OPTICS

Introduction

Basically optics is the branch of science which deals with the study of light. It is also known as the branch of physics, which deals with the study of properties and nature of light. Optics is mainly divided into two parts.

i) **Geometrical optics** which deals with the image formation by optical systems.

That is the Geometrical optics concerns with the formation of images, when light rays passes through an optical system, such as a lens and a prism.

ii) **Physical optics** which deals with the nature of light.

That is the physical optics deals with the nature of light, such as Interference, Diffraction and polarization.

Interference

Interference is that phenomena in which two wave trains, when superposed at a point, produce collinear oscillations such that the resultant intensity at the point of superposition not only depends on the amplitudes of the component waves but also on their phase difference at the point of interference.

Constructive interference

If two wave trains at the point of superposition produced collinear vibrations interfere in the same phase, then the interference is said to be constructive. This is possible when the phase difference of the two wave trains at the point of superposition is $2n\pi$, where n is an integer.

In that case the resultant amplitude is the sum of the individual amplitudes and the intensity is maximum. The corresponding path difference between the two interfering wave trains is an integral multiple of the wavelength, provided the sources are equiphased.

$\therefore$ Path difference = $n\lambda$, $n = 1,2,3,\ldots\ldots$

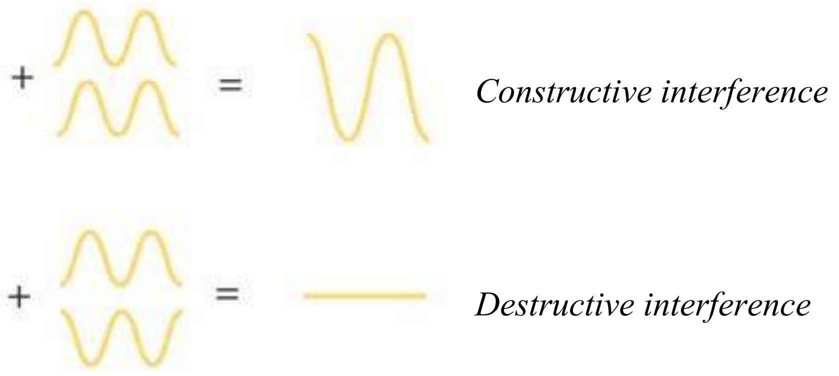
Destructive Interference

If the two wave trains interfere in the opposite phase, then the interference is said to be destructive. This is possible when the phase difference of the two wave trains at the point of super position is $(2n+1)\pi$, Where n = an integer.

In this case the resultant amplitude is the difference of the individual amplitudes and the intensity is minimum.

The corresponding path difference between the interfering waves should be an odd multiple of half the wavelength, if the sources are equally phased.

$\therefore$ Path difference = $(2n-1)\dfrac{\lambda}{2}, n = 1, 2, 3, ...$



Fir(1) . Types of interference

Interference in thin films

The colours of thin films, soap bubbles and oil slicks can be explained as due to the phenomena of interference. Let a plane wave front be allowed to incident normally on a thin film of uniform thickness t. The plane wave front is obtained with the help of a partially reflecting a glass plate G inclined at an angle 45^0 with the parallel monochromatic beam of light.

The plane wave front is partly reflected at the upper surface of the film and partly transmitted into the film. This is shown in figure (1). The transmitted wave front is reflected again from the bottom surface of the film and emerges through the first surface.

The wavefront reflected from the upper surface and the lower surface interfere with each other. The resultant interference pattern can be observed with eye without obstructing the incident wave front.

Here the following two points are observed.

i) The wavelength reflected from the lower surface of the film, traverses an additional path 2 μt. (μt from upper surface to lower surface and μt from lower surface to upper surface). Where μ is the refractive index of the film.

ii) When the film is placed in air, the wave front reflected from the upper surface undergoes an additional phase change of π (Because the reflection takes place at the surface of a denser medium). Here it should be noted that no phase change takes place at lower surface because the reflection takes place at the surface of rarer medium.

Now when the path difference, 2 μt = nλ, Constructive interference takes place and the film appears bright.

Here n = 1,2,3,……

When the path difference, $2\mu t = (2n+1)\frac{\lambda}{2}$,destructive interference takes place and the film appears dark.

Here n = 0,1,2,3……

Interference in the films by Reflection:

Let us consider a plane parallel film, as shown in figure (4) below. Let PA be a ray of light incidenting on the upper surface as shown in the figure (4). PA light ray makes an angle of incidence i. Now part of the light is reflected into the film in the direction AB and the other part is refracted into film .In the direction AC. The light AC which is refracted, is reflected at C and emerges at D. The emerged light DF is parallel to AB.
At the Normal incidence, the path difference between rays AB and DF is the two times the optical thickness of the film $(2\mu t)$.
The two parallel rays of light AB and DF will interfere in the field of Eye and produce interference pattern.

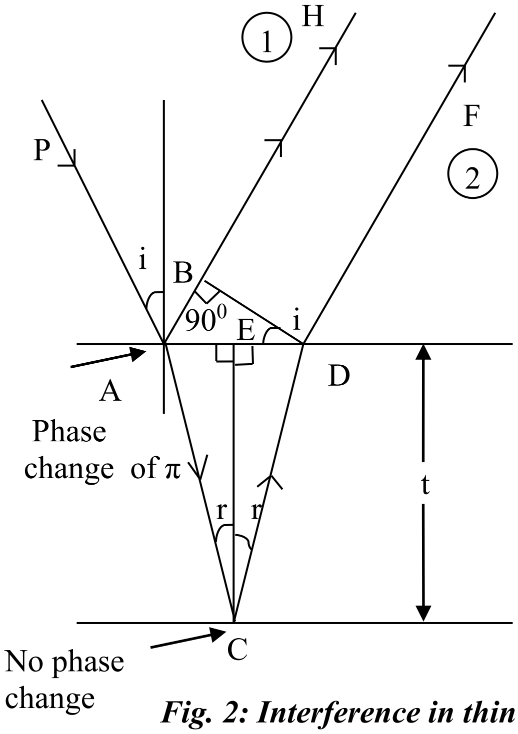


Fig. 2: Interference in thin films (thin parallel films)

The conditions for bright fringe and dark fringe are given below

$$2\mu t\cos r = (2n-1)\frac{\lambda}{2}$$ for Constructive interference

n= 1,2,3,4…….

$$2\mu t\cos r = n\lambda$$ or destructive interference

Where $n = 0,1,2,3,....$

Newton's Rings

When a Plano convex lens with its convex surface is placed on a plane glass plate, an air film of gradually increasing thickness is formed between the two. The thickness of the film at the point of contact is zero. If a monochromatic light is allowed to fall normally and viewed as shown in figure (5), then alternative dark and bright circular fringes are observed.

The fringes are circular because the air film has a circular symmetry.

Newton's Rings are formed because of the interference between the waves reflected from the top and bottom surfaces of the air film between the curved surface and the glass plate as shown in figure (5).

igure (5) shows the experimental setup for Newton's Rings. In the setup G, is the plane glass plate. L is a Plano convex lens. S is a monochromatic source of light. G_2 is the glass plate inclined at an angle 45^0 with the incident parallel light from the source S. C is a double convex lens. M is the microscope, through which we can observe interference fringes.

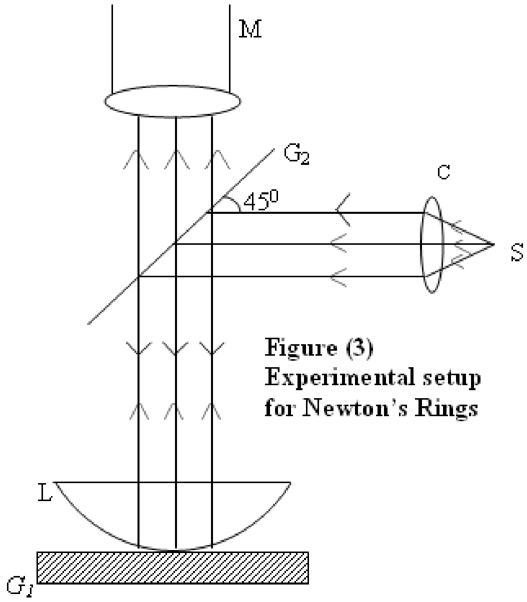


Figure (3)
Experimental setup for Newton's Rings

Radius of curvature of the Plano convex lens is given by

$$R = \frac{D_m^2 - D_n^2}{4\lambda(m-n)}$$

Here $m > n$.
If R is known, the wavelength of the source λ can be calculated as follows.

DIFFRACTION

Introduction

Diffraction confirm the wave nature of light. Usually waves bend round the corner of the obstacles their path. For example, water waves coming from a small hole spread out in all directions as if they have originated at the hole. Similarly sound waves pass round obstacles of moderate dimensions. Similarly light waves bends round the corners of an obstacle is called diffraction.

Diffraction – Explanation

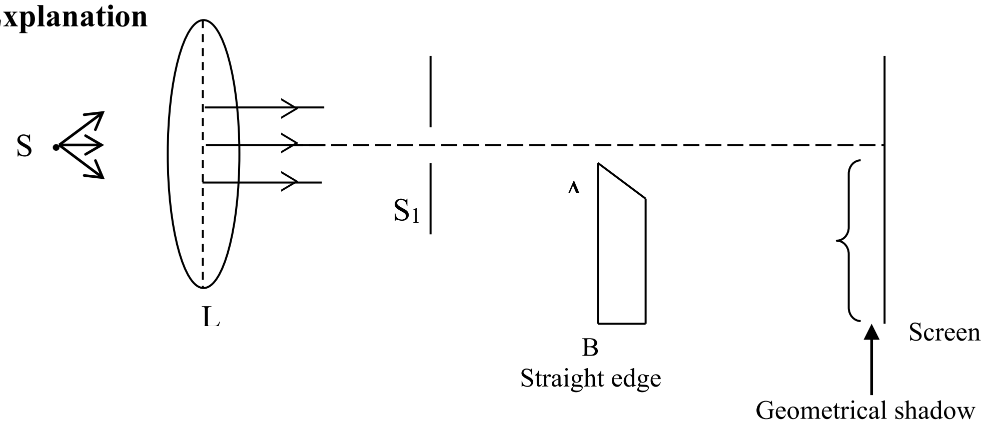


Figure (4) Diffraction at a straight edge.

Light from a monochromatic source 's' is allowed to fall on a lens L. Now the light is rendered parallel. S_1 is a slit. AB is a straight edge. The parallel beam of light passes through slit S_1. The light from the slit S_1 falls on the straight edge. Now a geometrical shadow is observed on the screen. The shadow is not a sharp one. Above the shadow, parallel to the edge A, several bright and dark bands are seen due to diffraction. Thus the bending of light waves round the edges of opaque obstacle or narrow slits and spreading of light into geometrical shadow region is known as diffraction of light.

Fraunhofer Diffraction: In this class of diffraction the source of light and the screen are at infinite distance from the diffraction aperture or obstacle. Due to this for focusing the light, we need a lens. This diffraction can be studied in any direction. Here the incident wavefront is a plane wave front.

Fraunhofer Diffraction at a Single slit

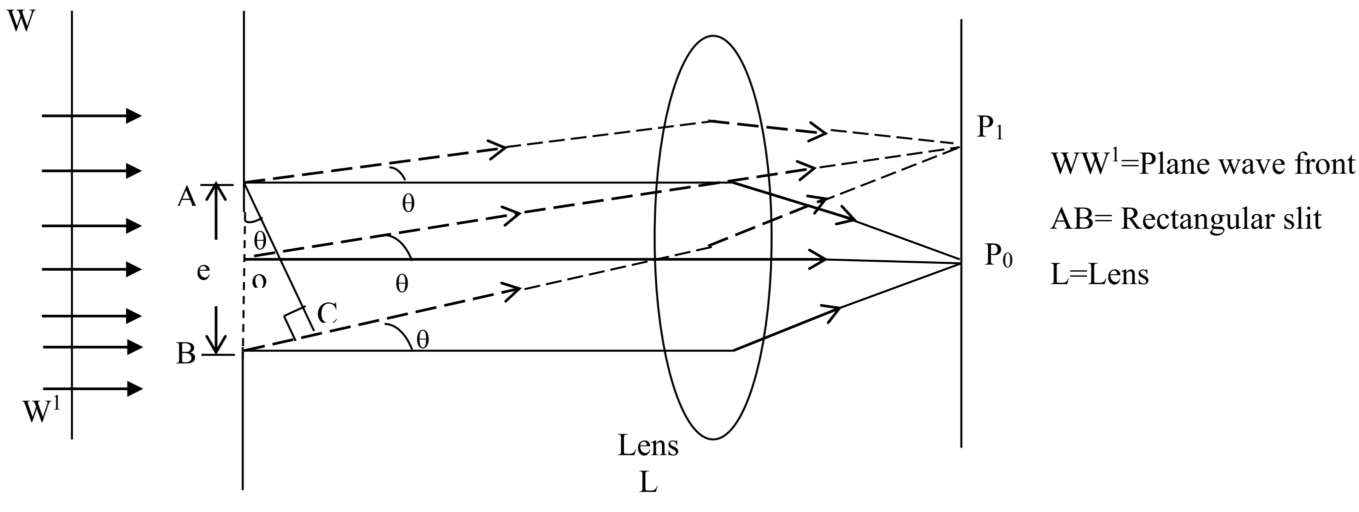


Figure (5) Fraunhofer diffraction at a single

Consider a slit AB of width 'e'. ww' is a plane wavefront of monochromatic light of wavelength λ is incidenting normally on the slit. The diffracted light through the slit is focused by using a convex lens on to a screen placed in the focal plane of the lens. According to Huygens – Fresnel every point on the wavefront in the plane of the slits a source of secondary wavelet. These secondary wavelets spread out in all directions to the right.

The secondary wavelets traveling normal to the slit, along the direction OP_0 are brought to focus at P_0 by the convex lens L. Thus P_0 is a central bright image. The central bright image is formed because there is no path difference for the Ray traveling normal to the slit.

The secondary wavelets traveling at an angle θ with the normal are brought to focus at a point p_1 on the screen. The intensity of point p_1 depends upon the path difference between the secondary waves originating from the corresponding points of the wavefront. To find intensity at p_1, draw a normal AC from A to the light ray at B. Now the path difference between the secondary wavelets from A and B in the direction θ is given by

Path difference = BC.

From the figure (2) triangle ABC is a right angled triangle.

$$\therefore \sin\theta = \frac{BC}{AB}$$

$$\Rightarrow BC = AB\sin\theta \text{ But AB = e}$$

$$\therefore BC = e\sin\theta \qquad \text{------ (1)}$$

Now the phase difference $\phi = \frac{2\pi}{\lambda} \times$ path difference.

$$\therefore \phi = \frac{2\pi}{\lambda} \times e\sin\theta \qquad \text{---- (2)}$$

Now let the width of the slit is divided into 'n' equal parts. The amplitude of the wave from each part is 'a'.

The phase difference between any two successive waves from these parts will be given by

$$\frac{1}{n}[\text{total phase}] = \frac{1}{n}\left[\frac{2\pi}{\lambda}e\sin\theta\right] = d \qquad \text{----- (3)}$$

By the method of vector addition of amplitudes, the Resultant amplitude R is given by

$$R = \frac{a\sin\left(\frac{nd}{2}\right)}{\sin\left(\frac{d}{2}\right)} \qquad \text{---- (4)}$$

From equations (3) and (4)

$$R = \frac{a\sin\left(\not{n}\frac{1}{\not{n}}\frac{2\not{\pi}}{\lambda\not{2}}e\sin\theta\right)}{\sin\left(\frac{\not{2}\pi}{n\lambda}\frac{e\sin\theta}{\not{2}}\right)}, \qquad R = \frac{a\sin\left(\frac{\pi e\sin\theta}{\lambda}\right)}{\sin\left(\frac{\pi e\sin\theta}{n\lambda}\right)}$$

Now let $\frac{\pi e\sin\theta}{\lambda} = \alpha$ ----- (5)

$$R = \frac{a\sin\alpha}{\sin\left(\frac{\alpha}{n}\right)}$$

In the above expression $\left(\frac{\alpha}{n}\right)$ is very small

Hence $\sin\left(\frac{\alpha}{n}\right) = \frac{\alpha}{n}$.

$$\therefore R = \frac{a\sin\alpha}{\left(\frac{\alpha}{n}\right)} \quad , \quad R = \frac{na\sin\alpha}{\alpha}$$

$$\Rightarrow R = \frac{A\sin\alpha}{\alpha}, \text{ Here } A = na \qquad \text{---- (6)}$$

We know that intensity of light is proportional to square of the amplitude.

Intensity $I = R^2$

$$\Rightarrow I = A^2\left(\frac{\sin\alpha}{\alpha}\right)^2 \qquad \text{---- (7)}$$

Diffraction Grating

Diffraction grating is an arrangement which consists of a large number of parallel slits of the same width. These parallel slits are separated by equal and opaque spacings, known as diffraction grating. Fraunhofer used the first grating consisting of large number of parallel wires placed side by side very closely at regular intervals. The gratings are designed by ruling equidistant parallel lines on a transparent material such as Glass with a fine diamond tip. The ruled lines are opaque to light while the space between any two lines is transparent to light and act as a slit. This is shown in figure (1). Usually gratings are designed by taking the cost of an actual grating on a transparent film like that of cellulose acetate.

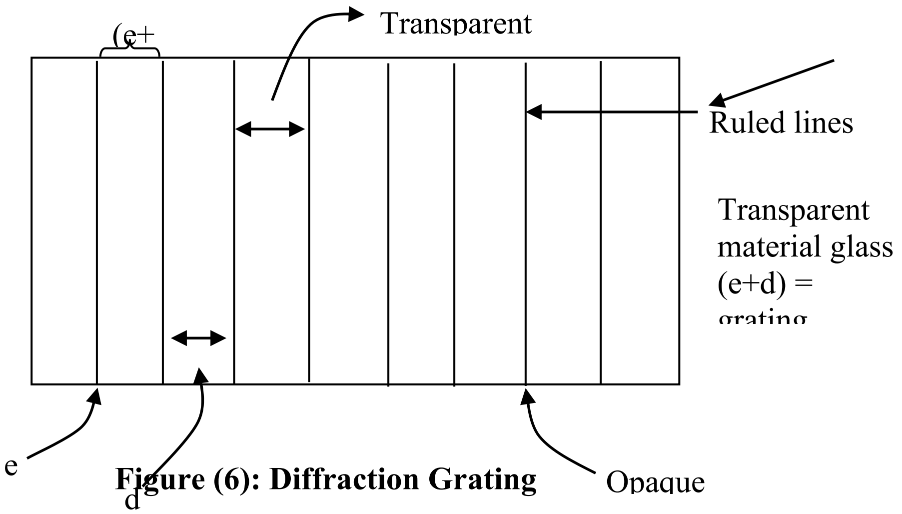


Figure (6): Diffraction Grating

Now solution of cellulose acetate is poured on the ruled surface and allowed to dry, for the formation of a thin film. This thin film is easily detachable from the surface. These impressions of a grating are preserved by mounting the film between two glass plate thin.

Let e be the width of each line.

Let d be the width of the slit.

Now $(e+d)$ is known as grating element.

If 'N' is the number of lines per inch on the grating, then

$N(e+d)$ grating elements are there per inch.

i.e. $N(e+d) = 1'' = 2.54cms$

$$(e+d) = \frac{2.54}{N}cm$$

Usually there will be 15,000 lines per inch (or) 30,000 lines per inch on the grating. Due to the narrow width of the slit, it is comparable to wavelength of light.

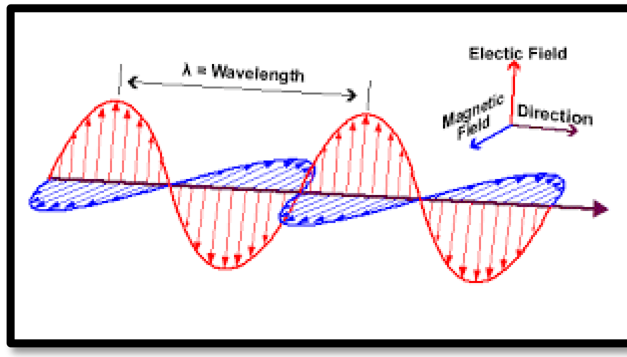
When light falls on the grating, the light is diffracted through each slit.

As a result, both diffraction and interference of diffracted light gets enhanced and forms a diffraction pattern. This pattern is known as Diffraction pattern.

Polarization

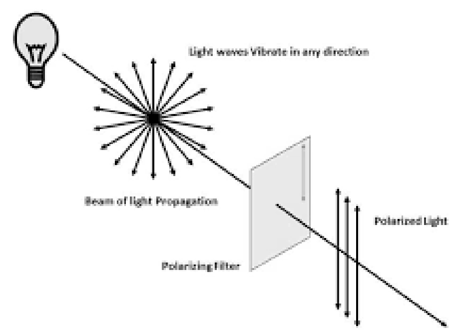
Introduction

The phenomenon of interference and diffraction pattern shows that light has wave nature. But they do not reveal that the light rays are having longitudinal or transverse wave nature form.



The Phenomenon of polarization shows that light has transverse nature form. Light is made up of electromagnetic waves. The electric and magnetic fields are represented by electric field vectors $\bar{E}$ and Magnetic field vectors $\bar{B}$. These field vectors are perpendicular to the direction of propagation of light rays. The polarization process was discovered by "Erasmus Bartholinus".

What is meant by Polarized light and unPolarized light?



<u>Polarized light</u>:- If the vibrations of a light are confined to only one directon, it is called polarized light.

<u>Unpolarized light</u>:- If the vibrations of a light are confined in all directions it is called unpolarized light.

There are three different types of polarized light.

1.Plane polarized light 2. Circularly polarized light

3. Elliptical polarized light

Explain the process of Polarization of a light wave.

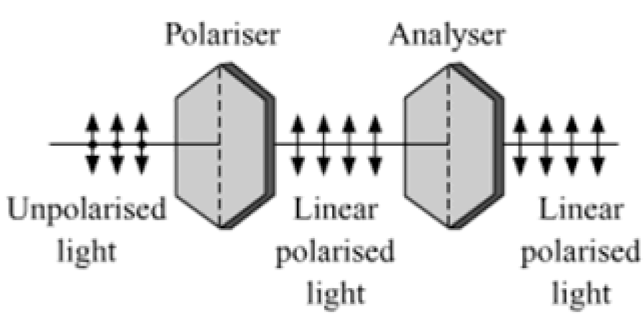
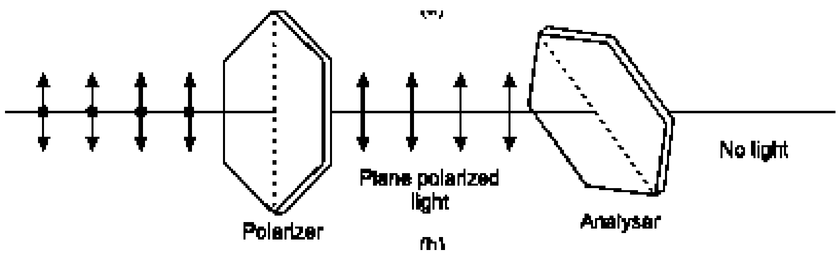


Fig:- Tourmaline crystal-Polarized light

Consider an ordinary beam of light or Unpolarized light passing through tourmaline crystal. This tourmaline crystal allows the components of light rays that are vibrating parallel to its axis and does not allow the light that are not parallel to the axis of the crystal.

If the tourmaline crystal is rotated by taking the incident beam as an axis, there is no variation in the intensity of the emergent beam. The emergent beam from tourmaline crystal vibrates parallel to the axis of the crystal.

The first tourmaline crystal that produces polarized light is called polarizer and second tourmaline crystal that produces polarized light is called analyzer.



If the emergent beam from first tourmaline crystal is passed through another tourmaline crystal, which is perpendicular to the first crystal, then no light is passed from the second tourmaline crystal.

If the second tourmaline crystal is rotated with the incident beam as an axis, then intensity of the emergent beam varies from the second crystal and it has maximum and minimum intensity two times within one complete rotation.

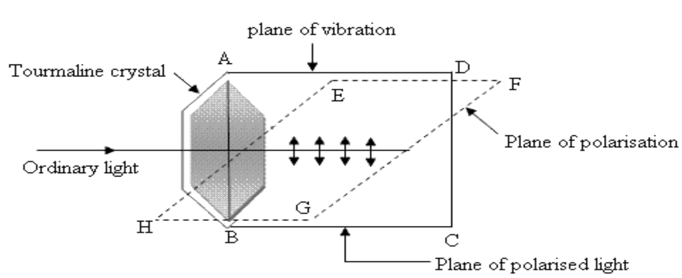
The emergent beam is maximum when two crystals are parallel to each other. The emergent beam is minimum when two crystals are perpendicular to each other.

What is meant by Plane of polarization and plane of vibration?

If the vibrations of a polarized light takes place in plane region, it is known as **plane of vibration**.

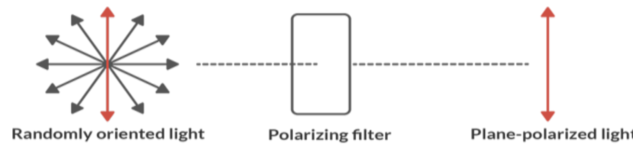
The plane perpendicular to the plane of vibration is known as **plane of polarization**.

From the Figure, the plane ABCD is plane of vibration and EFGH is plane of polarization and in this region no vibrations takes place.



Explain different types of polarizations.

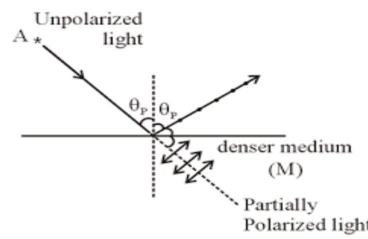
1. <u>Plane polarized light</u>:-



"If the vibrations are confined to a single plane then it is called plane polarized". If the direction of vibration is parallel to the plane of paper, it is represented by arrows.

If the direction of vibration is perpendicular to the plane of the paper are represented by dots.

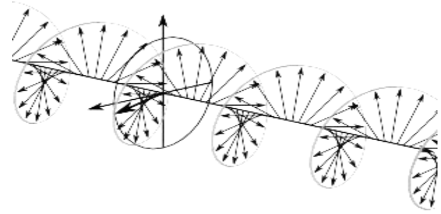
2. <u>Partially polarized light</u>:-



"If the linearly polarized light contains small additional components of unpolarized light, it becomes partially polarized light".

It is represented by either more arrows and less dots or less arrows and more dots.

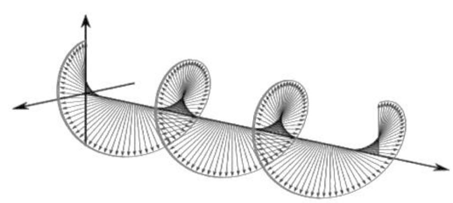
3. <u>Circularly polarized light</u>:-



(i). In circular polarization, the electric vector of constant amplitude no longer oscillates, but rotates while proceeding in the form of helix.

(ii). If the vector rotates in the clock wise direction with respect to the direction of propagation, it results in right circularly polarized light, while the rotation in anticlock wise direction results in left-circularly polarized light.

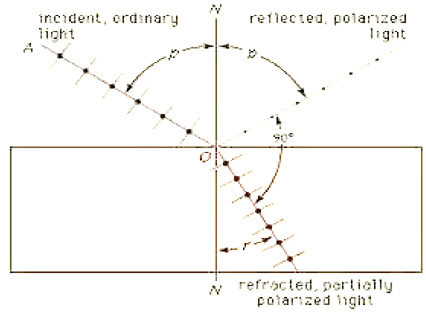
4. <u>Elliptical polarized light</u>:-



- If the amplitude of the electric vector is not a constant but varies periodically then it results in elliptical polarized light.
- The electric vector has maximum amplitude when oscillating horizontally, and minimum amplitude when oscillating vertically.

Explain the production of plane polarized light by reflection.

Brewster's angle or Polarization by reflection



In the year 1811, Sir David Brewster noticed that extent of polarization of reflected light is observed by varying the angle of incidence on the surfaces of different transparent materials.

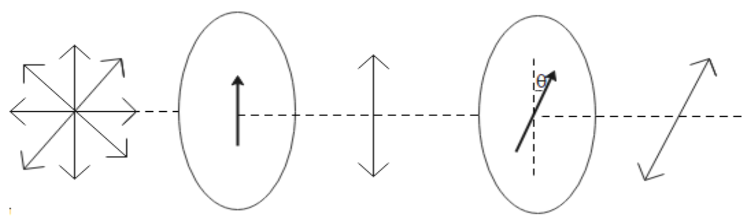
The Brewster angle for glass is 57°.

For a particular angle of incidence, the reflected light is completely plane polarized. This angle of incidence is known as Brewster's angles or angle of polarization.

The angle of polarization varies with material. If the incident light makes Brewster's angle then reflected light is completely plane polarized while transmitted light is partially plane polarized light.

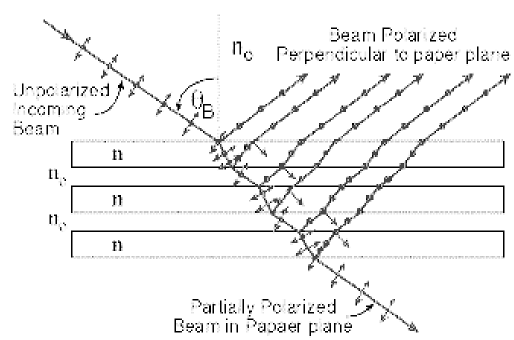
Explain the production of plane polarized light by refraction.

When un-polarized light is incident at a polarizing angle, the reflected light is completely plane polarized and transmitted light is partially polarized.



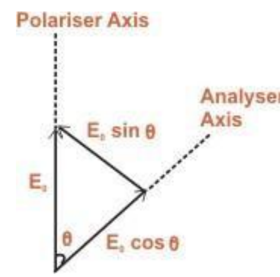
If the process of reflection at the polarized angle, is reflected using 15 plates, finally the transmitted light becomes purely plane polarized, such an arrangement is called pile of plates. Thus pile of plates acts as polarizer.

Malus law



" The intensity of the polarized light transmitted through the analyzer varies as the square of the cosine of the angle between the plane of transmission of the analyzer and the plane of polarizer".

- Let ‘a’ be the amplitude of the incident plane polarized light and ‘θ’ be the angle between the planes of polarizer and analyzer.
- The intensity of light transmitted through analyzer is $I_\theta = (a\cos\theta)^2 = a^2\cos^2\theta$
- If ‘I’ be the intensity of the incident polarized light, then $I = a^2$, $I_\theta = I\cos^2\theta$
- When θ= 0, the two planes are parallel i.e $I_\theta = I$
- When $\theta = \pi/2$, the two planes are perpendicular, $I_\theta = 0$.
- The above results are experimentally observed in case of two tourmaline crystals.

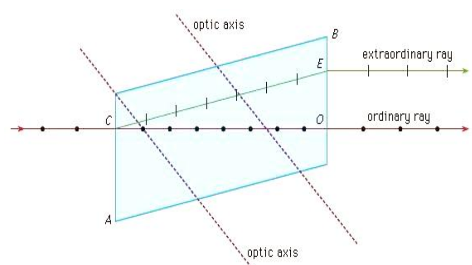


Explain the process of Double refraction.

When un-polarized light is passed through the calcite crystal, it is split into two plane polarized refracted lights. The one which obey the law of refraction and has vibrations perpendicular to the principal section is known as Ordinary ray.

The other which does not obey the law of refraction and has vibrations parallel to the principal section is known as Extra-ordinary (E-ray). This process is known as “double refraction”. It was discovered by Bartholinus.

The refractive indices of O-ray and E-ray for calcite crystal is given by $\mu_0 = \sin i/ \sin r_1$ and $\mu_E = \sin i/ \sin r_2$ $[\mu_0 > \mu_E , r_1 < r_2]$.



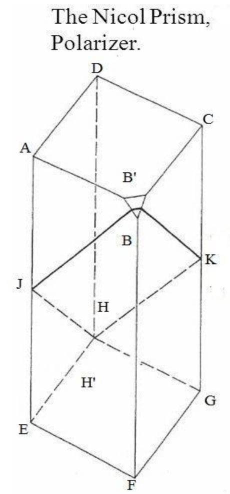
The velocity of O-ray is less than E-ray. Hence the O-ray travels with same velocities and it is represented by a spherical wave front, where as E-ray travels with different velocities in different directions and is given by ellipsoidal wave front.

Both the O-ray and E-ray travels with same velocity along optic axis.

Explain the construction and working of Nicol prism with its limitations.

- Nicol prism is an optical device made from the calcite crystal.
- It is used to produce & analyze plane polarized light.
- It is based on the principle of double refraction.
- It transmits only the E-ray and cut-off the O-ray.
- It was invented by William Nicol.
- Nicol Prism is constructed using a calcite crystal having a length three times of that its breadth.

<u>**Construction of Nicol prism**</u>



Consider a calcite crystal AB'CDEFGH' in which B'& H' are Blunt corners. The plane B'DH'F is known as principal section of the crystal plane and its angles are 71^0 & 108^0.

The upper & lower faces of the crystal AB'CD & EFGH' are grounded in such a way that the angles B'DH' and B'FH' are reduced from 71^0 to 68^0 . Let ABCD & EFGH are the new upper & lower faces of the crystal & new principal section is BDHF.

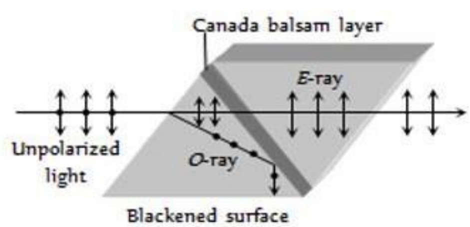
The crystal is cut into two pieces along the plane JHKB. The two cut surfaces are highly polished into optical flatness & then cemented together by means of Canada balsam.

The two end faces of the crystals are kept open while the sides are blackened so as to absorb total internal reflection of light rays.

Working of a Nicol prism

When Unpolarized light is incident on the surface of the Nicol prism, the incident beam is splitted into O-ray and E-rays.

The Canada balsam layer is acting as a rarer medium for the O-ray. Hence the O-ray undergoes total internal reflection at Canada balsam layer if the angle of incidence of O-ray is greater than critical angle.



Plane Polarized light by Nicol Prism

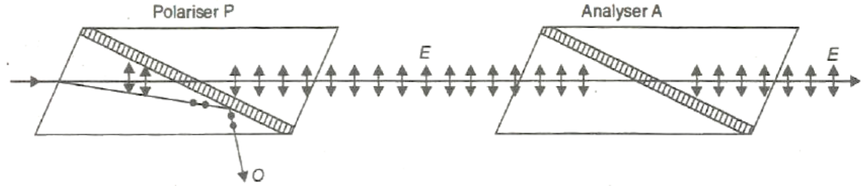


Fig- Production of Plane polarized light from Nicol Prism

♥ Nicol Prism is used to produce & analyze plane polarized light.

- When an un polarized light is passed through polariser 'P' the light splits into O-ray & E-ray. The O-ray is cutoff from calcite to canada balsam layer.
- The Extra ordinary light is passed through the canada balsam layer as shown in figure.
- If the second Nicol prism is rotated then the intensity of the E-ray decreases & it act as O-ray. So no light ray is come out of the second Nicol prism as shown in figure.

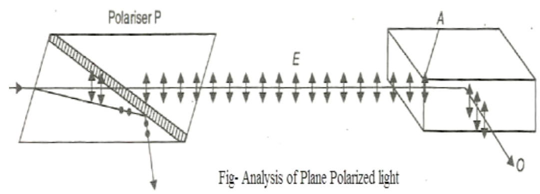
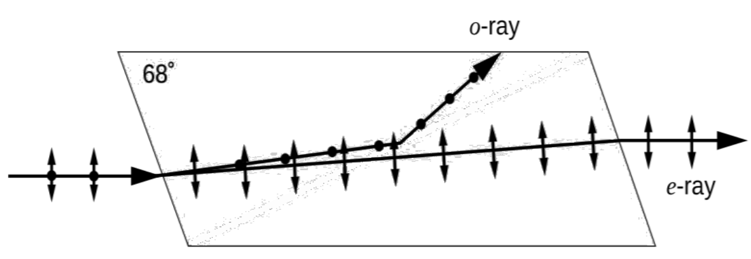


Fig- Analysis of Plane Polarized light

- The first Nicol prism is called Polariser (P) and second Nicol prism is known as Analyser (A).

Limitations of the Nicol prism

- Nicol prism act as a polarizer only for the light rays having slight convergent & divergent beam.
- If the incident beam is more divergent or convergent, the Nicol prism does not act as a polarizer.
- If the O-ray makes angle less than critical angle at canada balsam layer, the O-ray is also transmitted with the E-ray
- Nicol prism cannot be used for high convergent & divergent light beams.



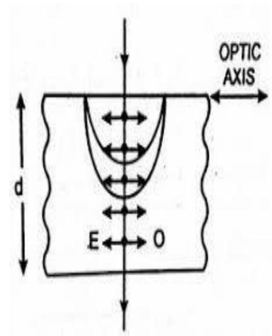
Explain the Quarter wave plate and Half wave plate with its applications.

Quarter wave plate

A Quarter wave plate is a device of double refracting material whose refracting faces are cut parallel to the direction of optic axis.

When an plane polarized light is passed through calcite crystal, it is capable of producing a path difference λ/4 between the O-ray and E-ray.

In calcite crystal, the velocity of E-ray is greater than the O-ray and refractive index of E-ray is less than O-ray, [$\mu_0 > \mu_E$] in the crystal.



The path difference between O-ray & E-ray is $\Delta = (\mu_0 - \mu_E)t$ ---- (1)

Quarter wave plate is cut in such a way that it can produce a path difference of λ/4 between O-ray & E-ray $\Delta = \lambda/4$ -------(2)

From (1) and (2) we get **$t = \lambda/4(\mu_0 - \mu_E)$**

and for quartz crystal $\mu_E > \mu_0$ and **$t = \lambda/4(\mu_E - \mu_0)$**

Uses – It is used to produce circular & elliptical polarized light.

Limitations- It is designed for a particular wavelength only. For other wavelengths it is not useful.

Half-wave plate

Half wave plate is similar to the quarter wave plate only. It introduces a path difference of λ/2 between O-ray & E-ray.

Let 't' be the thickness of the half wave plate and the path difference $\Delta = (\mu_0 - \mu_E)t$ -------1

The path difference between two rays is $\Delta = \lambda/2$ ------2

From 1 and 2 we get **$t = \lambda/2(\mu_0 - \mu_E)$** in calcite crystal.

For quartz crystal $\mu_E > \mu_0$ and **$t = \lambda/2(\mu_E - \mu_0)$.**

What is meant by optic axis, principal section and principal plane?

Optic axis:-A line joining any two blunt corners of the crystal is called optic axis. It is not the axis, but it is a direction in the crystal. Hence any parallel direction to the axis is called optic axis.

Crystals like calcite, quartz, tourmaline etc have only one optic axis, hence it is called uniaxial crystals.

Crystals like Borax, mica and selenite possess two optic axis hence they are called Biaxial crystals.

Principal section:- A Plane containing the optic axis and perpendicular to the two opposite faces of the crystal is known as "Principal section of the crystal".

Principal plane:- The plane containing the optic axis and ordinary ray is the principal plane of the O-ray. The plane containing the optic axis and extra ordinary ray is the principal plane of E-ray.