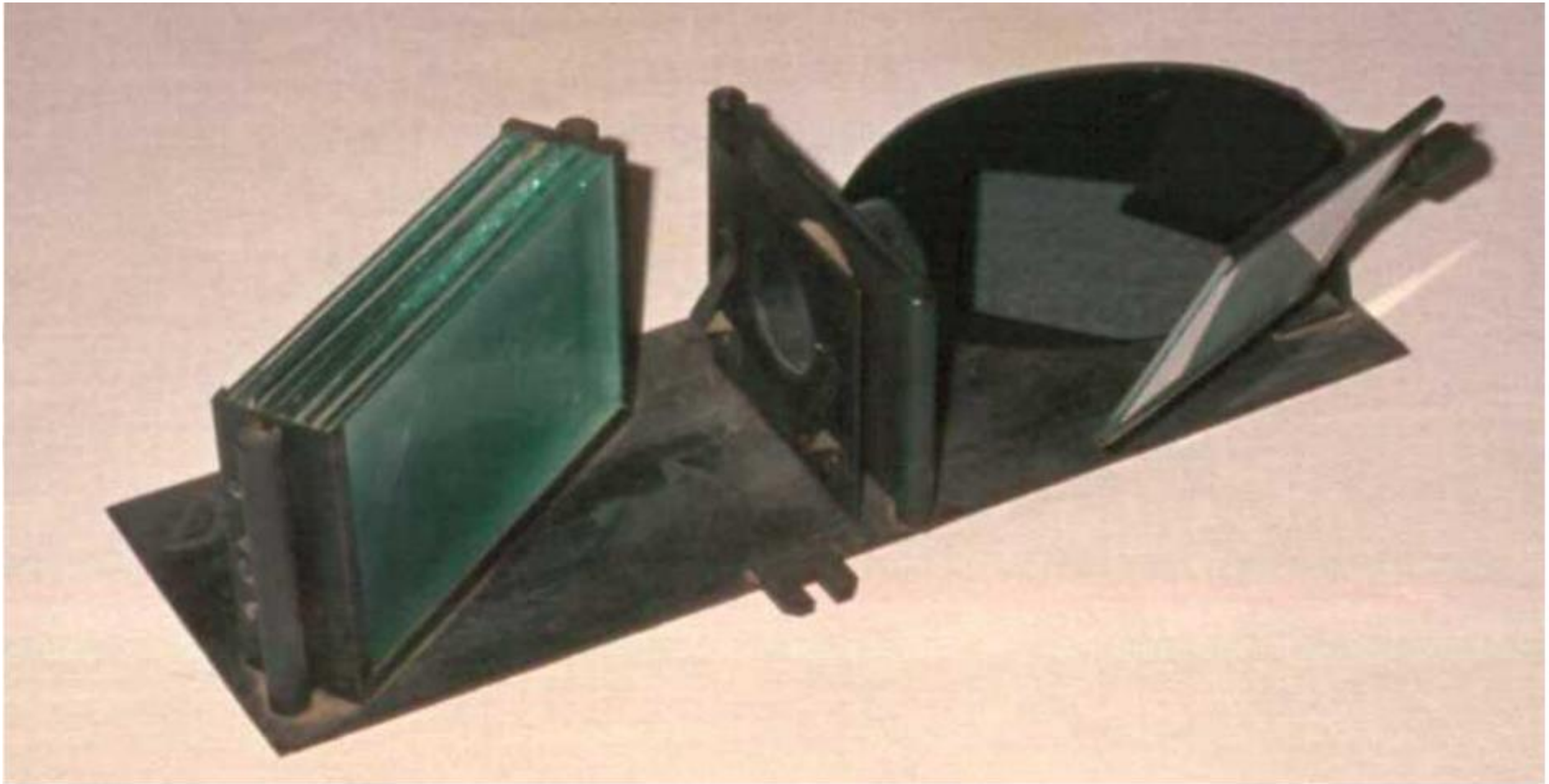
Refraction (Pile of Plates)

- It contains 15 plates in tube at angle 33^0 to the axis of tube
- Light incident at polarizing angle
- The vibrations perpendicular to the plane of incidence: **removed (reflected more) :**
- Vibrations parallel to the plane of incidence **: become more polarized (refracted ray):**

Polarization by refraction (piles of plates)

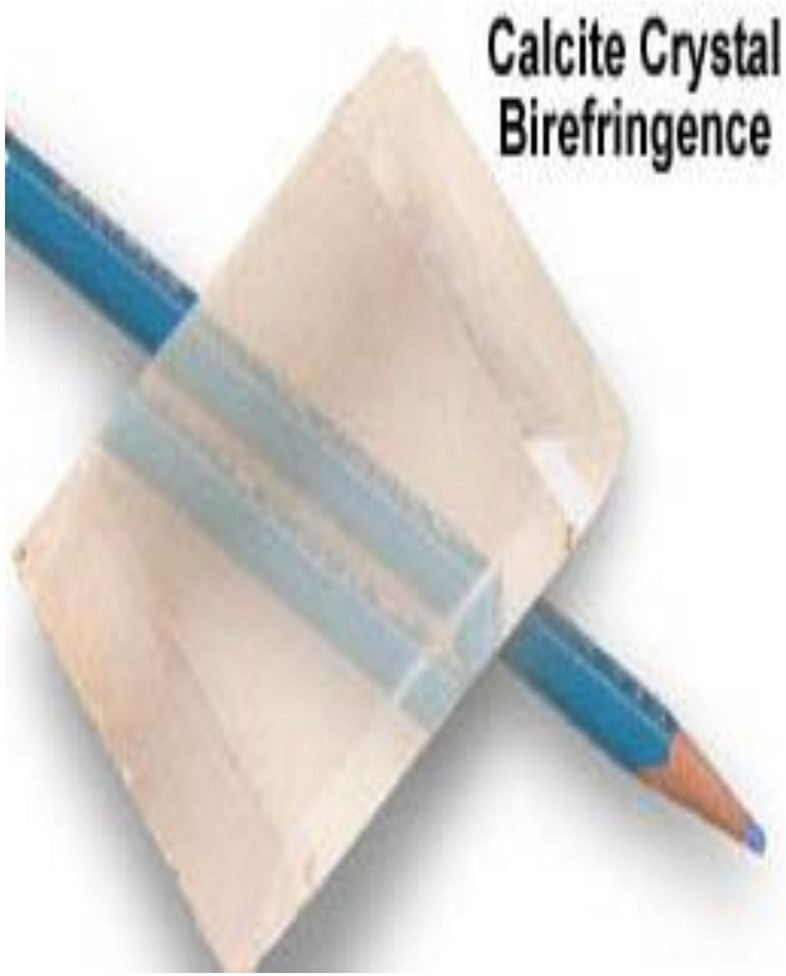


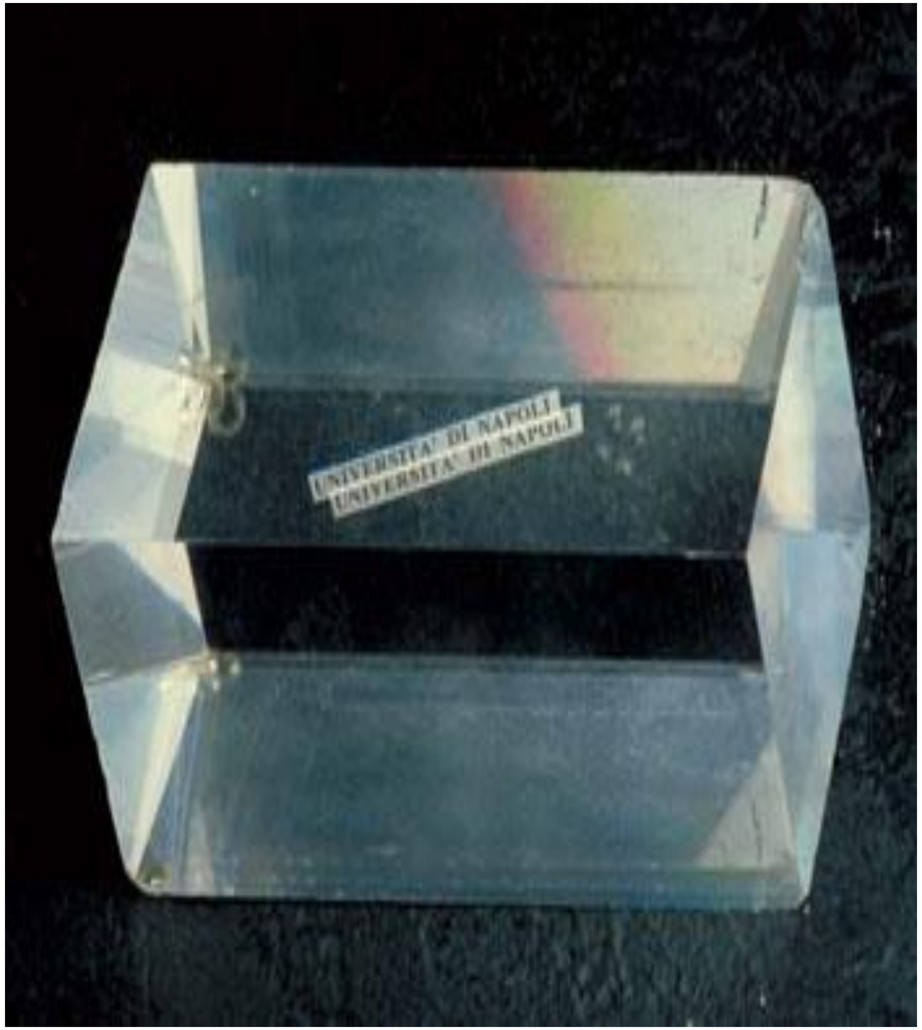
- When light is incident on glass at the polarizing angle, 100% of light having vibrations in the plane of incidence (parallel) is transmitted.
- 85% of light having vibration perpendicular to the plane of incidence is transmitted.
- 15% of light having vibrations perpendicular to the plane of incidence is reflected.



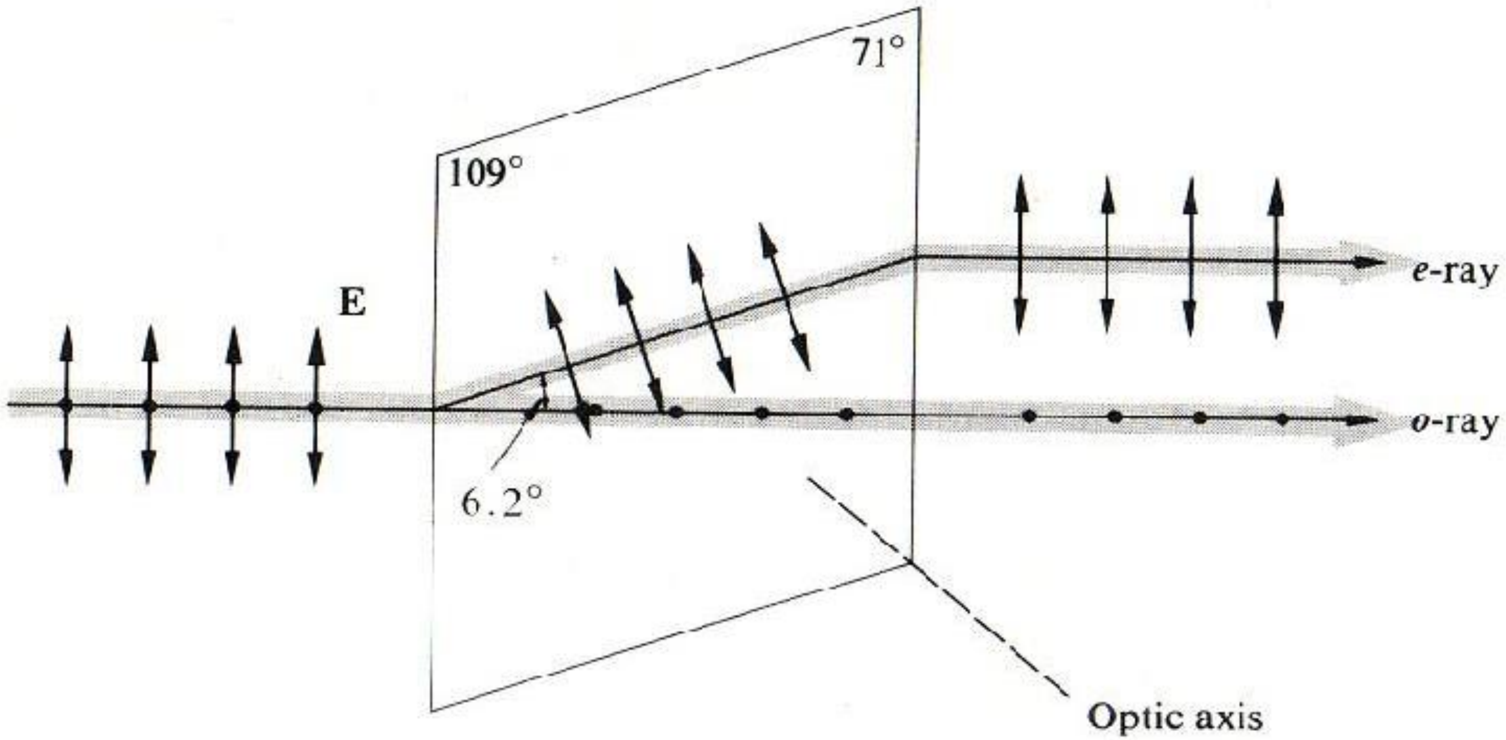
Polarisation of Light

Double Refraction





- When unpolarised light is incident on anisotropic crystal, it is found to produce two refracted rays with different properties. It is called double refraction or Birefringence

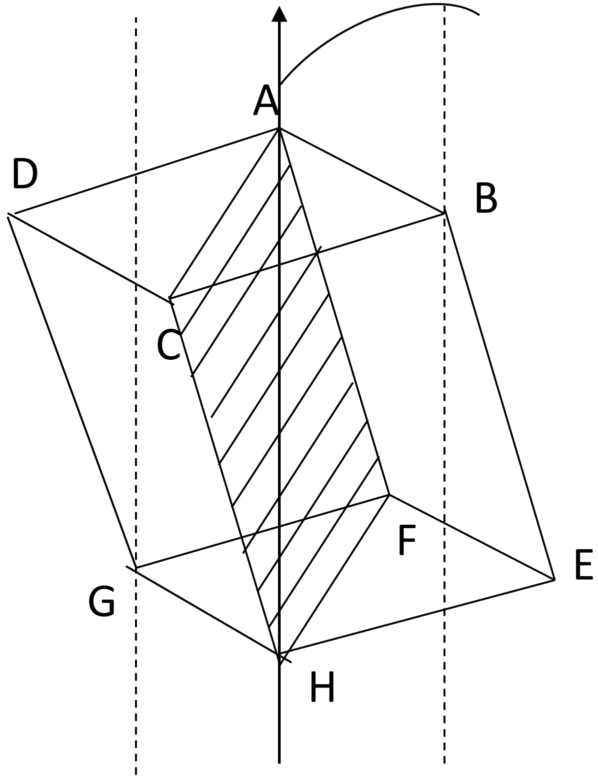


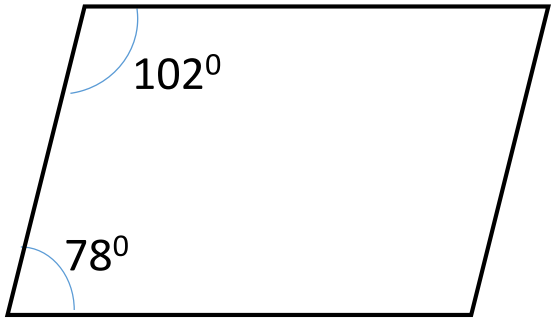
❑ Which crystals are useful to produce double refraction?

- Anisotropic crystal (different properties in different directions)
- After incident of light: two refracted rays with different direction and velocity
- Uniaxial (single optic axis): ordinary and extra-ordinary ray
- Biaxial crystal: both refracted rays are extra-ordinary
- Transparent
- Examples: calcite, quartz, ice etc. (uniaxial) and (biaxial) copper sulphate, cane sugar, mica (birefrigent)
- Glass is monorefringent

Geometry of Calcite Crystal

- Calcite : $CaCO_{3,}$ Transparent and Uniaxial crystal
- Crystal structure: Rhombohedral (hexagonal geometry)
- Three principle section
- Each face is a parallelogram with angles as 78° and 102°.
- An interesting feature of calcite: crystal can be made to slice or break along cleavage planes into two or more smaller crystals with faces that are parallelograms with angles 71° and 109°.
- Nicol prism as polarizer : made from calcite crystal

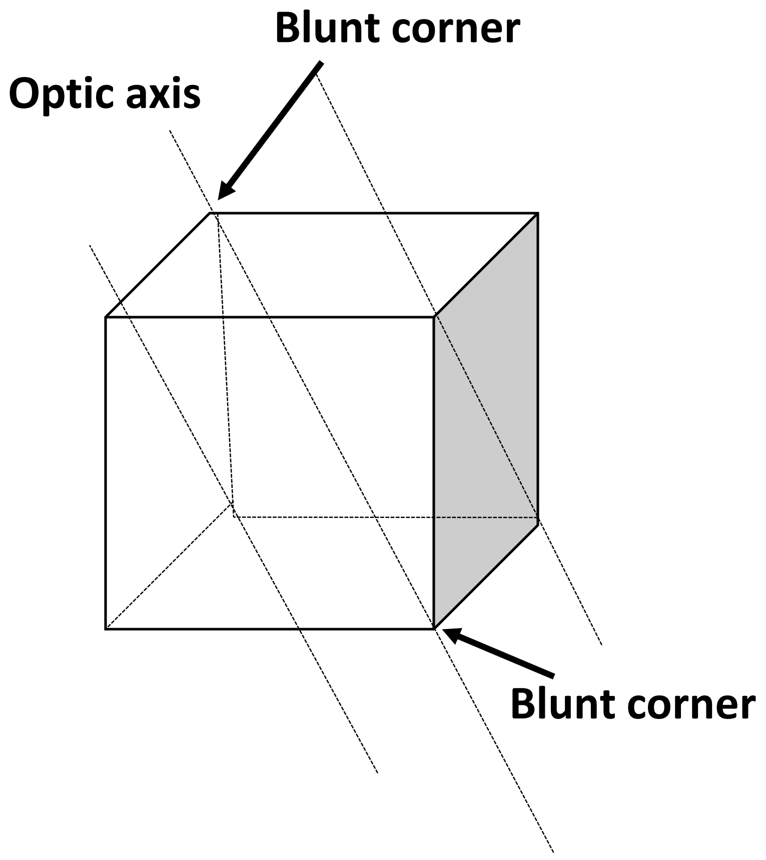




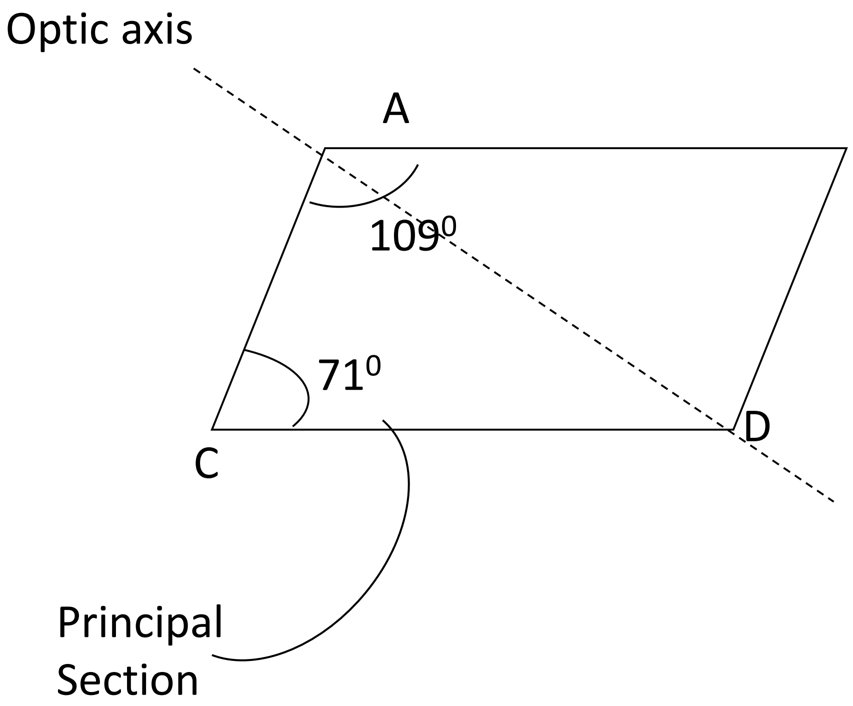
- **Optic axis:** It is axis of symmetry of the crystal. An imaginary line inside the crystal from one of the blunt corners making equal angles with all the three edges or any other line parallel to it.

Blunt corners :

Two diagonally opposite corners in the crystal where all the angles are obtuse.

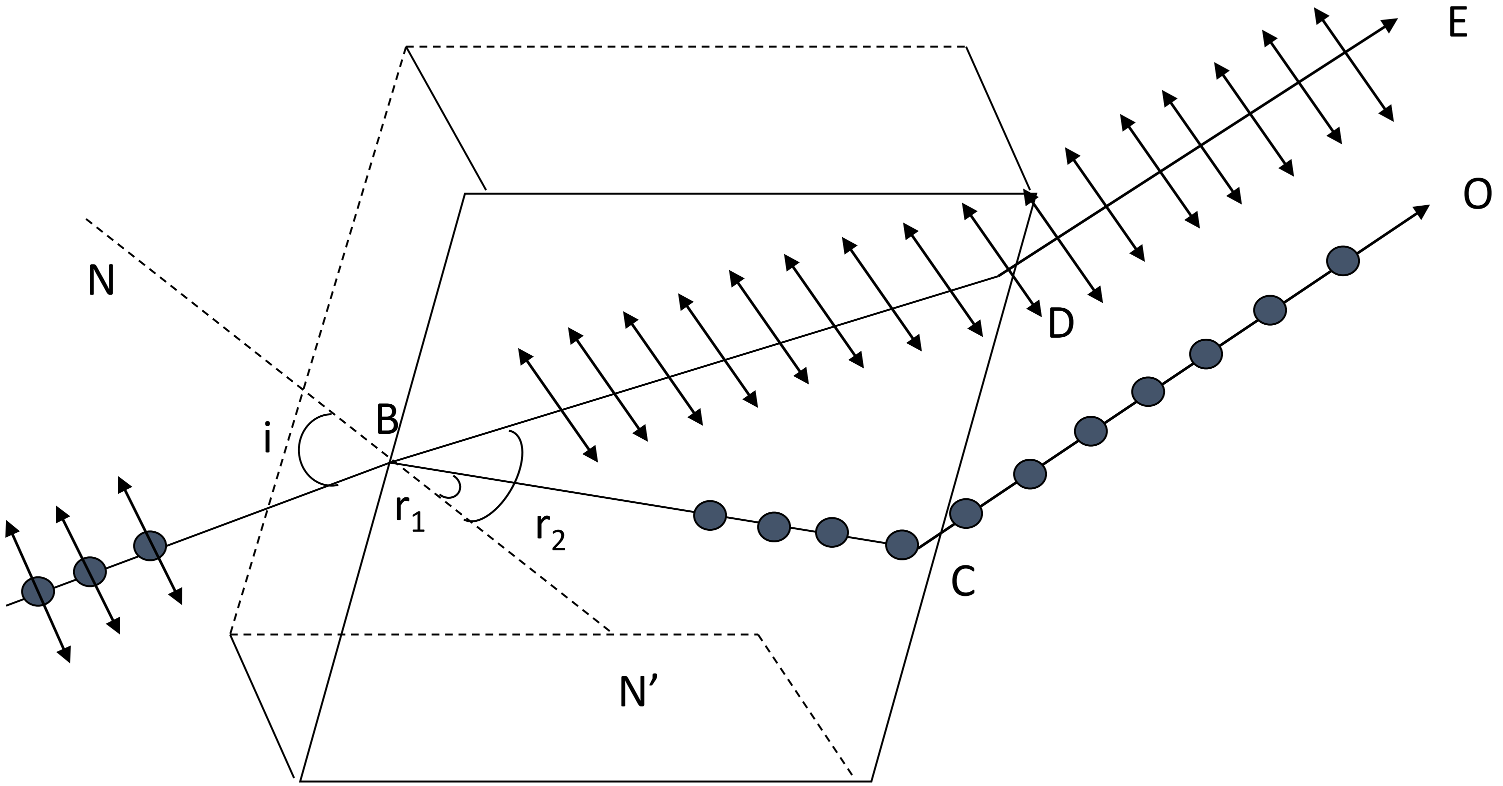


- **Principle Plane/section:** A plane perpendicular to that face of the crystal on which light is incident and which contains the optic axis is called the principle section. This cuts the crystal surface in parallelogram with angles 109^0 and 71^0



- **Principle Plane for O-ray and E-ray:**
- Plane containing optic axis and O-ray: Principle plane of O-ray
- Vibrations of O-ray: perpendicular to the principle section
- Vibrations of E-ray: parallel to the principle section

Phenomenon of Double Refraction



- Double refraction is an optical property in which a single ray of unpolarised light when passes through a uniaxial crystal gets split into two refracted rays, each propagating in a different direction.

- These two rays are named as O-ray (ordinary ray) and E-ray (extra-ordinary ray). Therefore, the phenomenon of splitting of light into two rays is known as double refraction.

- **O-ray:** obeys Snell’s law and **E-ray** does not obey Snell’s law

- Both the rays are plane polarised and their vibrations are at right angles to each other and to the direction of propagation.

- **Refractive index for O-ray:** constant (same velocity for all directions)

- **Refractive index for E-ray:** different (different velocity for different directions)

Huygen's theory of double refraction

- According to Huygen's theory of light: light (unpolarised) travels or propagates in the form of wavefront

- Same concept is applied for polarized light by considering E – ray and O – ray in terms of wavefront

Huygen's theory of double refraction

1. **Monochromatic light incidents on a doubly refracting crystal**
   - ➢ Corresponding point source gives rise to two wave fronts
   - ➢ It corresponds to two refracted rays
2. **Ordinary ray (O-ray)**
   - The wave velocity (v_0) is same in all directions and constant R.I. ($\mu = c/v_0$)
   - Corresponding wave front is spherical
3. **Extra-ordinary ray (E-ray)**
   - The wave velocity (v_e) varies with direction of the wave inside the crystal and different R.I ($\mu = c/v_0$)
   - Corresponding wave front is ellipsoidal

4. Along optic axis

Velocities of both E-ray and o-ray are same.

5. Positive crystals

- Velocity of O-ray > velocity of E-ray
- $\mu_0 < \mu_e$
- Examples: quartz, ice

6. Negative crystals

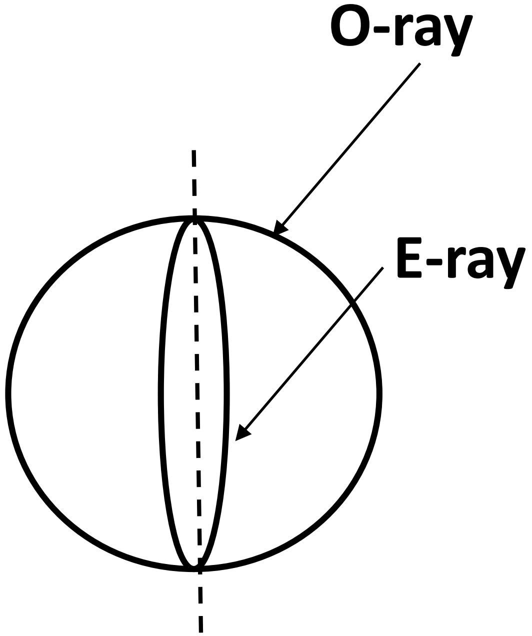
- Velocity of O-ray < velocity of E-ray
- $\mu_o > \mu_e$
- Examples: calcite, tourmaline, etc.

Representation of Positive and Negative crystals

Positive crystal:

Velocity of O-ray > velocity of E-ray

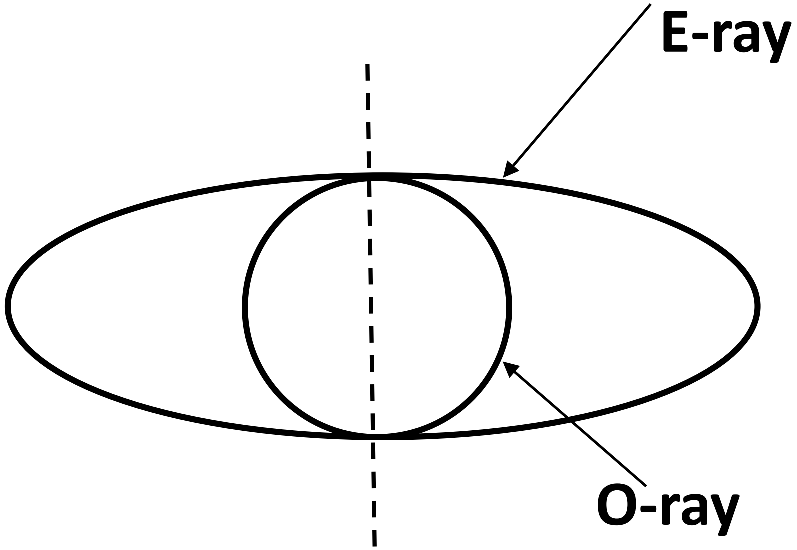
The spherical wavefront is outside and elliptical wavefront is inside



Negative crystal:

Velocity of O-ray < velocity of E-ray

The spherical wavefront is inside and elliptical wavefront is outside



Refractive indices for common materials

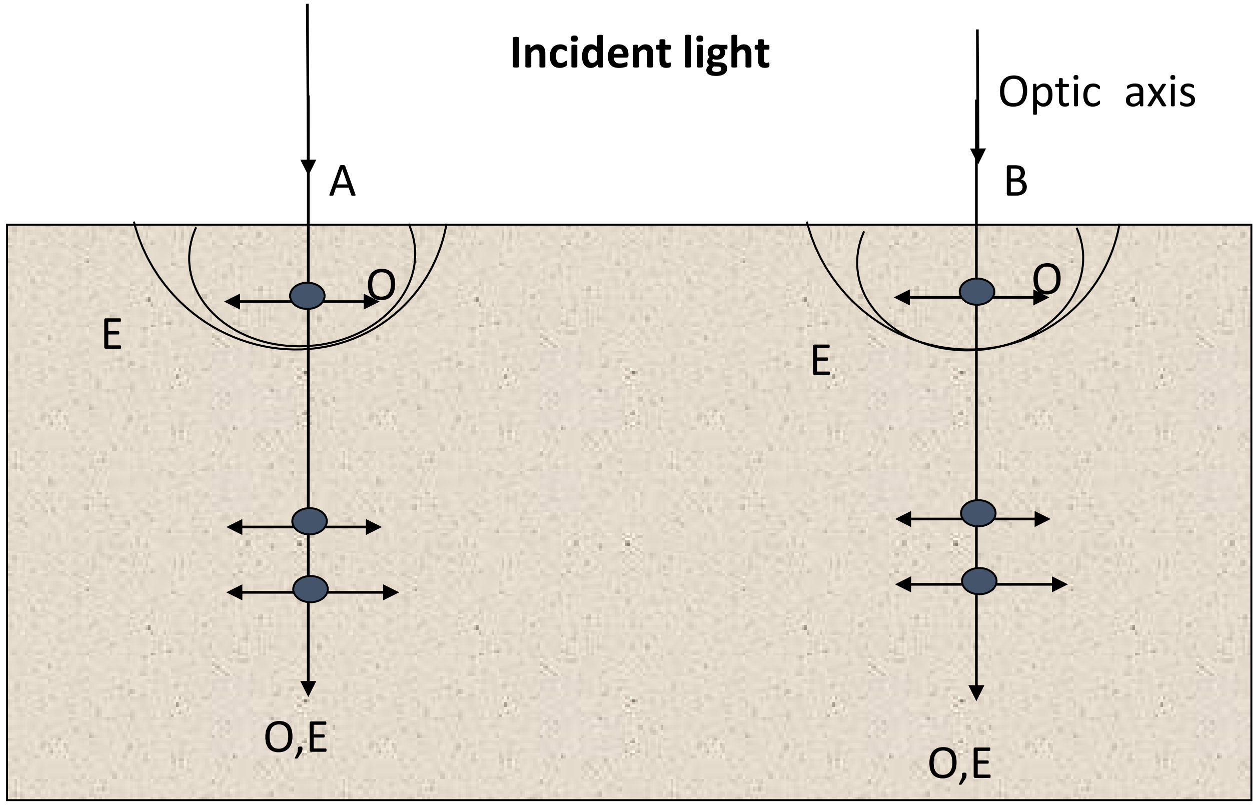
substance	μ_e	μ_o	**Type of crystal**
Calcite	1.486	1.658	Negative
Quartz	1.553	1.544	Positive
Tourmaline	1.620	1.640	Negative
Sodium Nitrate	1.337	1.585	Negative
Ice	1.307	1.306	positive

Propagation of light in calcite crystal

- Negative uniaxial crystal
- Crystal can be cut in three ways:
  1. Optic axis perpendicular to crystal surface
  2. Optic axis parallel to crystal surface
  3. Optic axis inclined to crystal surface

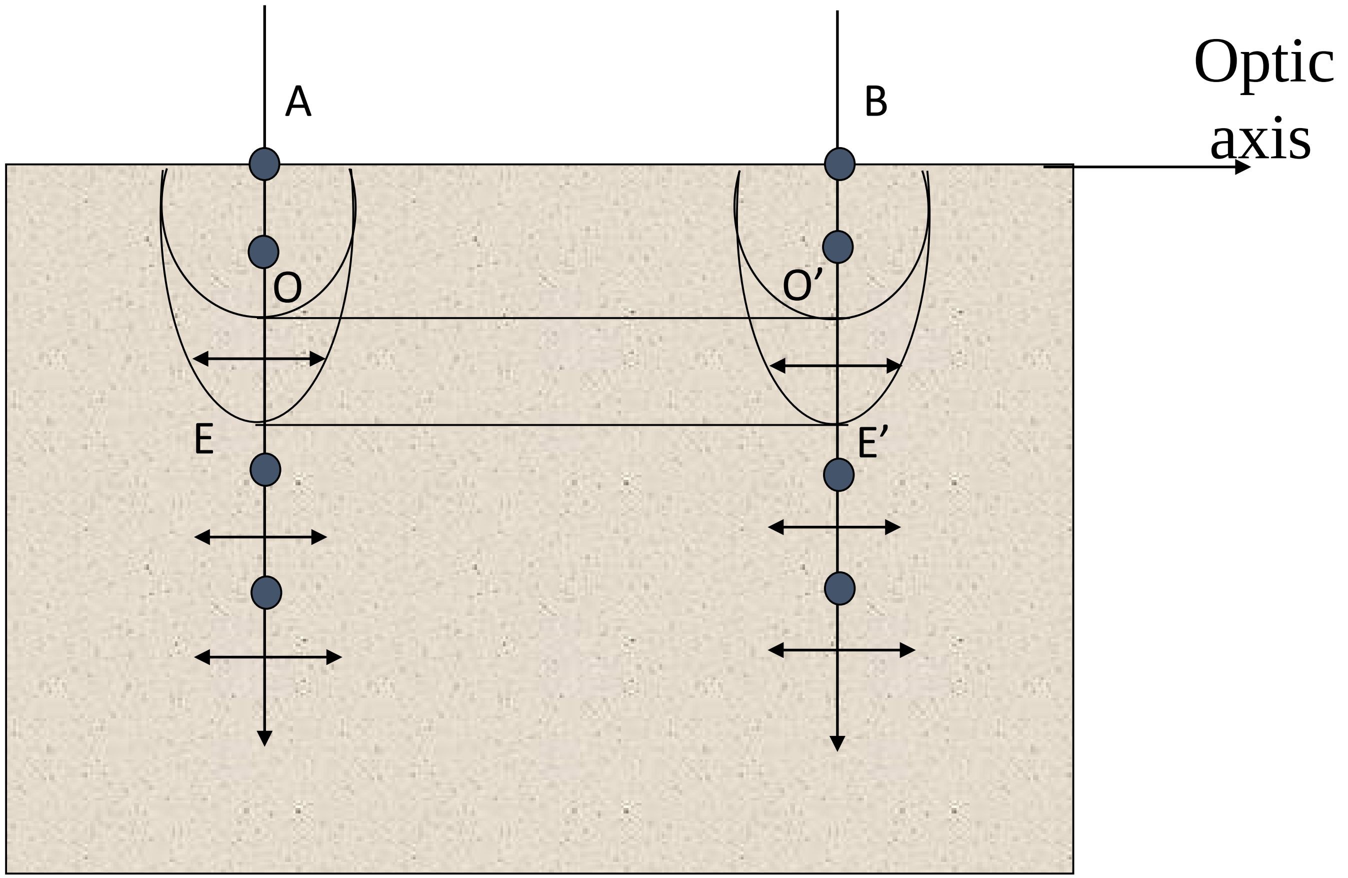
1. Optic axis perpendicular to crystal surface

- **O-ray and E-ray :** travel in same direction and with same velocity
- **Double refraction is absent:** O-ray and E-ray are coincide with each other
- No image



2. Optic axis parallel to crystal surface :

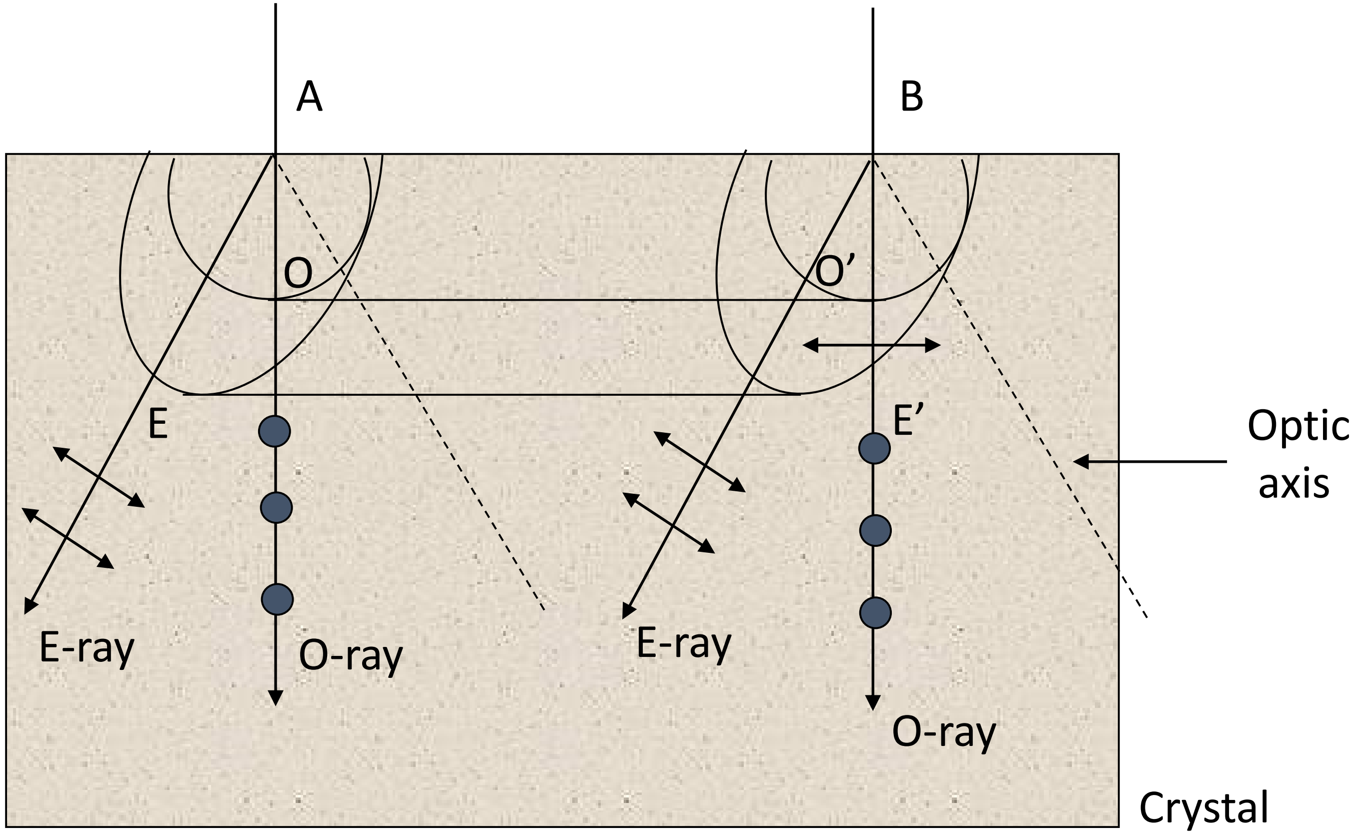
- **O-ray and E-ray :** travel in same direction and with different velocities
- Wavefronts of E-ray and O-ray are separated
- Path difference is present (depends on thickness of crystal)
- No image
- Retardation plates



3. Optic axis inclined to the crystal surface :

- **O-ray and E-ray :** travel in different directions and with different velocities

- Double refraction is present



Retardation Plates

- Used to produce phase difference between O-ray and E-ray
- Optic axis parallel to crystal surface : same direction and different velocity of O-ray and E-ray
- Path difference is produced: depends on thickness of crystal
- Consider negative crystal with thickness t and R.I.(μ) : $\mu_e < \mu_0$
- Optical path difference refracted ray = μt
- Optical path difference for negative crystal $\Delta = \mu_0 t - \mu_e t$
- Phase difference, $\phi = k. \Delta = 2\pi/\lambda .\Delta$
- Positive crystal, $\Delta = \mu_e t - \mu_0 t$

❖ Retardation plates:

A plate of proper thickness cut from double refracting crystal with its faces parallel to optic axis to produce definite value of phase difference between O-ray and E-ray of polarized light

Retarders

- Used to introduce a desired path difference between e-component and o-components of the polarized light

- In retarders, one polarization gets ‘retarded’, or delayed, with respect to the other one

- There is a final phase difference between the 2 components of the polarization. Therefore, the polarization is changed.

- Most retarders are based on birefringent materials (quartz, mica, polymers) that have different indices of refraction depending on the polarization of the incoming light.

Types of Retardation Plates

1. Quarter Wave Plate (QWP)

2. Half Wave Plate (HWP)

Quarter Wave Plate (QWP)

- The crystal is cut with its faces parallel to optic axis

- The thickness is such that it introduces a path difference of λ/4 between E-ray and O-ray (phase difference of 90^0)

- For negative crystal (calcite)

$$t = \frac{\lambda}{4(\mu_0 - \mu_e)}$$

- For positive crystal

$$t = \frac{\lambda}{4(\mu_e - \mu_0)}$$

- Emerging light : circularly polarized (if QWP at 45^0 with incident ray) and elliptically polarized (except 0^0, 45^0 and 90^0)

Half-Wave plate (HWP)

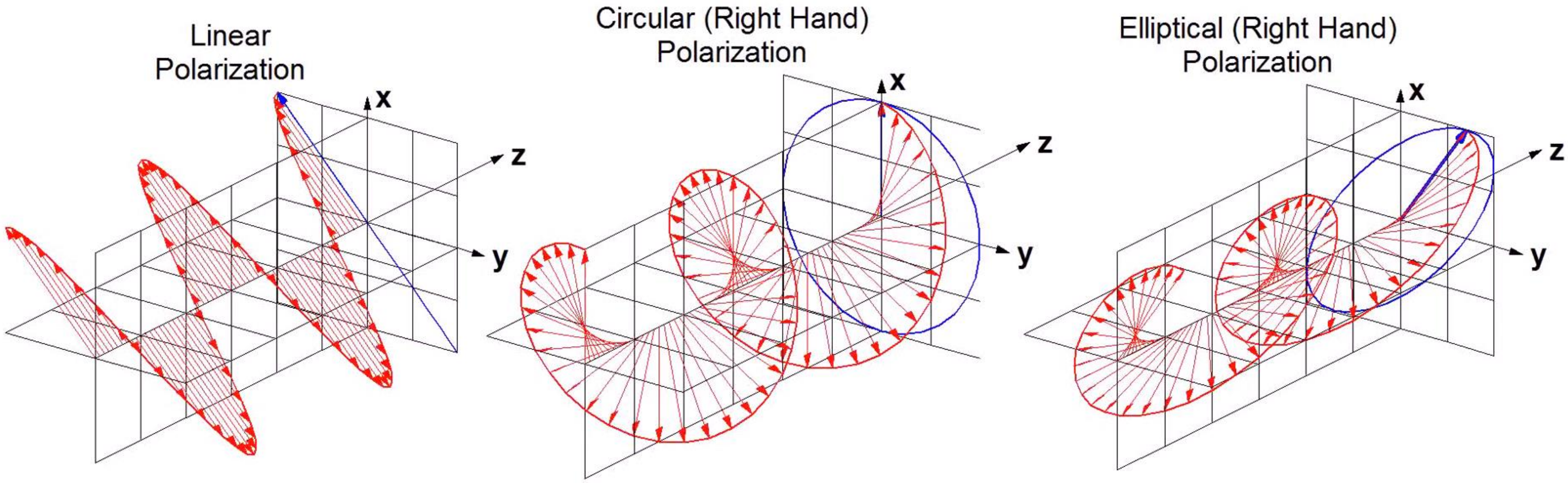
- The crystal is cut with its faces parallel to optic axis

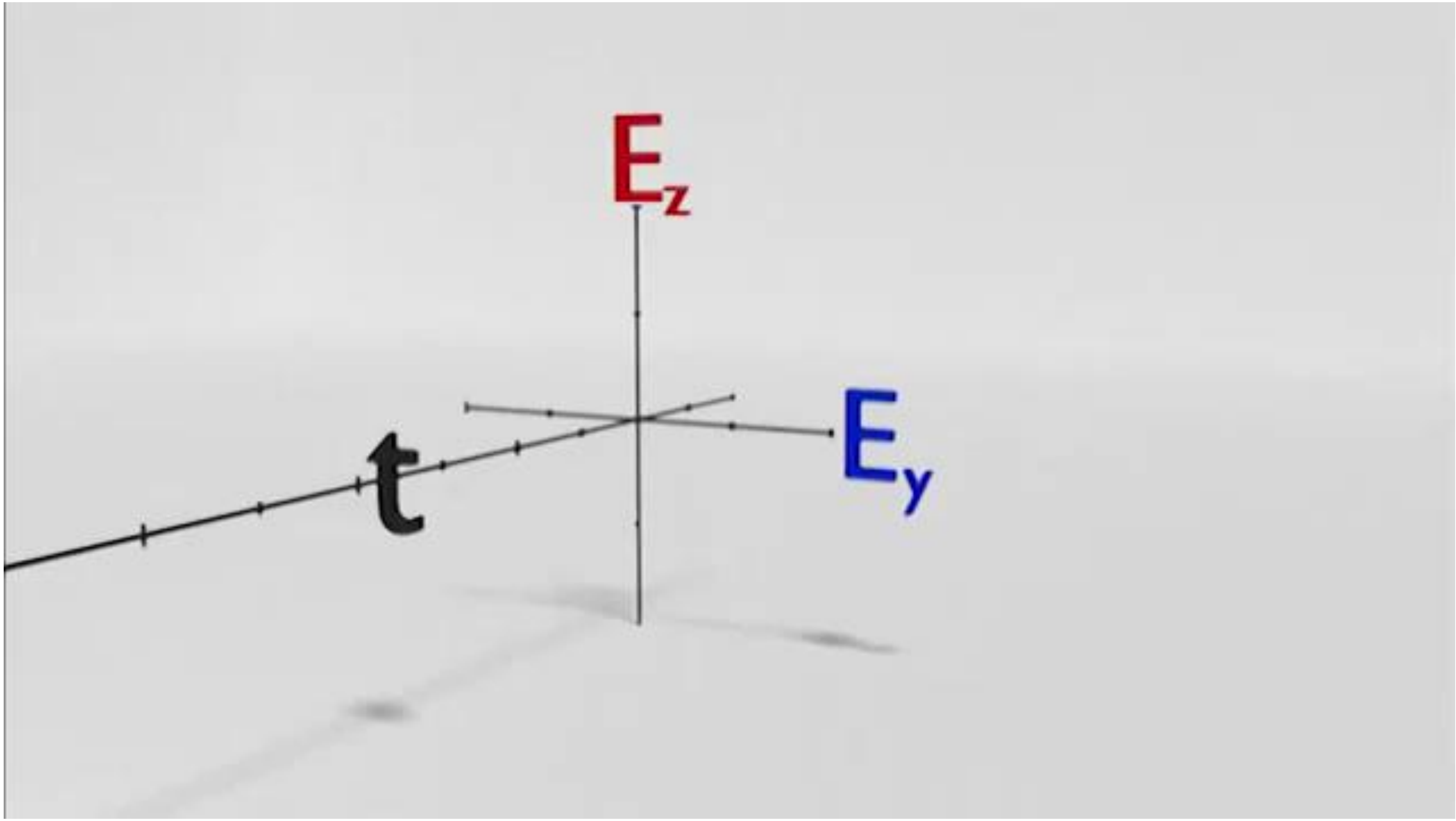
- The thickness is such that it introduces a path difference of $\lambda/2$ between E-ray and O-ray (phase difference of π or 180^0)

- For negative crystal $$t = \frac{\lambda}{2(\mu_o - \mu_e)}$$

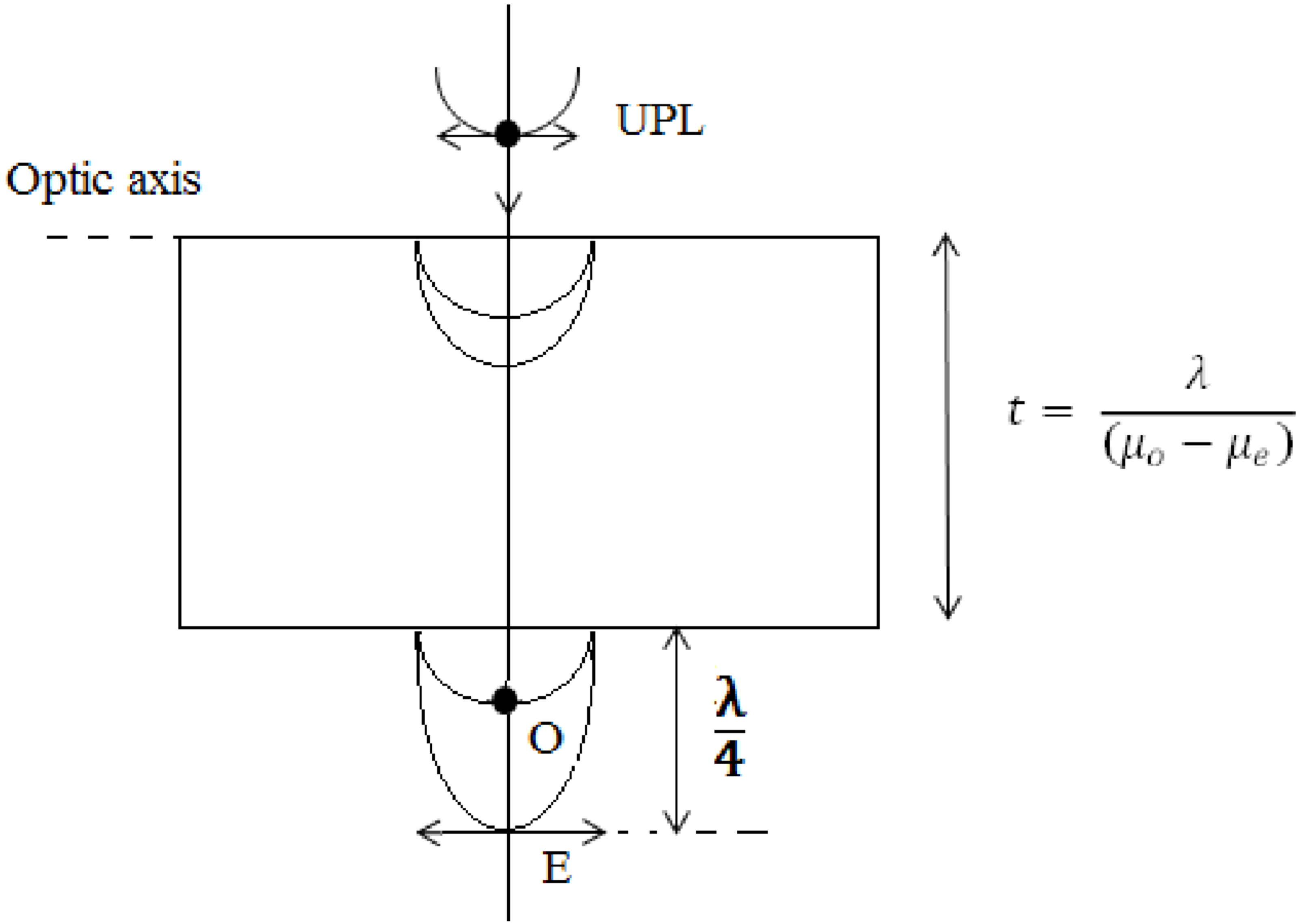
- For positive crystal $$t = \frac{\lambda}{2(\mu_e - \mu_o)}$$

- Incident ray (at θ with optic axis of plate) and emergent ray (at 2θ); both are plane polarized

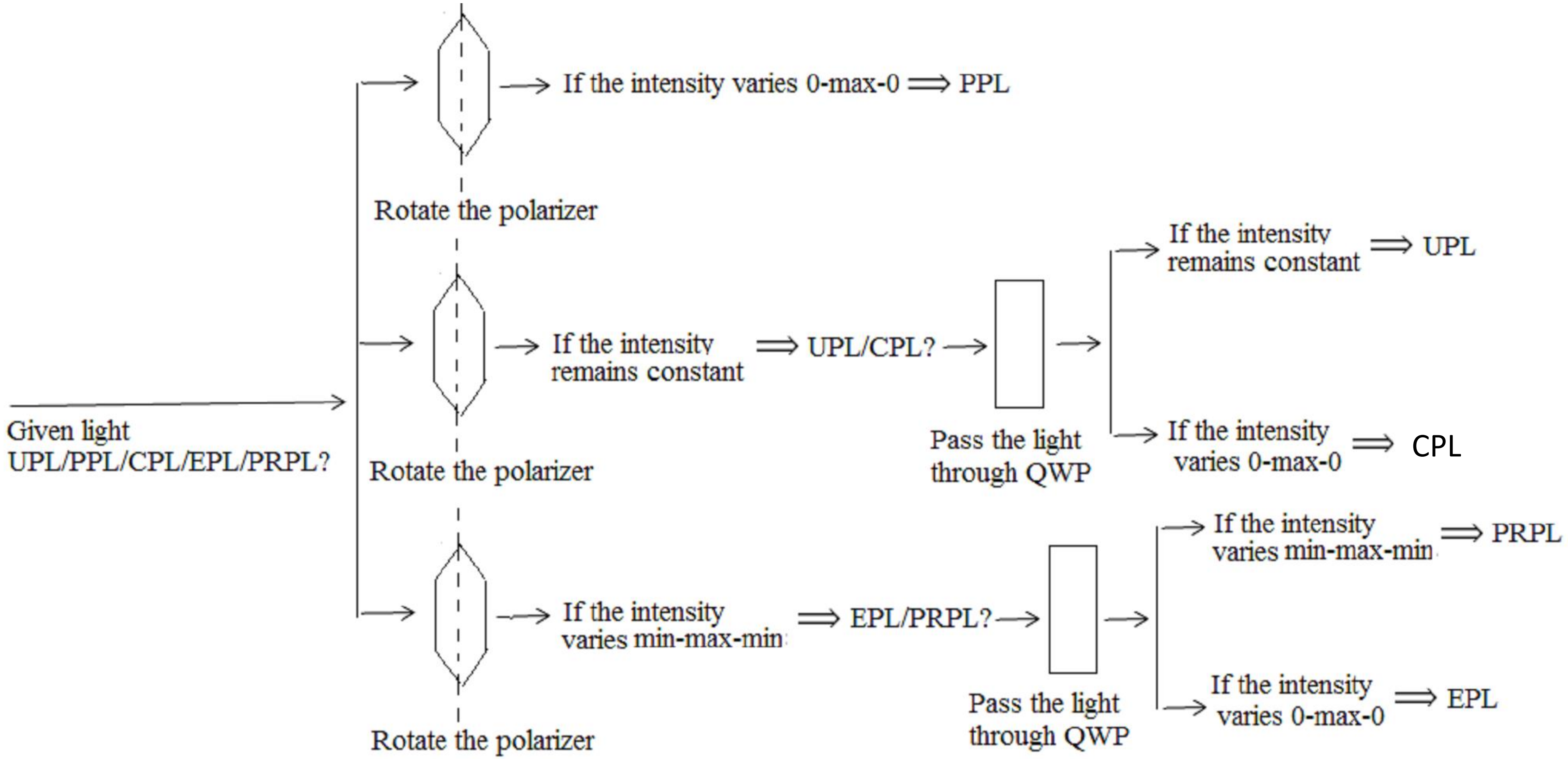

Linear
Polarization
x
z
y
Circular (Right Hand)
Polarization
x
z
y
Elliptical (Right Hand)
Polarization
x
z
y


E_z
E_y
t

Quarter Wave Plate (QWP) made of calcite crystal



Detection of kind of polarized light

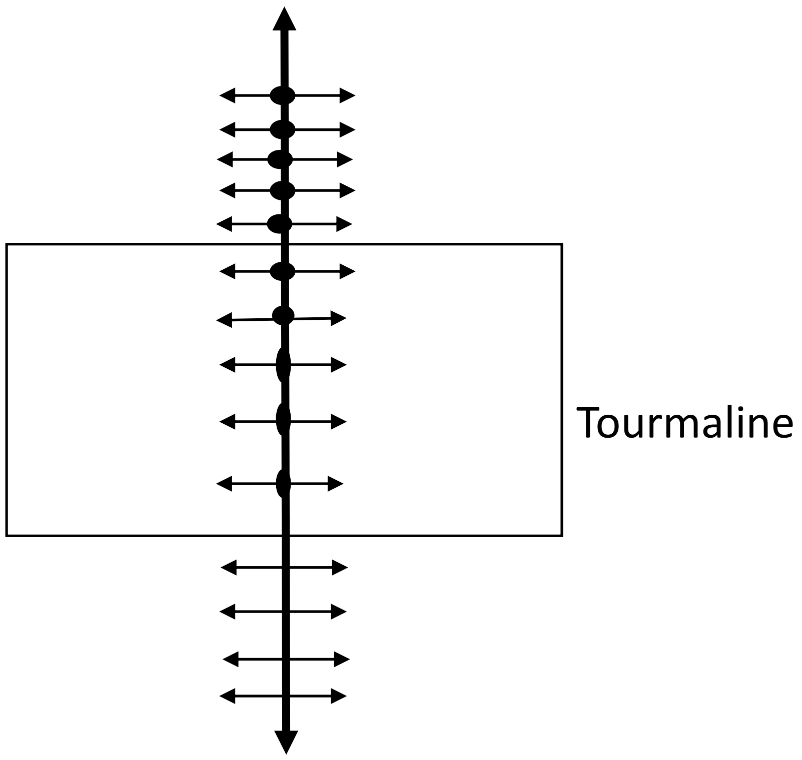


Polarization by Selective Absorption (Dichroism)

The property of doubly refracting crystals to absorb either O-ray or E-ray to larger extent than the other. This phenomenon is called Dichroism.

Example: Tourmaline crystal (also called dichroic materials)

absorbs – O-ray > E-ray



Polarization by Scattering

Sky appears Blue – daytime
Yellowish-red- sunset and sunrise

Scattering power $\propto 1/\lambda^4$

If the earth had no atmosphere?

Polaroids

- Polaroids use dichroism property for polarization of light
- A thin sheet is obtained in which crystals are arranged with their axis parallel to each other.
- This sheet is sandwiched between two glass or plastic sheets.
- The film enclosed between glass plate is called as Polaroid.
- PVA or idosulphate of quinine is used to form polaroids
- It is constructed by stretching a sheet of polyvenyl alcohol which orients the molecules in the direction of the stress and makes them double refracting.

Applications of Polaroids

- ❖ To produce and analyse plane polarized light

- ❖ Sun glasses, camera filters to remove the glare from unwanted object

- ❖ Windows of trains and aeroplanes to control the light intensity

- ❖ Used in Liquid Crystal Displays (LCD)

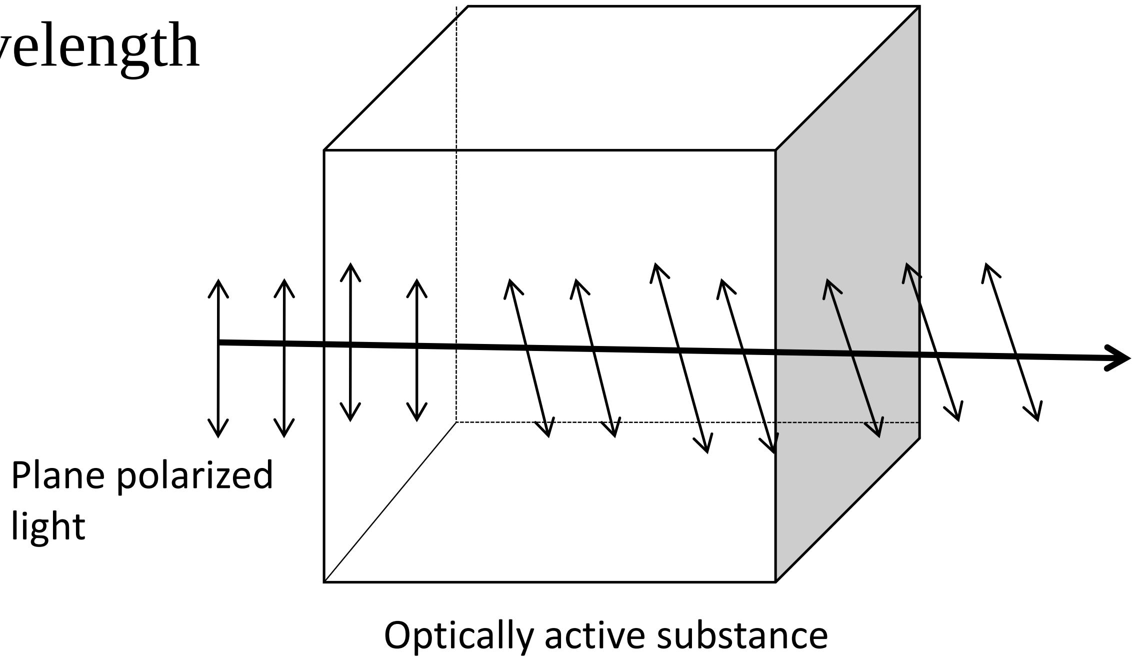
Optical activity

❖ If a plane polarized light is made to pass through certain substances, it is found that the plane of polarization of the emergent light is not the same as that of the incident light and it is rotated through certain angle.

❖ Examples: quartz, sodium chlorate, turpentine, sugar crystal or sugar solution

❖ Rotation amount: distance travelled and wavelength

1. Dextro – rotatory (right handed)
2. Levo – rotatory (left handed)



Specific Rotation of Solution

- It is rotation of plane of vibration of plane polarized light produced by 1decimetre (10 cm) length of solution when the concentration of the solution is 1 gm/cc

$$S = 10\ \theta/(l \times c)$$

Calculate the thickness of doubly refracting crystal required to introduce a phase difference of ∏ radians between O and E rays. Given: Wavelength is 6000 A, $\mu_0 = 1.55$ and $\mu_e = 1.54$

Liquid Crystal

- Intermediate phase between solid and liquid phases of matter

- Flow like any other liquid but a certain degree of molecular arrangement is present

- Tendency to get aligned parallel to an externally applied electric field

- **Types of Liquid Crystals**

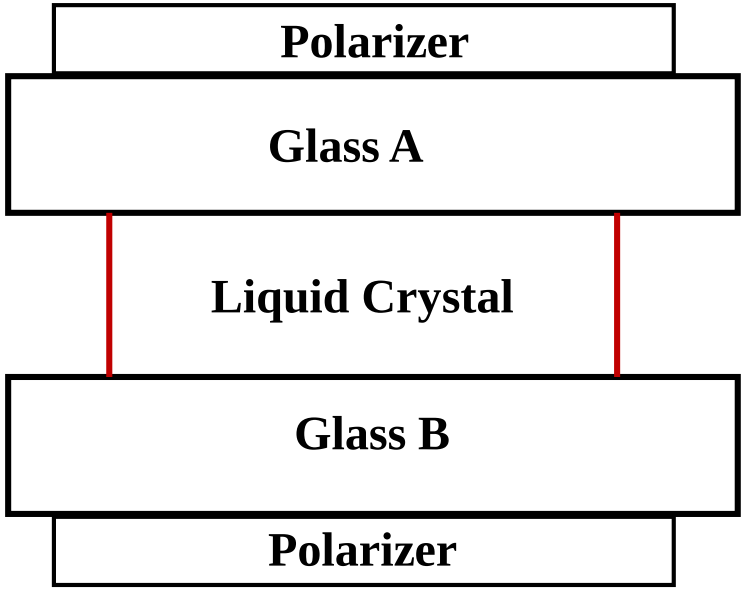
1. Thermotropic phase: temperature dependent

    a. Nematic
    b. Smectic
    c. Cholesteric
    d. Discotic

2. Lyotropic phase: temperature and concentration of liquid crystals molecules dependent

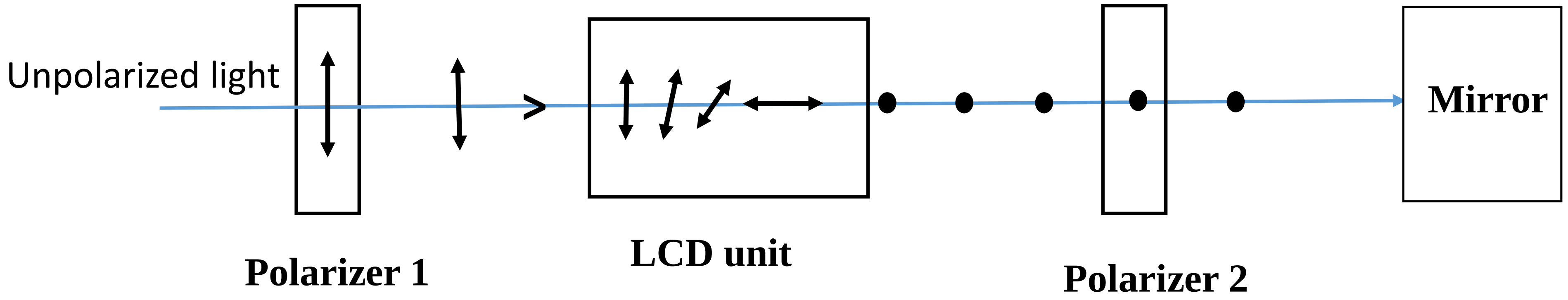
Liquid Crystal Display (LCD)

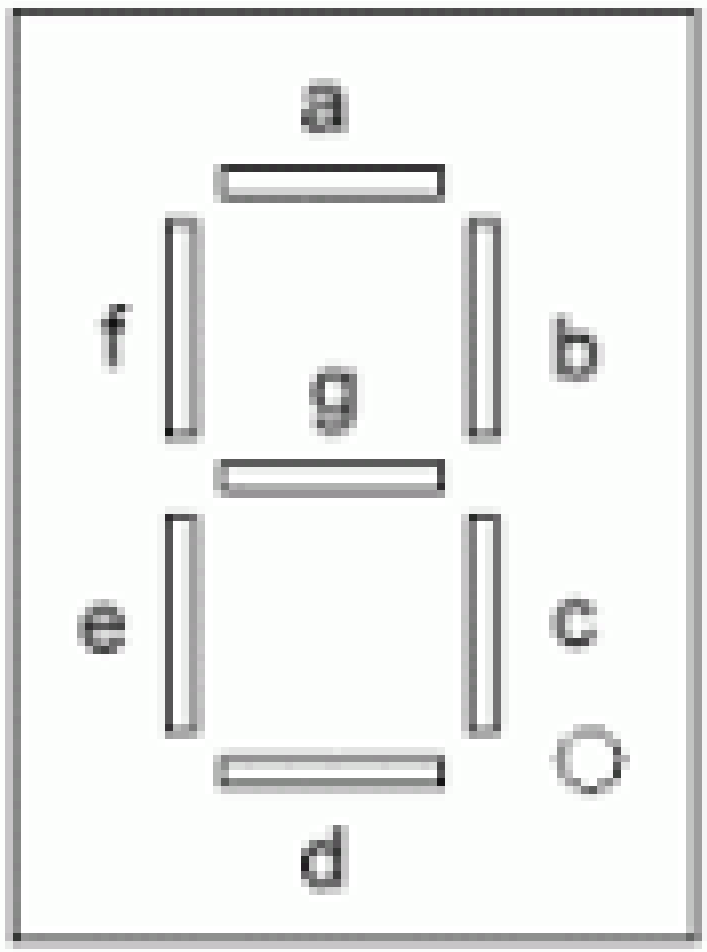
- It is a combination of two states of matter, solid and liquid
- It works on the principle of polarization
- Applications: TV, calculators, clocks, laptops, video games and other electronic instruments
- Liquid crystal material: double refracting and thickness is 10 μm
- It is sandwiched between two conducting glass plates
- Conducting glass plate: 7 segment display for digit and alphabet
- The light that is used on the LCD can be polarized.
- Liquid crystals should be able to both transmit and change polarized light.



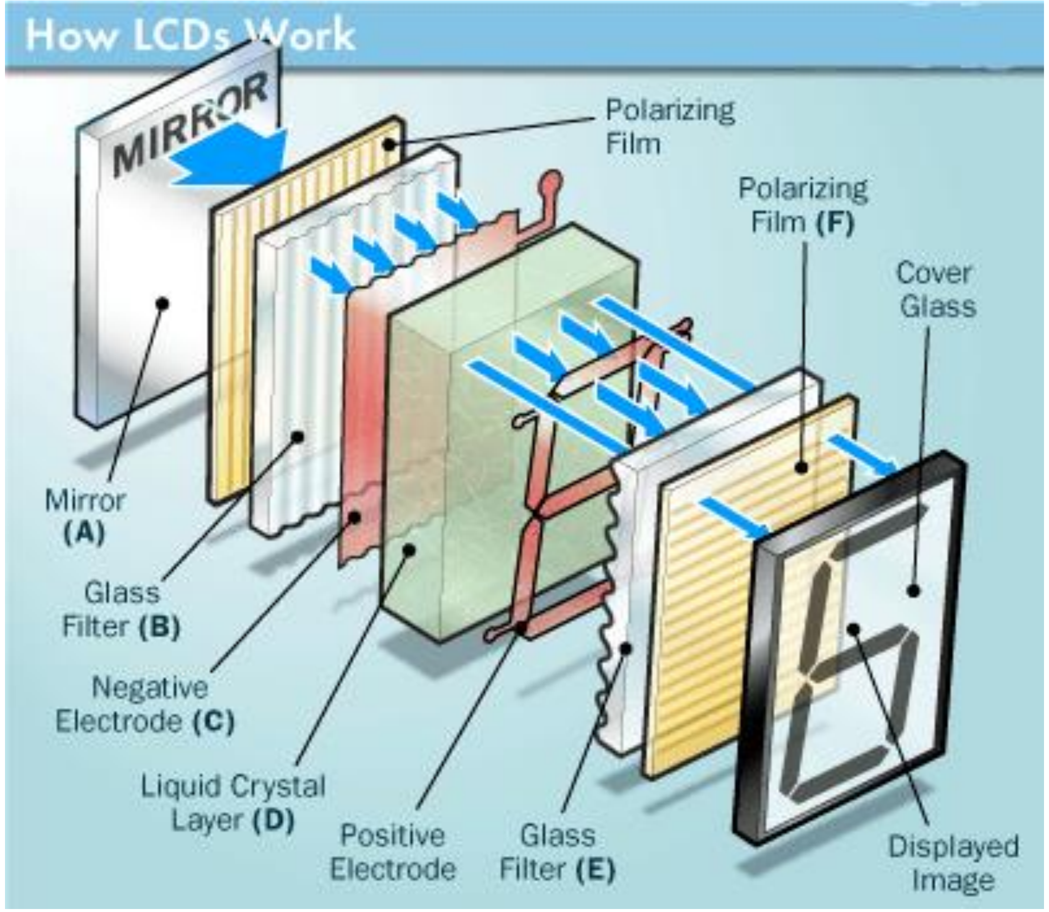
Working Principle of LCDs

- LCD rotates the plane of polarization of plane polarized light.
- Thickness: It should rotates the plane of polarization by 90^0
- Polarizer 1: linearly polarized light
- LCD unit: polarized light rotated by 90^0
- Polarizer 2 (perpendicular to 1): rotated light will pass
- Mirror: act as reflector to send the light back and hence uniform illumination
- External voltage: Molecules will align along field direction
- Plane of polarized will not change and absorb by polarizer




a
f
b
g
e
c
d

- When an electric current is applied to liquid crystal molecules, they tend to untwist.
- This causes a change in the light angle passing through them.
- This causes a change in the angle of the top polarizing filter with respect to it.
- So little light is allowed to pass through that particular area of LCD.
- Thus that area becomes darker comparing to others.



- **Polarization in 3D movies**

- **Photoelasticity:**

➢ Changes in the optical properties of a material under mechanical deformation

➢ The property exhibited by some transparent solids, whereby they become doubly refractive, or “birefringent,” when subjected to stress

➢ To calculate stress in material

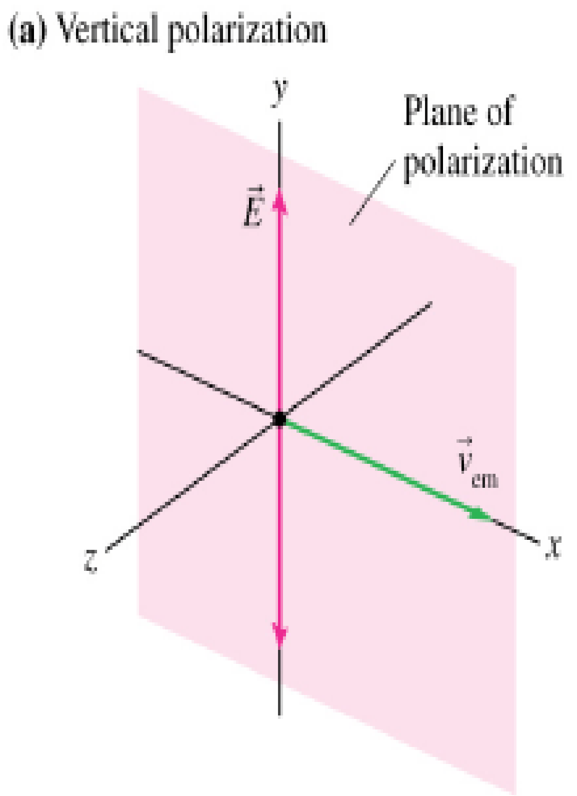
➢ Instruments designed to observe objects under polarized light are called polariscopes or strain viewers

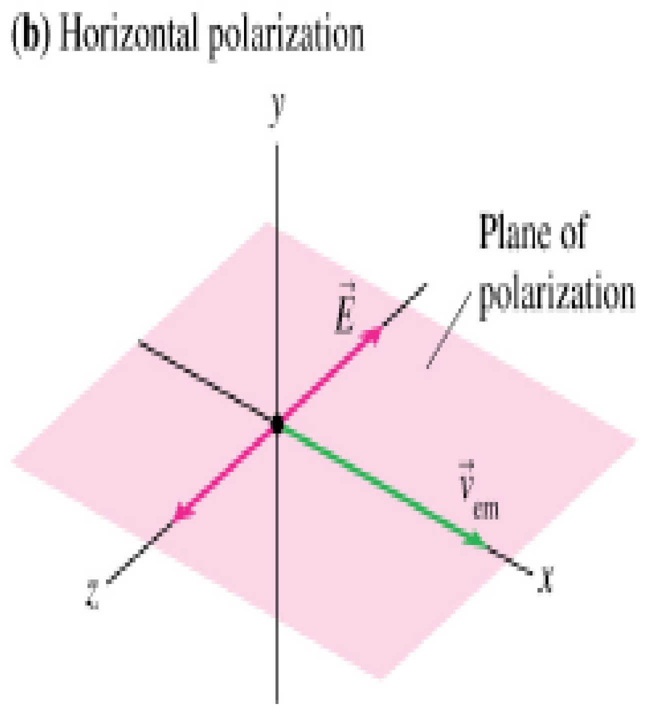
➢ Plane polariscope setup

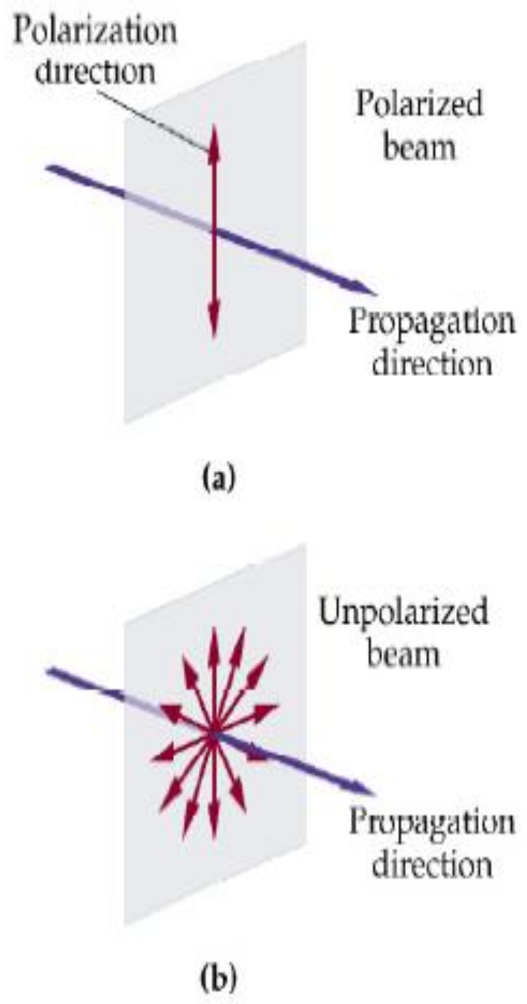
➢ Circular polariscope setup

Plane of Polarization

The plane in which E component is vibrating







- If thickness and wavelength are constant, definite amount of phase difference can be add
- Wavelength = 5893 A^0
- If thickness of plates or crystal is fixed; phase difference can be definite

Que	In the light wave the electric field and magnetic field vibrate ____________________to each other.
A	Parallel
B	Inclined
C	Perpendicular
D	Opposite

Ans	C
Marks	1

Que	The transverse nature of light is shown by
A	Interference
B	Refraction
C	Polarization
D	Dispersion

Ans	C
Marks	1

Que	Plane polarized light has vibrations
A	In one plane and perpendicular to direction of propagation
B	In one plane and along the direction of propagation
C	In all planes and perpendicular to direction of propagation
D	In two planes and perpendicular to direction of propagation

Ans	A
Marks	1

Que	Which of the following cannot be polarized?
A	Radio waves
B	Sound waves
C	Light waves
D	X-rays

Ans	B
Marks	1

Que	When unpolarized light is converted to polarized light its intensity
A	is increased
B	remains same
C	is decreased
D	None of these

Ans	C
Marks	1

Que	**For complete polarization, light should be**
A	Monochromatic
B	Dichromatic
C	From mercury vapour source
D	None of these

Ans	**A**
Marks	1

Que	We use sun glasses in the summer season, which acts as a
A	Polarizer
B	Analyzer
C	Bothe A and B are correct
D	None of these

Ans	A
Marks	1

Que	The device used to produce the polarized light is called as
A	Analyzer
B	Polarizer
C	Prism
D	None of these

Ans	B
Marks	1

Que	In the electromagnetic wave the electric field vibrates in _______________ possible plane/planes perpendicular to the direction of propagation of light.
A	one
B	two
C	three
D	all

Ans	D
Marks	1

Que	A plane in which, the vibrations of electric vector of a plane polarized light comes is called as
A	Plane of polarization
B	Plane of vibration
C	Plane of polarized vibration
D	None of these

Ans	B
Marks	1

Que	A plane perpendicular to the plane of vibration is called as
A	Plane of polarization
B	Plane of vibration
C	Plane of polarized vibration
D	None of these

Ans	A
Marks	1

Que	A plane perpendicular to the vibrations of electric vector of a plane polarized light is called as
A	Plane of polarization
B	Plane of vibration
C	Plane of polarized vibration
D	None of these

Ans	A
Marks	1

Que	What is the angle between the plane of vibration/oscillation and plane of polarization of the polarized light?
A	0
B	$\pi/2$
C	$\pi/4$
D	π

Ans	B
Marks	1

Que	When un-polarized light is incident on the reflecting surface with angle of incident other than polarizing angle, the reflected light is
A	Un-polarized
B	Plane polarized
C	Partially polarized
D	Circularly polarized

Ans	C
Marks	1

Que	**When a Polaroid is rotated, the intensity of light varies but never reduces to zero. It shows that the incident light is**
A	Plane polarized
B	Partially polarized
C	Unpolarized
D	None of these

Ans	**B**
Marks	2

Que	**When a polaroid is rotated, the intensity of light varies from zero to maximum and vice versa. It shows that the incident light is**
A	Plane polarized
B	Partially polarized
C	Unpolarized
D	None of these

Ans	A
Marks	2

Que	The angle of incidence at which maximum polarization occurs is known as
A	Angle of polarization
B	Angle of reflection
C	Angle of refraction
D	Critical angle

Ans	A
Marks	1

Que	The angle of incidence at which maximum polarization occurs is known as
A	angle of reflection
B	Brewester's angle
C	angle of refraction
D	critical angle

Ans	B
Marks	1

Que	When un-polarized light is incident on the reflecting surface with polarizing angle, the reflected light is
A	un-polarized
B	plane polarized
C	partially polarized
D	circularly polarized

Ans	B
Marks	1

Que	Polarizing angle is,
A	same for different reflecting surfaces.
B	different for same reflecting surface.
C	different for different reflecting surfaces.
D	circularly polarized

Ans	C
Marks	1

Difference between polarized and unpolarized light

Polarized light	Unpolarized light
In polarized light vibrations i.e. electric vectors are present in one particular direction which is perpendicular to the direction of propagation.	In unpolarized light vibrations i.e. electric vectors are present in all directions with respect to the direction of propagation
If a rotating Nicol is placed in front of polarized light, the intensity of output light varies from maxima to minima.	If a rotating Nicol is placed in front of unpolarized light, the intensity of output light remains constant.