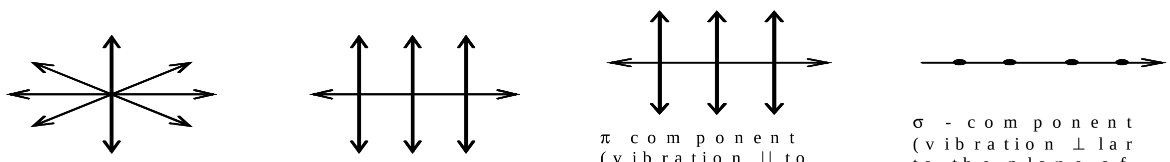
PHYSICAL OPTICS
3. POLARIZATION

POINTS TO REMEMBER

1. The phenomena of restricting the vibrations of a transverse wave into a particular direction is called polarization.

2. Polarisation establishes the fact that the light waves are transverse in nature.



π component (vibration || to the plane of the paper)

σ - component (vibration ⊥ lar to the plane of the paper)

Un-polarized light   Polarized light

3. The intensity of polarized light transmitted through the analyzer varies as the square of the cosine of the angle between the plane of transmission of the polarizer and analyzer. $I = I_0 \cos^2 \theta$

4. Polarization by reflection :

a) If the light is incident on a surface at a certain angle known at Brewster's angle (θ_b), then the reflected light is completely polarized having oscillations perpendicular to the plane of incidence. The Brewster's angle is also called polarizing angle. The refracted ray is partially polarized.

b) Brewster's law: It states that "The tangent of the angle of polarization is equal to the refractive index of the reflecting medium". $\mu = \mathrm{T}an\, i_p$

At this angle the reflected ray and refracted ray are perpendicular to each other.

5. Double Refraction (Bertholinus): When a beam of un-polarized light is incident on a calcite crystal exactly perpendicular to the optic axis of the crystal the ray splits into two refracted beams as they enter the crystal. This phenomenon is called double refraction or Birefringence.

6. Polaroids :The tourmaline crystal is a natural polarizer. Man made polarizing materials is called as polaroids.Polaroid is a thin transparent film containing tiny synthetic dichroic crystals with their optic axes is lined up parallel. A modern Polaroid is a molecular polarizer containing long chains of molecules of poly vinyl alcohol oriented in a preferred direction and stained with an ink containing iodine.

7. Uses of Polaroid:

1. There are used widely as polarizing sun-glasses.
2. Polaroid films are used in 3-D films or pictures.
3. Polaroid sheets are used as polarizer and analyzers.

LONG ANSWER QUESTIONS

1. Explain how plane polarized light is obtained by reflection and refraction. (June2005,May2007)

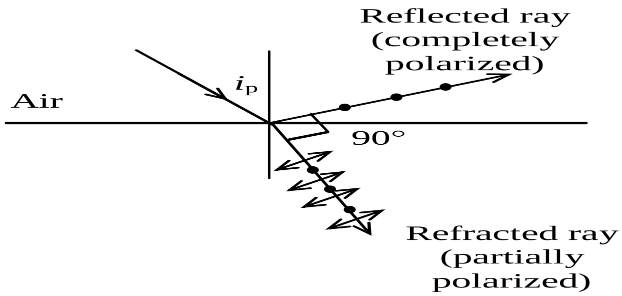
A. 1. Reflection: When an un-polarized light is incident on the surface of a transparent medium, the reflected ray is partially polarized. The vibrations of the reflected beam are parallel to the reflecting surface and perpendicular to the plane of incidence. The particular angle of incidence of light for which the reflected ray is completely polarized is called polarizing angle (i_p) or Brewster's angle.

Brewster's law

It states that "The tangent of the angle of polarization is equal to the refractive index of the reflecting medium".

$$\mu = \mathrm{T}an\, i_p$$

At this angle the reflected ray and refracted ray are perpendicular to each other.

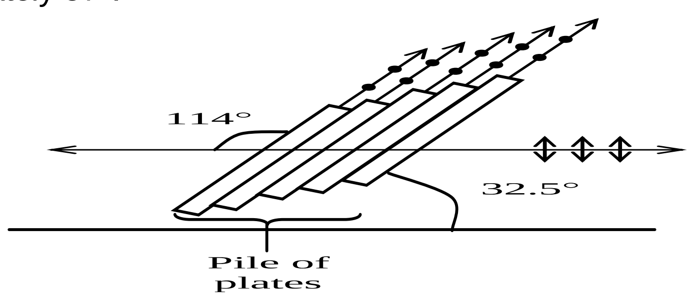


The refracted ray is also partially polarized with vibrations parallel to the plane of incidence and with some vibrations perpendicular to the plane of incidence. Polarizing angle depends upon the wavelength of light.

- Polarizing angles : Air – glass - 57°

  Glass – Air - 33° and Air – water - 53°

2. Refraction: When light is incident on a transparent medium such as glass, the transmitted light is partly polarized. For complete polarization a pile of plates is used. Pile of plates consists of a no of cover glasses arranged parallel to each other. These are fixed in a suitable tube with an angle of inclination 32.5° with the axis of the tube. The angle of incidence is approximately 57°.



The angle between the incident and reflected is about 114°.At each reflection dot components are reflected so that the refracted ray is completely polarized. This can be analyzed by a tourmaline crystal.

SHORT ANSWER QUESTIONS

1. Explain how plane polarized light is obtained by reflection. (May2009)

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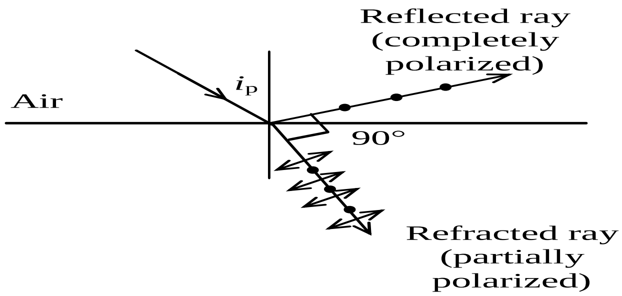
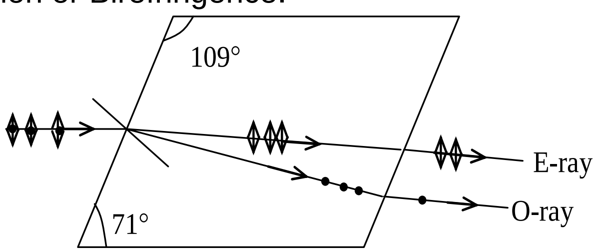


The refracted ray is also partially polarized with vibrations parallel to the plane of incidence and with some vibrations perpendicular to the plane of incidence. Polarizing angle depends upon the wavelength of light.

- Polarizing angles : Air – glass - 57°
  Glass – Air - 33° and Air – water - 53°

2. Explain double refraction or Birefringence of light.
(June2010)

A. When a beam of un-polarized light is incident on a calcite crystal exactly perpendicular to the optic axis of the crystal the ray splits into two refracted beams as they enter the crystal? This phenomenon is called double refraction or Birefringence.



$$\mu_0 = \frac{\sin i}{\sin r_1} \qquad \mu_e = \frac{\sin i}{\sin r_2}$$

The emergent rays are parallel to the incident rays. If a calcite crystal is placed on an ink dot, one can observe two images called ordinary and extra ordinary. If the crystal is rotated, the ordinary image remains stationary and the extraordinary image rotates around the ordinary image. Ordinary ray obeys the laws of refraction and has a fixed value of refractive index for all angles of incidence. The extraordinary ray does not dry the laws of refraction and value of refractive index varies with angle of incidence. Velocity of O-ray is same in all direction and hence its wave front is spherical. Velocity of E-ray is different in different directions and hence the wave front is elliptical. The velocity of O-ray and E-ray is same in a particular direction ($\mu_0 = \mu_e$) called optic axis.

If the crystal has one axis, it is called Uni-axial crystal. Eg quartz, calcite.

If the crystal has 2 optic axes, it is called biaxial crystal. Eg mica, topaz
The vibrations of the electric vector of O-ray and perpendicular to the optic axis and that of E-ray are parallel to the optic axis.
Nichol prism transmits only E-ray and O-ray is totally internally reflected.

3. What are the applications of polarization of light? (March2010)

A. The phenomenon of polarization of light is used in
1. Liquid crystal display in watches, calculators and computers.
2. Using polarization in sunglasses glare from sunlight reflected from water, ice, can be minimized.
3. It is used in making halo grams.
4. By using Polaroid's 3D effect in motion pictures can be created.
5. Used to specific rotator power of a solution.

VERY SHORT ANSWER QUESTIONS

1. The fact that light consists of transverse waves rather than longitudinal waves were known even before the electromagnetic wave nature of light was proved. How this fact was determined?

A: Longitudinal waves require material medium for their propagation. They cannot travel through vacuum. Light waves do not require medium to travel.
Longitudinal waves cannot be polarized whereas transverse can be polarized. Therefore sound waves cannot be polarized whereas light waves can be polarized.
For polarization, the waves need not be electromagnetic. They should be transverse by nature.

2. If a polarizer is placed in front of each slit, what changes be observed in the interference fringes
a) When the two polarizing axes are parallel?
b) When the two polarizing axes are perpendicular?

A: a) when the planes of transmission of two Polaroid are parallel, the light transmitted by the first, can also be transmitted by the second and emergent beam is plane polarized.
b) When the two Polaroid are perpendicular, the transmission of light is not possible i.e., light gets extinguished.

3. Light is reflected from a lead glass plate with index of refraction 1.96. At what angle of incidence must light strike the plate so that the reflected ray is completely plane polarized?

A: $\mu = 1.96$.
$\mu = \tan i_p$ where i_p is angle of polarization
$\Rightarrow i_p = \tan^{-1}(\mu) = \tan^{-1}(1.96) = 62.97^0$

SOVLED PROBLEMS

1. An un-polarized light of intensity I_0 is transmitted by a polarizer and then by the second one. The angle θ between the special directions (transmission directions) is 30^0.What is the intensity of the light received by the observer from the second polarizer?

Sol: The intensity of light that is allowed by the 1st polarizer is half of the intensity I_0 i.e., $I_0/2$.
According to the intensity of light transmitted by the second one is

$I^1 = (I_0/2)\cos^2 30^0 \quad = \frac{I_0}{2}\times\frac{3}{4} \quad = \frac{3I_0}{8}$.

2. Two polarizes are oriented at 34.0^0 to one another. Light polarized by 17.0^0 angle to the optic axis of first polarizer in incident on the first polarizer. What reduction in intensity takes place for the emerging light from the two polarizes?

Sol: The light falling on the polarizer is already polarized by 17.0^0 with respect to that polarizer. According to Malus law

$I_1 = I_0[\cos(17.0^0)]^2$

I_0 is the un-polarized intensity and I_1 is the intensity of light that emerges from the first polarizer.

As the polarizes are oriented 34.0^0 to each other, the intensity of light emerging from the second one can be written as

$I_1 = I_1(\cos 34.0^0)^2$.

$\therefore I_2 = I_0(\cos 17.0^0)^2(\cos 34.0^0)^2 = I_0(0.956)^2(0.829)^2$

Or $I_2 = 0.628 I_0$

$\therefore$ Intensity is reduce by 37.2%

UNSOVLED PROBLEMS

1. A polarizer and an analyzer are oriented so that the maximum amount of light is transmitted. To what fraction of its maximum value is the intensity of the transmitted light reduced when the analyzer is rotated through?

a) 30^0 **b)** 45^0 **c)** 60^0

Sol: Intensity of light transmitted = I

Maximum intensity of light $= I_0$

$I = I_1\cos^2\theta$

a) $\theta = 30^0$

$\Rightarrow I = \frac{I_0}{2}\cos^2 30^0 \Rightarrow I = 0.375 I_0$

b) $\theta = 45^0$

$I = \frac{I_0}{2}\cos^2 45^0$

$\Rightarrow I = 0.25 I_0$

c) $\theta = 60^0$

$I = \frac{I_0}{2}\cos^2 60^0 = 0.125 I_0$

2. Un-polarized light of intensity I_0 incident on a polarizer and the emerging light strikes a second polarized filter with its axis at 45^0 to that of the first. Determine

a) The intensity of the emerging beam and b) its state of polarization.

Sol: $I = I_1, \cos^2\theta$

a) $\theta = 45^0$, $I_1 = \frac{I_0}{2} \Rightarrow I = \frac{I_0}{2}\cos^2 45^0 = \frac{I_0}{2}\times\frac{1}{2} = \frac{I_0}{4}$ b) Parallel to second filter

3. A parallel beam of natural light is incident at an angle of 58^0 on a plane glass surface. The reflected beam is completely linearly polarized.
a) What is the angle of refraction of the transmitted beam? (b) What is the refractive index of the glass?

Sol: $i_p = 58^0$

a) $i_p + r = 90^0 \quad \Rightarrow r = 90^0 - i_p = 90^0 - 58^0 = 32^0$

b) $\mu = \tan\ i_p \quad = \tan 58^0 = 1.6$

4. The refractive index of a certain flint glass is 1.65. For what incident angle is the light reflected from the surface of the glass completely polarized if the glass is immersed in (a) air and (b) water?

Sol: $\mu_g = 1.65$

a) When glass is in air

$\mu = \tan i_p \Rightarrow \tan i_p = \mu_g = 1.65 \Rightarrow \tan i_p = \tan 58^0 47^1$

$i_p = 58^0\ 47^1$ (or) 58.8^0 $(\because 0.8^0 = 47^1)$

b) When glass is immersed in water

$$\mu = \tan i_p \Rightarrow \tan i_p = \frac{\mu_g}{\mu_w} = \frac{1.65}{1.33} = 1.2406 \Rightarrow \tan i_p = \tan 51^0\ 6^1$$

$\Rightarrow i_p = 51^0\ 6^1$ (or) 51.1^0

5. A beam of light is incident on a liquid of 1.0 refractive index. The reflected rays are completely polarized. What is the angle of refraction of the beam?

Sol: $\mu = 1.0$

$\mu = \tan i_p \Rightarrow \tan i_p = \mu = 1.4000 \Rightarrow \tan i_p = \tan 54^0\ 28^1$

$\Rightarrow i_p = 54^0\ 15^1$

$i_p + r = 90^0 \Rightarrow r = 90^0 - i_p = 35^0.45'$

6. At what angle should the axes of two Polaroid's be placed so as to reduce the intensity of the incident un-polarized light to a) $\frac{1}{3}$ b) $\frac{1}{10}$?

Sol: $I = \frac{1}{3} I_0$

a) $I = I_1 \cos^2\theta \Rightarrow I = \frac{I_0}{2}\cos^2\theta \left\{\because i_1 = \frac{I_0}{2}\right\}$

$$\Rightarrow \frac{1}{3} I_0 = \frac{I_0}{2}\cos^2\theta$$

$$\Rightarrow \cos^2\theta = \frac{2}{3} \Rightarrow \cos\theta = \sqrt{\frac{2}{3}} \quad \Rightarrow \theta = 35^0 18^1 \text{ (or) } 35^0 \text{ nearly}$$

b) $I = \frac{1}{10} I_0$

$$I = I_1 \cos^2\theta \Rightarrow \frac{I_0}{10} = \frac{I_0}{2}\cos^2\theta$$

$$\Rightarrow \cos^2\theta = \frac{2}{10} \Rightarrow \cos\theta = \sqrt{\frac{2}{10}}$$

$\Rightarrow \cos\theta = 0.4471 = \cos 63^0\ 24^1$

$\Rightarrow \theta = 63^0 24^1$ (Or) 63^0 nearly

7. The critical angle for total internal reflection for a substance is 45^0.What is the polarizing angle for this substance?

Sol: $C = 45^0$

$$\mu = \frac{1}{Sin\,C} \Rightarrow \mu = \frac{1}{Sin\,45^0} = \sqrt{2}$$

$$\mu \tan i_p \Rightarrow \tan i_p = \mu = 1.414 \Rightarrow \tan i_p = \tan 54^0\,44^1$$

$$\Rightarrow i_p = 54^0\,44^1$$

8. A horizontal beam of vertically polarized light of intensity $43 w/m^3$ is sent through two polarizing sheets. The polarizing direction of the first is 60^0 to the vertical and that of the second is horizontal. What is the intensity of the light transmitted by the pair of sheets?

Sol: $I_0 = 43\,wm^{-2}$

Intensity of light emerging out from polarizer $= I_1 = A_0^2 \cos^2 60^0 = I_0 \left(\frac{1}{4}\right) = \frac{I_0}{4}$

Angle between planes of two sheets $= \theta = 30^0$

$I = I_1 \cos^2 \theta$

$$\Rightarrow I = \frac{I_0}{4} \cos^2 30^0 = \frac{43}{4} \times \frac{3}{4} = 8.1\,w/m^2$$

<u>ASSESS YOURSELF</u>

1. Can two polarized waves interfere? Give the conditions for their interference.

A. Plane polarization of waves must be the same and the waves must be coherent.