Huyghen's principle and interference of light

1. Introduction

Light is a form of energy .This fact was predicted by Maxwell on theoretical grounds and was verified by Lebedew experimentally in 1901

Since light is a form of energy, its transmission from one place to another can be understood in terms of transmission of energy

There are only two modes of propagation of energy through any material medium

energy is carried by stream of material particles travelling with finite velocity

Transfer of energy by wave motion without actual travelling with matter

First mode of energy transfer leads to Newton□s corpuscular theory of light in which he tried to understand travel of light in the straight line assuming that luminous body emits very minute and weightless particles called corpuscles travelling through empty space in straight lines in all directions with the speed of light and carry KE with them

This corpuscular theory of light can fairly explain the phenomenon of reflection .refraction and rectilinear propagation of light but failed to explain the phenomenon of interference, diffraction and polarization etc

Second mode of energy transfer leads the wave theory of light which was put forward by Dutch physicist Christian Huygens in 1678

Huygens suggested that light may be a wave phenomenon produced by mechanical vibrations of an all pervading hypothetical homogenous medium called eather just like those in solids and liguid .This medium was supposed to be mass less with extremely high elasticity and very low density

At first wave theory of light was not accepted primarily because of Newton□s authority and also light could travel through vacuum and waves require a medium to propagate from one point to other

Wave theory of light first begin to gain acceptance when double slit experiment of Thomas Young in 1801 established that light is indeed a wave phenomenon

After Young's double slit interference experiment ,many experiments were carried out by scientists involving interference and diffraction of light waves which could only be satisfactory explained by assuming wave model of light

Later on in nineteenth century Maxwell put forwards his electromagnetic theory and predicted the existence of electromagnetic waves and calculated the speed of EM waves in free space and found that this value was very close to the measured value of speed of light

He then suggested light must be an EM wave associated with changing electric and magnetic field which result in the propagation of light or EM waves in vacuum .So no material medium (like ether suggested by Huygens) is required for the propagation of light wave from one place to another .This argument established that light is a wave phenomenon

In this chapter we will study the various phenomenon related to wave nature of light

2) Wave fronts and rays

Consider the figure given below in which a point source of light S starts a distance or wave in air

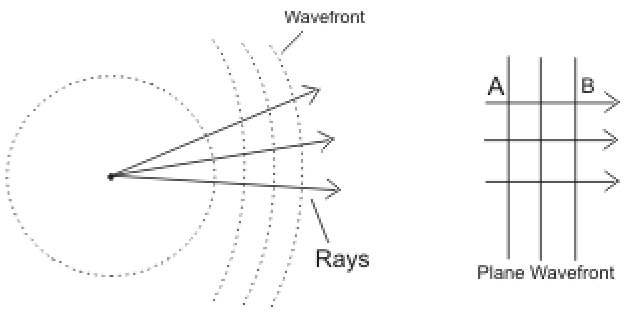

Figure 1.Wavefronts and rays

These waves will travel in all directions with the same velocity c, which is the velocity of light

After time t, distance travelled by the wave would be equal to ct and light energy thus reaches the surface of the sphere of radius ct with S as its center as shown in figure 1

The surface of such a sphere is known as wave front of light at this instant and all the particles forming wave front are in the same phase of vibration

With the passage of time wave travels farther and new wave fronts are obtained .These are all the surfaces of spheres of center S

Thus at any instant of time wave front may be defined as the locus of all the particles in the medium which are being distributed at the same instant of time and are in the same phase of vibration

At points very far away from source S such as A or B the wave fronts are parts of the sphere of very large radius so at any such large distances from source wave fronts are substantially plane

Rays are defined as normal□s to the wave fronts and in case of plane wave fronts ,rays are all parallel to one another as shown in figure 1.

3) Huygens□s principle

Huygens principle of wave propagation is a geometrical description used to determine the new position of a wave front at later time from its given position at any given instant of time. It is based on two principles

Each point on a given or primary wave front acts like a new source sending out disturbance in all directions and are known as secondary wavelets

The envelope or the tangential plane to these secondary wavelets consitutes the new wave front

To understand the propagation of wave on the basis of these postulates consider the figure given below

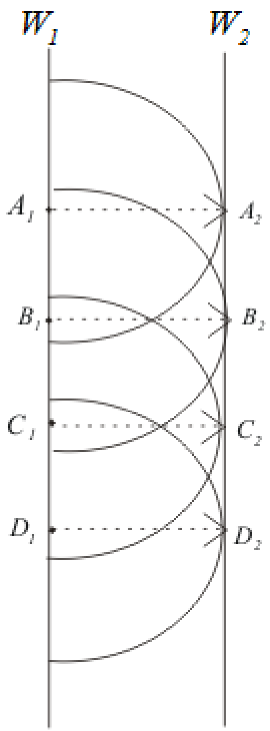

Figure 2. Huygen's geometrical construction for wave propagation

For simplicity we are considering the simple case of a plane wave

a) Let at time t=0,W_1 be the wave front which spates those part of the medium which are undisturbed from those where wave has already reached

b) Each point on W_1 acts as a source of secondary waves by sending out spherical wave of radius vt where v is the velocity of the wave

c) After some time t, the disturbance in the medium reaches all points within the region covered by all t these secondary waves. The boundary of this region is new wave front W_2 and W_2 is the surface tangent to all spheres and is known as forward envelope of these secondary wave fronts

d) The secondary wave fro pint A_1 on W_1 touches W_2 at A_2.The line connecting point A_1 and A_2 on wavelength W_1 and W_2 respectively is a ray of length vt.This is the reason why rays are perpendicular to the wave fronts

e) We can repeat this construction starting with W_2 to get the next wave fronts W_3 at some later time t_2 and so on

We have explained Huygens construction using a place wave fronts but the construction is more general than our simple example .The wave fronts can have any shape and sped of waves can be different at different places and in different direction's

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4) Reflection of and Refraction of plane waves using Huygens□s principle

i) Reflection of plane wave at plane surface:-

Consider the figure given below which shows incident and reflected wave fronts when a plane wave fronts travels towards a plane reflecting surface

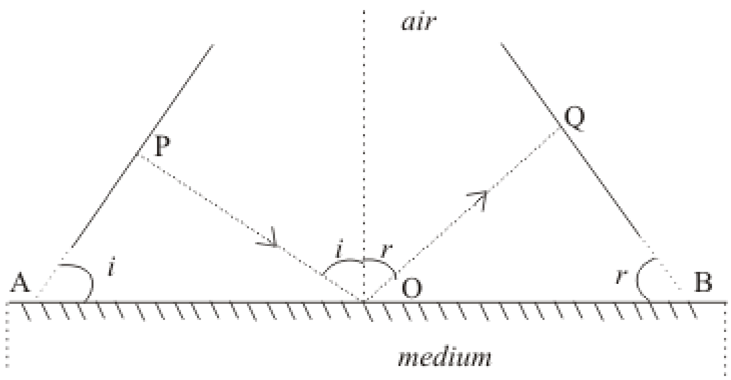

Figure 3. Wavefronts and corresponding waves for reflection at plane reflecting surface

POQ is the ray normal to both incident and reflected wave fronts

The angle of incidence i and angle of reflection r are the angles made by incidence and reflected rat respectively with the normal and these are also the angles between the wave fronts and the surface as shown in the figure 3

The time taken by the ray POQ to travel from incident wave front to then reflected one is

Total time from P to Q= $t=PO/v_1 + OQ/v_1$

where v_1 is the velocity of the wave. From figure (3)

$$t=\frac{AO\sin i}{v_1}+\frac{OB\sin r}{v_1}$$

$$=\frac{OA\sin i+(AB-OA)\sin r}{v_1}$$

$$=\frac{AB\sin r+OA(\sin i-\sin r)}{v_1} \qquad (1)$$

There can be different rays normal to incident wave front and they can strike plane reflecting surface at different point O and hence they have different values of OA

Since tome travel by each ray from incident wave front to reflected wave front must be same so, right side of equation (1) must be independent of OA.This conditions happens only if

(sini-sin r)=0

or i=r

Thus law of reflection states that angle of incidence i and angle of reflection are always equal

ii) Refraction of plane waves at plane surfaces:-

Consider the figure given below which shows a plane surface AB separating medium 1 from medium 2

v_1 be the speed of light in medium 1 and v_2 the speed of light in medium 2

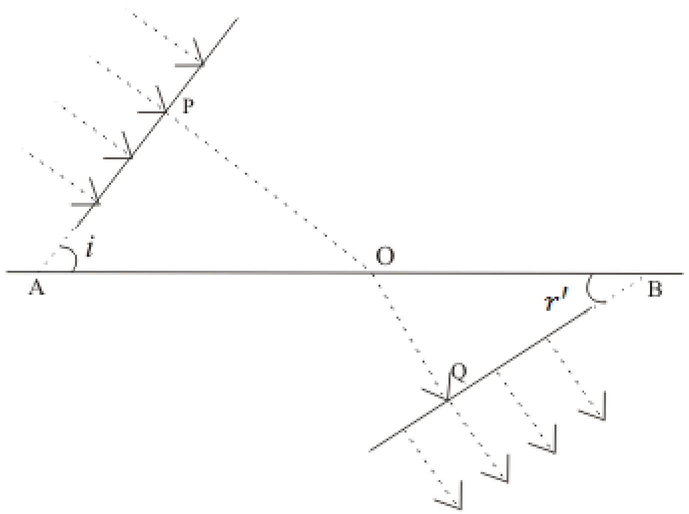

Figure 4. Refraction at plane wavefront and corresponding rays by a plane surface

Incident and refracted wave front makes angles i and r' with surface AB where r' is called angle of refraction

Time taken by ray POQ to travel between incident and refracted wave fronts would be

$$t = \frac{PO}{v_1} + \frac{OQ}{v_2}$$

$$= \frac{OA\sin i}{v_1} + \frac{(AB - OA)\sin r'}{v_2}$$

$$= \frac{AC}{v_2}\sin r' + OA\left(\frac{\sin i}{v_1} - \frac{\sin r'}{v_2}\right) \qquad (2)$$

Now distance OA would be different for different rays .So time t should be independent of any ray we might consider

This can be achieved only if coefficient of OA in equation (2) becomes equal to zero or

$$\frac{sini}{sinr'} = \frac{v_1}{v_2} = n(constant) \qquad (3)$$

Equation (3) is nothing but ***Snell□s law of refraction*** where n is called the reflective index of second medium with respect to the first medium.

iii) Refractive index

The ratio of phase velocity of light c in vacuum to its value v_1 in a medium is called the refractive index n_1 (or μ_1) of the medium .Thus

$$\mu_1 = n_1 = {}^{c}/_{v_1} \qquad (4)$$

When light travels from medium 1 to medium 2,what we measure is the refractive index of medium 2 relative to medium 1 denoted by n_{12} (or μ_{12}).Thus

$$n_{12} = \frac{sini}{sinr'} = \frac{v_1}{v_2} = \frac{n_2}{n_1} \qquad (5)$$

where n_1 is refractive index of medium 1 with respect to vacuum and n_2 is refractive index of medium 2 w.r.t. vacuum

When light travels from one medium to another the frequency $v=1/T$ remains same i.e. $v_1=v_2$

Since the velocities of light v_1 and v_2 are different is different medium ,the wavelength λ_1 and λ_2 are also different i.e.,

$$v = \nu\lambda$$
$$\Rightarrow \frac{v_1}{v_2} = \frac{\nu_1\lambda_1}{\nu_2\lambda_2} \qquad (6)$$

the wavelength of light in the medium is directly proportional to phase velocity and hence inversely proportional to the refractive index

5) Principle of Superposition of waves

When two or more sets of waves travel through a medium and cross one another the effects produced by one are totally independent of the

At any instant the resultant displacement of a particle in the medium depends on the phase difference between the waves and is the algebraic sum of the displacement it would have at the same instant due to each separate set. This is known as the principle of superposition of waves and forms the basis of whole theory of interference of waves discovered by Young in 1801

If at any instant $\mathbf{y_1},\mathbf{y_2},\mathbf{y_3}$,--- are the displacements due to different waves present in the medium then according to superposition principle resultant displacement **y** at any instant would be equal to the vector sum of the displacements ($\mathbf{y_1},\mathbf{y_2},\mathbf{y_3}$) due to the individual waves i.e.,

$$y = y_1 + y_2 + y_3 + \cdots$$

The resultant displacement of the particles of the medium depends on the amplitude ,phase difference and frequency of the superposing waves

Consider two waves of same frequency f and wavelength λ travelling through a medium in the same direction and superpose at any instant of time say t

Equation of these waves at time t is

$$\mathbf{y}_1 = \mathbf{a}_1 \sin\left[\frac{2\pi}{\lambda}(ft - x)\right]$$

$$\mathbf{y}_2 = \mathbf{a}_2 \sin\left[\frac{2\pi}{\lambda}(ft - x) + \phi\right] \qquad \text{---(7)}$$

where φ is the phase difference between the waves

According to principle of superposition of waves ,resultant displacement of particles equals

$$\mathbf{y} = \mathbf{y}_1 + \mathbf{y}_2$$

$$\mathbf{y} = \mathbf{a}_1 \sin\left[\frac{2\pi}{\lambda}(ft - x)\right] + \mathbf{a}_2 \sin\left[\frac{2\pi}{\lambda}(ft - x) + \phi\right] \qquad \text{-----(8)}$$

Now from trigonometry identity

$$\sin(A + B) = sinAcosB + cosAsinB$$

So,

$$\sin\left[\frac{2\pi}{\lambda}(ft - x) + \phi\right] = \sin\frac{2\pi}{\lambda}(ft - x)\cos\phi + \cos\frac{2\pi}{\lambda}(ft - x)\sin\phi$$

Putting it in equation (8) we find

$$y = a_1 \sin\left[\frac{2\pi}{\lambda}(ft - x)\right] + a_2 \sin\left[\frac{2\pi}{\lambda}(ft - x)\right]\cos\varphi + a_2 \cos\frac{2\pi}{\lambda}(ft - x)\sin\varphi \qquad \text{---(9)}$$

Let us suppose

$$Acos\theta = a_1 + a_2 cos\phi \ and \ Asin\theta = a_2 sin\phi$$

Putting them in equation (9) we have

$$y = A\cos\theta\sin\frac{2\pi}{\lambda}(ft - x) + A\sin\theta\cos\frac{2\pi}{\lambda}(ft - x) = A\sin\left[\frac{2\pi}{\lambda}(ft - x) + \theta\right] \qquad \text{------(10)}$$

where

$$A = \sqrt{a_1^2 + a_2^2 + 2a_1a_2\cos\phi} \qquad \text{----- (11)}$$

$$\theta = \tan^{-1}\left[\frac{a_2\sin\phi}{a_1 + a_2\cos\phi}\right] \qquad \text{---- (12)}$$

We know that intensity of waves is proportional to its amplitude i.e.

$I \propto A^2 = a_1^2 + a_2^2 + 2a_1a_2 cos\phi$
For maximum intensity
$\cos\phi = 1$

$\phi = 2n\pi$

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

Therefore,
$I_{max} = (a_1 + a_2)^2$ --- (13)
For $a=a_1=a_2$
$I_{max}=4a^2$
For minimum intensity
$\cos\varphi = -1$

$\phi = (2n+1)\pi$

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

$I_{\min} = (a_1 - a_2)^2$ --- (14)
For $a_1 = a_2 = a$
$I_{min}=0$

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6) Interference of light waves

Interference of light wave is the modification in distribution of light energy obtained by superposition of two or more waves

At some points where crest of the one wave falls on the crest of another ,resultant amplitude is maximum

At some points where crest of one wave falls on trough of another, the resultant amplitude become minimum and hence intensity of the light is minimum

At points, where the resultant intensity of light is maximum ,the interference is said to be constructive

At points where resultant intensity of light is minimum ,interference is said to be destructive

7) Coherent Sources

Coherent sources are those sources of light which emit continuous light waves of same wavelength ,same frequently and are in same phase or have a constant phase difference

For observing interference phenomenon ,coherence of waves is a must

For light waves emitted by two sources of light to remain coherent ,the initial phase difference between waves should remain constant in time. If the phase difference changes continuously or randomly with time then the sources are incoherent

Two independent sources of light are not coherent and hence cannot produce interference because light beam is emitted by millions of atoms radiating independently so that phase difference between waves from such fluctuates randomly many times per second

Two coherent sources can be obtained either by the source and obtaining its virtual image or by obtaining two virtual images of the same source. This is because any change in phase in real source will cause a simultaneous and equal change it its image

Generally coherence in interference is obtained by two methods

i) Division of wave front where wave front is divided into two parts by reflection ,refraction or diffraction and those two parts reunite at a small angle to produce interference such as in case of Young Double slit experiment ,Fresnel bi-prism .

ii) Division of amplitude whose amplitude of a section of wave front is divided into two parts and reunited later to produce interference such as in case of interference due to thin films

Laser light is almost monochromatic with light spreading and two independent laser sources can produce observable interference pattern

8) Conditions for sustained interference of light waves

Two sources should continuously emit waves of same wavelength or frequency

The amplitudes of the two interfering waves should be equal or approximately equal in order to reduce general illumination

The sources of light must be coherent sources

Two sources should be very narrow as a broad source is equivalent to large number of narrow sources lying side by side which causes loss of interference pattern resulting general illumination

Two sources emitting set of interfering beams must be placed very close to each other so that wavelength interact at very small angles

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9)Young Double slit experiment

Young in 1801 demonstrated interference phenomenon through double slit experiment

In his experiment ,he divided a single wave front into two and these two slit wave fronts acts as if they emerged from two sources having fixed relationship

when these two waves were allowed to interfere ,they produce a sustained interference pattern

In his original experiment he illuminates a pin hole S using a light source and light diverging from pinhole which contains two sets of pinholes S_1 and S_2 equidistant from S and very close to one another as shown below in the figure

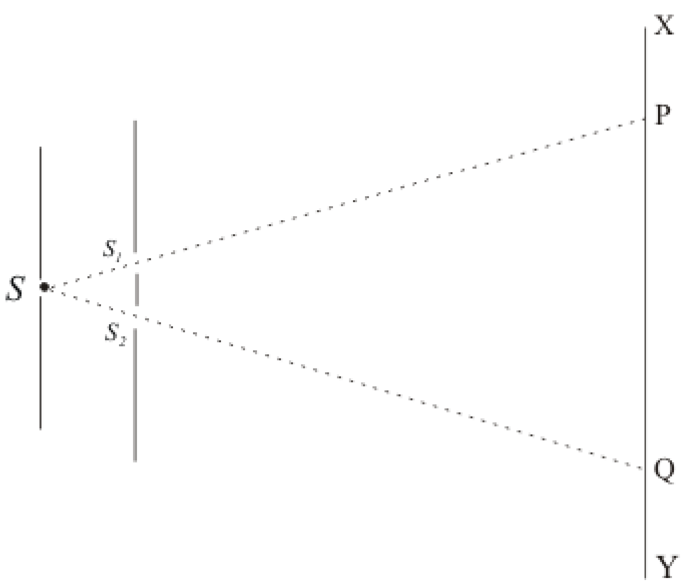


Figure 5. Young's experiment on interference

Two two sets of spherical waves coming out of the pin holes S_1 and S_2 were coherent and interfered with each other to form a symmetrical pattern of varying intensity on screen XY

This interference pattern disappear when any one of the pinholes S_1 or S_2 is closed

Young used the superposition principle to explain the interference pattern and by measuring the distance between the fringes he managed to calculate the wavelength of light.

10) Theory of interference fringes

In young's double slit experiment ,light wave produce interference pattern of alternate bright and dark fringes or interference band

To find the position of fringes, their spacing and intensity at any point P on screen XY .Consider the figure given below

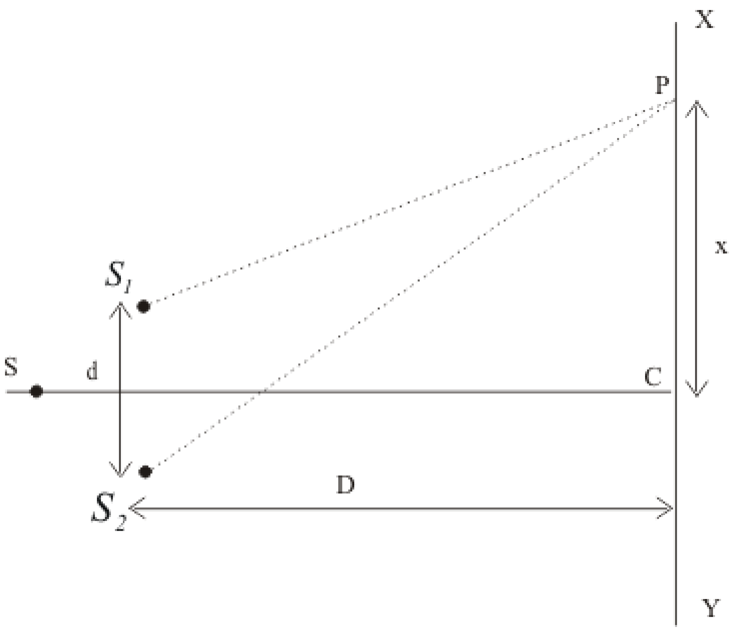


Figure 6. Interference in Young's double slit experiment

Here S_1 or S_2 two pin holes of YDS interference experiment and position of maxima and minima can be determined on line XOY parallel to Y-axis and lying on the plane parallel to S,S_1 or S_2

Consider a point P on XY plane such that CP = x.The nature of interference between two waves reaching point P depends on the path difference S_2P-S_1P

from figure (6)

$$S_1P^2 = D^2 + (x - \frac{d}{2})^2 \quad = D^2\left[1 + \frac{(x - d/2)^2}{D^2}\right] \qquad \text{---- (15)}$$

$$S_2P^2 = D^2\left[1 + \frac{(x + d/2)^2}{D^2}\right] \qquad \text{--- (16)}$$

$$S_2P^2 - S_1P^2 = (x + \frac{d}{2})^2 - (x - \frac{d}{2})^2 \quad = 2xd \qquad \text{---- (17)}$$

$$(S_2P - S_1P)(S_2P + S_1P) = 2xd$$

$$S_2P - S_1P = \frac{2xd}{(S_2P + S_1P)} \qquad \text{---- (18)}$$

for x, d<<< D , S_1P+S_2P =2D

with negligible error included , path difference would be

$$S_2P - S_1P = \frac{2xd}{2D} = \frac{xd}{D} \qquad (19)$$

And corresponding phase difference between wave is

$$\phi = path\ difference \times \frac{2\pi}{\lambda}$$

$$phase\ difference = \frac{2\pi}{\lambda} \times \frac{xd}{D} \qquad (20)$$

i) Condition of bright fringes(constructive interference)

If the path difference (S_2P-S_1P) is even multiple of λ/2,the point P is bright

$$\therefore \frac{xd}{D} = \frac{2n\lambda}{2}$$

$$or, x = \frac{n\lambda D}{d} \qquad (21)$$

Equation (21) gives the condition for bright fringes or constructive interference

ii) Condition for dark fringes (destructive interference)

If the path difference is an odd multiple of λ/2,the Point P is dark. So,

$$\therefore \frac{xd}{D} = \frac{(2n-1)\lambda}{2}$$

$$or, x = \frac{(2n-1)\lambda D}{d} \qquad (22)$$

Equation (22) gives the condition for dark fringes or destructive interference

From equations (21) and (22) ,we can get position of alternate bright and dark fringes respectively

Distance between two consecutive bright fringes is given by

$$x_{n-1} - x_n = \frac{D}{2d}(n-1)\lambda - \frac{D}{2d}n\lambda = \frac{D}{d}\lambda$$

And for dark fringes

$$x_{n-1} - x_n = \frac{D}{2d}(2n+1)\lambda - \frac{D}{2d}(2n-1)\lambda = \frac{D}{d}\lambda$$

Thus the distance between two successive dark and bright fringes is same. This distance is known as fringe width and is denoted by β. Thus

$$\beta = \frac{D}{d}\lambda \qquad (23)$$

Huyghen's principle and interference of light

11) Displacement of fringes

when a film of thickness t and refractive index μ is introduced in the path of one of the source of light ,then fringe shift occur as optical path difference changes

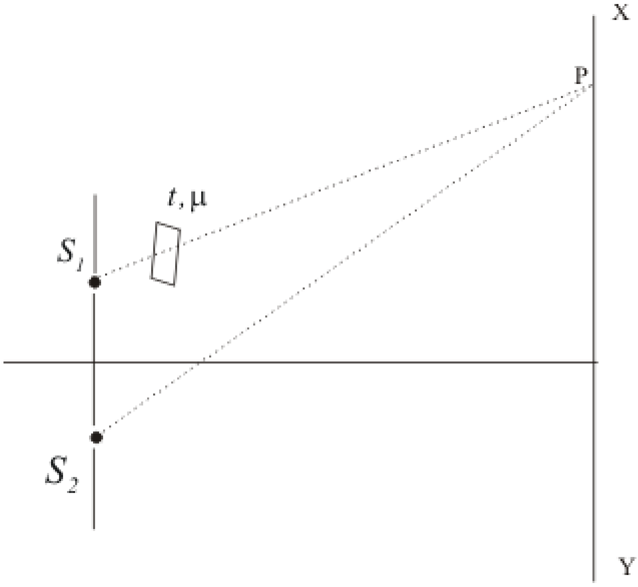


Figure 7. Thin film is introduced in path of one of source of light

Time required by light to reach from S_1 to point P

$$= \frac{S_1P - t}{c} + \frac{t}{v}$$

where v=c/μ

$$T = \frac{S_1P + t(\mu - 1)}{c}$$

Hence equivalent path that is covered by light in air is $S_1P+t(\mu-1)$

Optical path difference at P

$$= S_2P - [S_1P + \mu t - t]$$
$$= S_2P - S_1P - [\mu -]t$$
$$= \frac{xd}{D} - [\mu -]t$$

Therefore nth fringe shift is given by

$$\Delta x = \frac{D(\mu - 1)t}{d}$$

as,

$$\beta = \frac{D}{d}\lambda$$

$$\Delta x = \frac{\beta(\mu - 1)t}{\lambda}$$

where λ is the wavelength of the wave

Diffraction and polarization of light

1. Introduction

It is a common observation with the waves of all kind that they bend round the edge of an obstacle

Light like other waves also bends round corners but in comparison to sound waves small bending of light is due to very short wavelength of light which is of the order of 10^{-5}

This effect of bending of beams round the corner was first discovered by grimed (Italy 1618-1663)

We now define diffraction of light as the phenomenon of bending of light waves around the corners and their spreading into the geometrical shadows

Fresnel then explained that the diffraction phenomenon was the result of mutual interference between the secondary wavelets from the same dif wave front

Thus we can explain diffraction phenomenon using Huygens□s principle

The diffraction phenomenon are usually divided into two classes

i) Fresnel class of diffraction phenomenon where the source of light and screen are in general at a finite distance from the diffracting aperture

ii) Fruanhofer class of diffraction phenomenon where the source and the screen are at infinite distance from the aperture, this is easily achieved by placing the source on the focal plane of a convex lens and placing screen on focal plane of another convex lens. This class of diffraction is simple to treat and easy to observe in practice

Here in this chapter we will only be considering fraunhofer class diffraction by a single slit

2. Fraunhofer Diffraction by single slit

Let us first consider a parallel beam of light incident normally on a slit AB of width 'a' which is of order of the wavelength of light as shown below in the figure

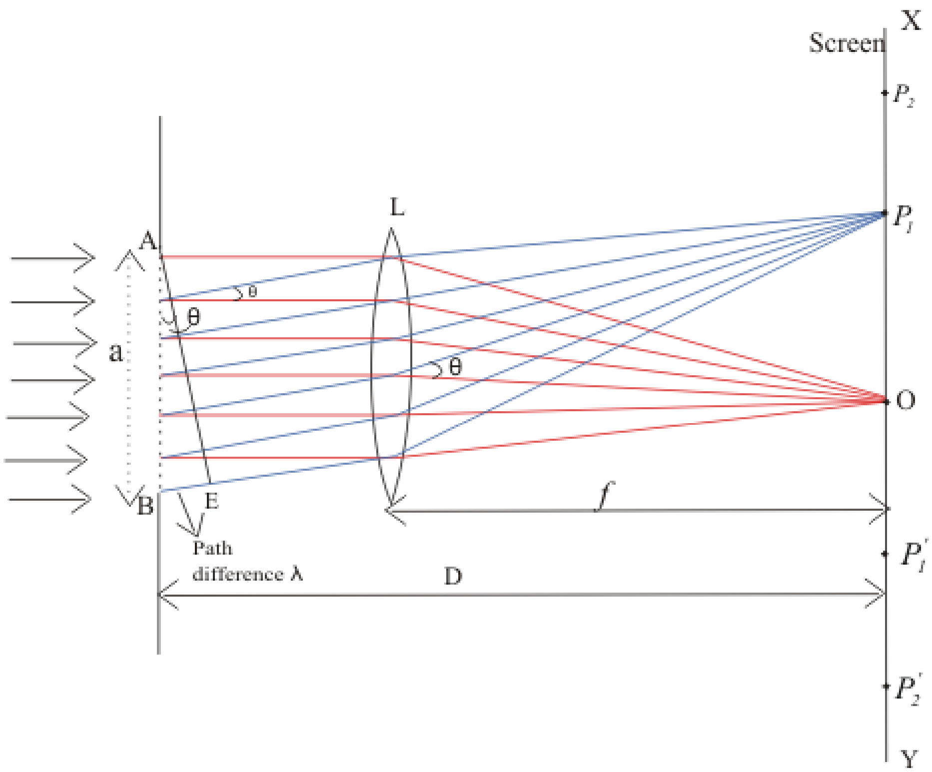


Figure 1. Fraunhofer diffraction of a plane wave at single slit

A real image of diffraction pattern is formed on the screen with the help of converging lens placed in the path of the diffracted beam

All the rays that starts from slit AB in the same phase reinforce each other and produce brightness at point O on the axis of slit as they arrive there in the same phase

The intensity of diffracted beam will be different in different directions and there are some directories where there is no light

Thus diffraction pattern on screen consists of a central bright band and alternate dark and bright bands of decreasing intensity on both sides

Now consider a plane wave front PQ incident on the narrow slit AB. According to Huygens principle each point t on unblocked portion of wavefront PQ sends out secondary wavelets in all directions

Their combined effect at any distant point can be found y summing the numerous waves arriving there from the principle of superposition

Let C be the center of the slit AB.The secondary waves, from points equidistant from center C of the clit lying on portion CA and CB of wave front travel the same distance in reaching O and hence the path difference between them is zero

These waves reinforce each other and give rise to the central maximum at point O

i) Condition for minima

We now consider the intensity at point P_1 above O on the screen where another set of rays diffracted at a angle θ have been bought to focus by the lens and contributions from different elements of the slits do not arise in phase at P_1

If we drop a perpendicular from point A to the diffracted ray from B,then AE as shown in figure constitutes the diffracted wavefront and BE is the path difference between the rays from the two edges A and B of the slit.

Let us imagine this path difference to be equal to one wavelength.

The wavelets from different parts of the slit do not reach point P_1 in the phase because they cover unequal distance in reaching P_1.Thus they would interfere and cancel out each other effect. For this to occur

$BE=\lambda$

Since $BE=AB\sin\theta$

$a\sin\theta=\lambda$

or $\sin\theta=\lambda/a$

or $\theta=\lambda/a$ ---(1)

As angle of diffraction is usually very small so that

$\sin\theta=\theta$

Such a point on screen as given by the equation (1) would be point of secondary minimum

It is because we have assume the slit to be divided into two parts, then wavelets from the corresponding points of the two halves of the slit will have path difference of #955;/2 and wavelets from two halves will reach point P_1 on the screen in a opposite phase to produce minima

Again consider the point P_2 in the figure 1 and if for this point path difference $BE=2\lambda$,then we can imagine slit to be divided into four equal parts

The wavelets from the corresponding points of the two adjacent parts of the slit will have a path difference of $\lambda/2$ and will mutually interfere to cancel out each other

Thus a second minimum occurs at P_2 in direction of θ given by

θ=2θ/a

Similarly n_{th} minimum at point P_n occurs in direction of θ given by

$\theta_n = n\theta/a$ ---(2)

ii) Positions of maxima

If there is any point on the screen for which path difference

BN=asinθ=3θ/2

Then point will be position of first secondary maxima

Here we imagine unblocked wavefront to be divided into three equal parts where the wavelets from the first two parts reach point P in opposite phase thereby cancelling the e effects of each other

The secondary waves from third part remain uncancelled and produce first maximum at the given point

we will get second secondary maximum for BN=5θ/2 and n_{th} secondary maxima for

$BN=(2n+1)\theta/2 = a\sin\theta_n$ ---(3)

where n=1,2,3,4..

Intensity of these secondary maxima is much less then central maxima and falls off rapidly as move outwards

Figure below shows the variation of the intensity distribution with their distance from the center of the central maxima

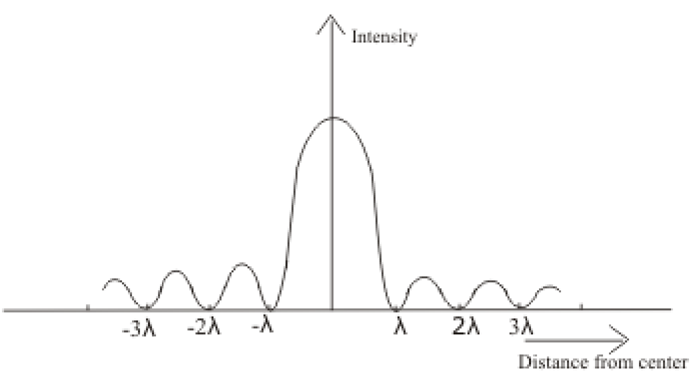


Figure 2. Intensity distribution in the diffraction due to single slit

Diffraction and polarization of light

3) Resolving power

When two objects are very close to each other they may appear as one and we might not see them as separate objects just by magnifying them

To separate two objects which are very close together, optical instrument such as telescope ,microscope,prism,grating etc are employed

The separation of such close object is termed as resolution and the ability of an optical instrument to produce distinctly separate images of two close objects is called its resolving power

Every optical instrument has a limit up to which it can produce distinctly separate images to two objects placed very close to each other

After detailed study of the intensity of diffraction pattern of two very close point objects ,lord Rayleigh suggested that the two objects will be just resolved when central maximum of diffraction pattern of first object lies on first secondary minimum of diffraction pattern of second object

The minimum distance between two point object which can just appear to be as separate by optical instrument is called the limit of resolution of the instrument

we will discuss about the resolving power of optical instrument when we study exclusively about optical instruments

4) Polarization of light

Waves are generally of two types

i) Longitudinal waves: In case of longitudinal waves ,particles of the medium oscillates along the direction of the propagation of the waves

ii) Transverse waves: In this case direction of oscillation of particles is perpendicular to the direction of propagation of waves

we already know that light is an EM wave in which electric and magnetic field vector vary sinosoidally,perpendicular to each other as well as perpendicular to the direction of propagation of light wave

This shows that light waves consists of transverse waves

The fact that light consists of transverse waves can be confirmed in the experiments in which beams of lights were allowed to pass through Polaroid which are artificial crystalline materials that allow lights vibrations to pass through only in a particular plane

We would now observe the light passing through two Polaroid A and B placed one behind another in from of source of light as shown below in the figure

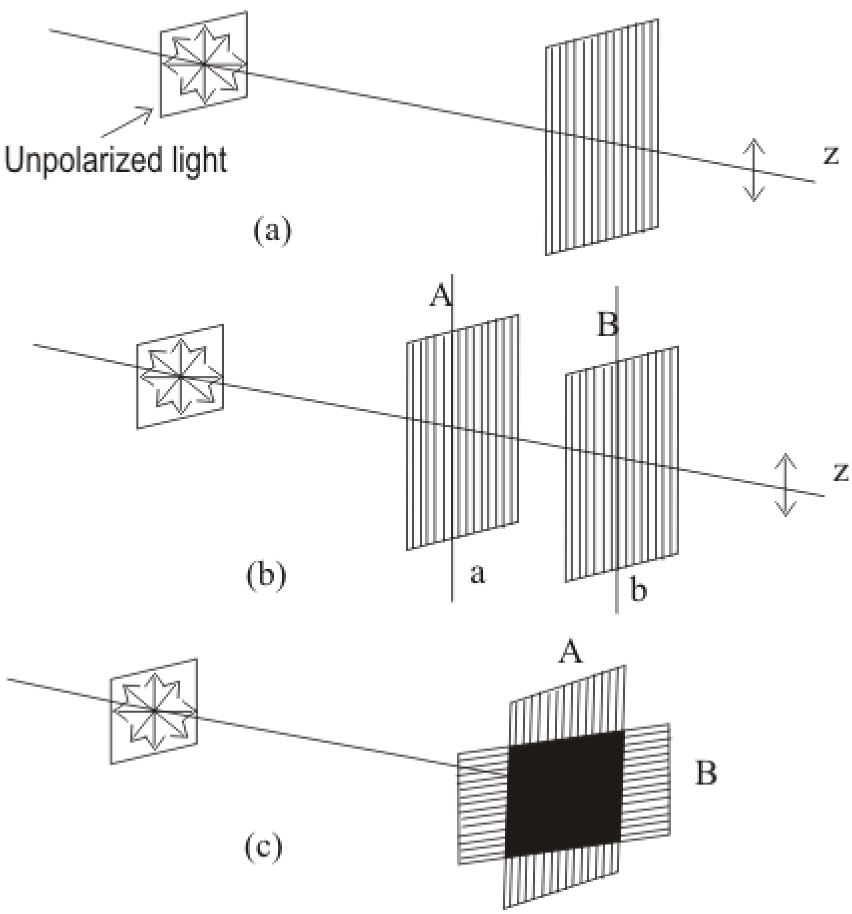


Figure 3. Plane polarization of light

when axes a and b of Polaroid A and B respectively are parallel to each other then the light through Polaroid B appears slightly darker intensity of light is reduced after being transmitted from Polaroid A

Since axis of both the Polaroid are parallel to each other so light transmitted from Polaroid A is transmitted as it is by Polaroid B

Now if start rotating Polaroid B about the z-axis ,one will observe the variation of intensity i.e. light passing through crystal B becomes darker and darker and disappears at one stage

This happens when axis a of Polaroid A is perpendicular to axis b of the Polaroid B as shown in fig 3(b)

Again on rotating Polaroid B in same direction light reappears and becomes brightest when the axis a and b are again parallel

This simple experiment proves that light consists of transverse waves

Here in this experiment Polaroid A acts as polarizer and the beam transmitted through polarizer is linearly polarized and second Polaroid acts as analyzer

Diffraction and polarization of light

5) Vibrations in unpolarized and polarized light

A light wave is a transverse wave having vibration at right angles to the direction of propagation

An ordinary beam of light consists of million of lights waves each with its own plane of vibration so it have wave vibrating in all possible plane with equal probability .Hence an ordinary beam of light in unpolarized

If we consider the light beam being propagated in a direction perpendicular to the plane of paper while its vibrations are in the plane of the paper then figure 4 given below shows that vibrations in ordinary lights occurs in every plane perpendicular to the direction of propagation of light and are in the plane of the paper

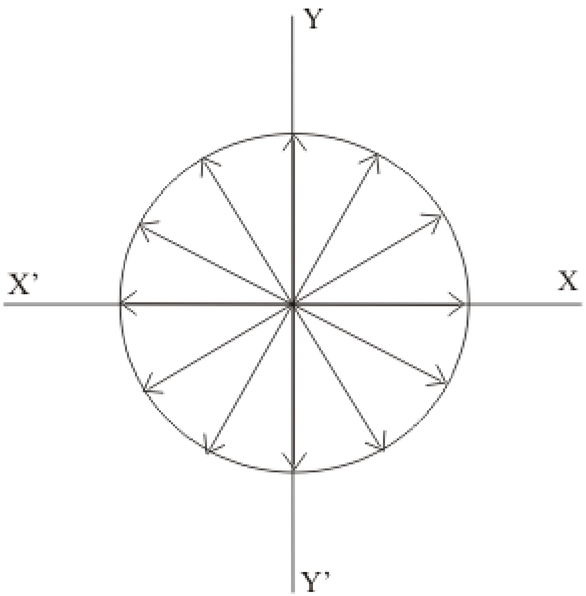


Figure 4. Vibrations of the beam of unpolarised light

As it can be seen from the figure that amplitude of vibrations are all equal

When such a beam of unpolaroized light is incident on a Polaroid the emergent light is linearly polarized with vibrations in a particular directions

The direction of vibrations of beam transmitted by the Polaroid depends on the orientation of the Polaroid

Consider the vibrations in ordinary light when it is incident on the polaroid as shown in figure 3(a). Each vibrations can be resolved into two components, one in a direction parallel to a which is the direction of transmission of light through polaroid and the other direction m perpandicular to a as shown in the figure given below.

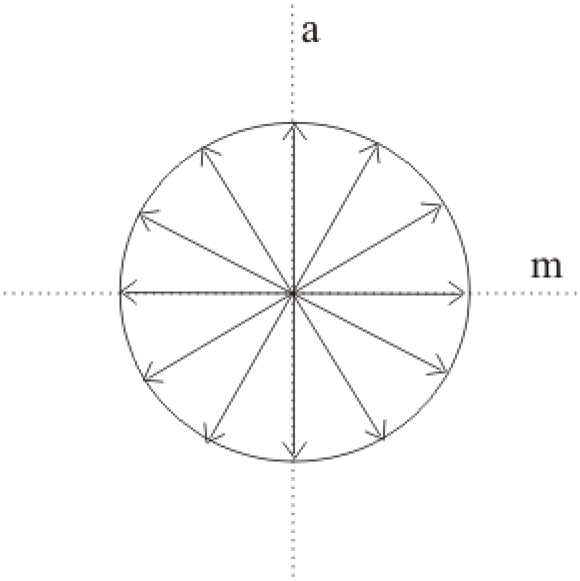


Figure 5. Plane polarised waves by selective absorption

Polaroids absorbs the light due to vibrations parallel to m , known as ordinary rays but allow light due to other vibration , known as extra ordinary rays, to pass through.

So the plane polarised light due to vibrations in one plane is produced as shown in figure 3(a).

The Polaroid absorbs the light vibration along a particular direction and the component at right angles to it is allowed to pass through the Polaroid.

This selective absorption of light vibrations along a particular direction is also shown by certain natural crystals for example tourmaline crystal

6) Polarization of reflection

This simple method of obtaining plane polarized light by reflection was discovered by malus in 1808

We found that when a beam of light is reflected from the surface of a transparent medium like glass or water, the reflected light is partially polarized and degree of the polarization varies with angle of incidence

The percentage of polarized light is greatest in reflected beam when light beam is incident on the transparent medium with an incident angle equal to the angle of polarization

For ordinary glass with refractive index =1.52 ,angle of polarization is 57.5^0

Figure below shows the polarization of light by reflection

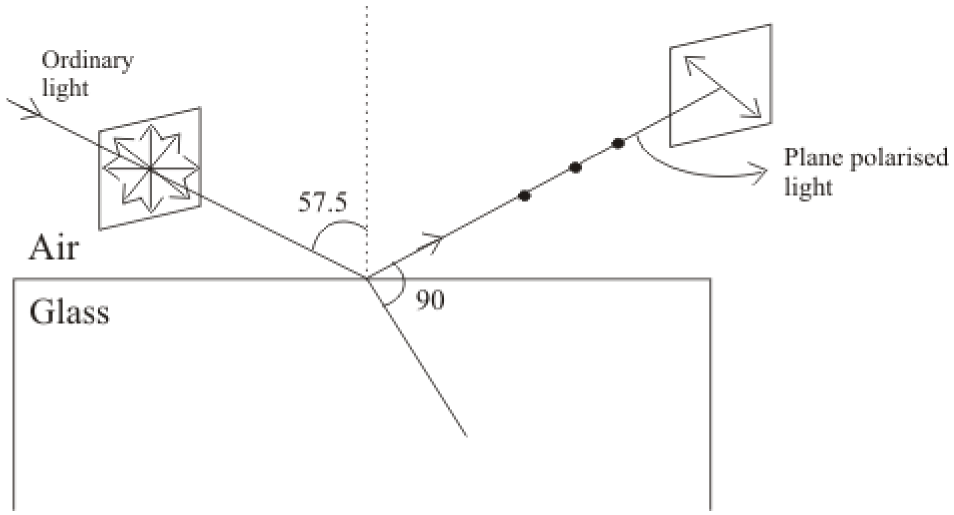


Figure 6. Plane polarised light by reflection

we can use a Polaroid as an analyzer to show that reflected light is plane polarized . we rather say that reflected light is partially plane polarized

the examination of transmitted light shows the variation in intensity indicating that the light is partially polarized

The vibrations of this plane polarized reflected light are found to be perpendicular to the plane of incidence and therefore ,the reflected light is said to be plane polarized in the plane of incidence

7) polarization by scattering

when an unpolarized beam of light is allowed to pass through a medium containing gas or molecules it gets scattered and the beam scattered at 90^0 to the incident beam is plane polarized (having vibrations in one plane). This phenomenon is called polarization by scattering

The blue light we receive from sky is partially polarized ,although our eye can not distinguish it from an umpolaroized light but if we view it through a Polaroid which can be rotated we can clearly see it to be as partially polarized

Diffraction and polarization of light

We generally define direction of light vibration to be that of the electric vector **E**

For an ordinary unpolarised beam electric vector keeps changing its direction in random manner

when light is allowed to pass through a Polaroid the emergent light is plane polarized with its electric vector vibrating in a particular direction

The direction of vector of emergent beam depends on the orientation of the Polaroid and the plane of polarization is designed as the plane containing E-vector and light ray

Figure below shows the plane polarized light due to i) a vertical E-vector ii) a horizontal E-vector

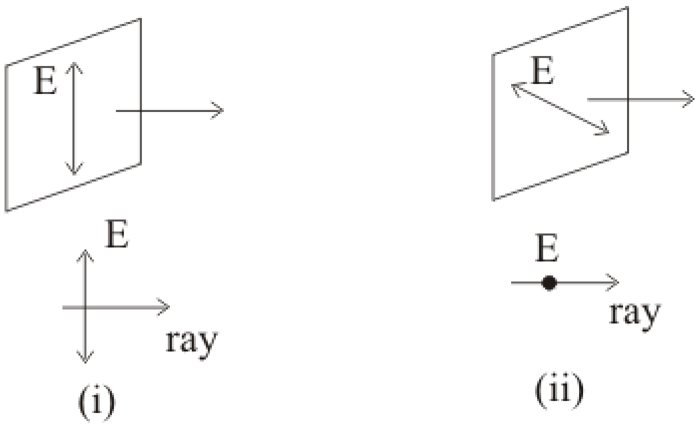


Figure 7. Electric vectors in plane polarised light

9)Law of Malus

consider the figure given below in which an unpolarized light passes through a Polaroid P_1 and then through Polaroid P_2 making an angle θ with y ax-s

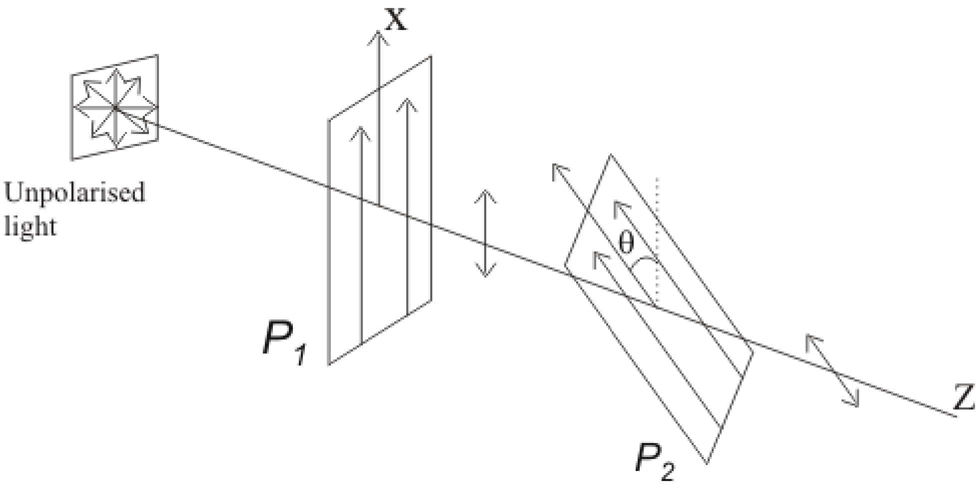


Figure 8. Illustrating Malus Law

After light propagating along x-direction passes through the Polaroid P_1 ,the electric vector associated with the polarized light will vibrate only along y-axis

Now if we allow this polarized beam to again pass through a polarized P_2 making an angle θ with y-axis then if E_0 is the amplitude of incident electric field on P_2 then amplitude of wave emerging from P_2 would be $E_0\cos\theta$ and hence intensity of emerging beam would be

$I=I_0\cos^2\theta$ ---(4)

where I_0 is the intensity of beam emerging from P_2 when $\theta=0$

This equation (4) represents the law of malus

Thus when a plane polarized light is incident on an analyzer ,the emerging light varies in accordance with the equation (4) where θ is the angle between the planes of transmission of the analyzer and the polarizer

10) Brewster's law

Brewster law is a simple relationship between angle of maximum polarization and the refractive index of the medium

Brewster�s law is given by relationship

$\mu = \tan i$ --(5)

where i is the Polarizing angle

μis the index of refraction

It is clear from equation (5) that when light is incident at polarizing angle then reflected ray is at right angles to the reflected ray

- **Wave front:**
  It is the locus of points having the same phase of oscillation.
- **Rays:**
  Rays are the lines perpendicular to the wave front, which show the direction of propagation of energy.
- **Time Taken:**
  The time taken for light to travel from one wave front to another is the same along any ray.
- **Huygens' Principle:**
  a) According to Huygens' Each point on the given wave front (called primary wave front) acts as a fresh source of new disturbance, called secondary wavelet, which travels in all directions with the velocity of light in the medium.
  b) A surface touching these secondary wavelets, tangentially in the forward direction at any instant gives the new wave front at that instant. This is called secondary wave front,
- **Principle of Huygens' Construction:**
  a) It is based on the principle that every point of a wave front is a source of secondary wave front.
  b) The envelope of these wave fronts i.e., the surface tangent to all the secondary wave front gives the new wave front.
- **Snell's law of refraction:**

$$ {}_1\mu_2 = \frac{c_1}{c_2} = \frac{\text{Speed of light in first medium}}{\text{Speed of light in second medium}} $$

- **Refraction and Reflection of Plane Waves Using Huygens' Principle:**
  The law of reflection (i = r) and the Snell's law of refraction

$$ \frac{\sin i}{\sin r} = \frac{v_1}{v_2} = \frac{\mu_2}{\mu_1} = \mu_{21} $$

  can be derived using the wave theory. (Here v1 and v2 are the speed of light in media 1 and 2 with refractive index $\mu_1 and \mu_2$ respectively).
- **Relation between Frequency and Speed:**
  The frequency v remains the same as light travels from one medium to another. The speed v of a wave is given by

$$ v = \frac{\lambda}{T} $$

  Where λ is the wavelength of the wave and $T(=1/v)$ is the period of oscillation.

- **Doppler Effect:**
  It is the shift in frequency of light when there is a relative motion between the source and the observer. The effect can be used to measure the speed of an approaching or receding object.
- **Change in Frequency:**
  For the source moving away from the observer $v < v_0$, and for the source moving towards the observer $v > v_0$,. The change in frequency is

$$\Delta v = v - v_0 = -\frac{v}{c} v_0$$

So, finally,

$$\frac{\Delta v}{v_0} = -\frac{v}{c}$$

- **Coherent and Incoherent Addition of Waves:**

a) Two sources are coherent if they have the same frequency and a stable phase difference.

b) In this case, the total intensity I is not just the sum of individual intensities I_1 and I_2 due to the two sources but includes an interference term,

$$I = I_1 + I_2 + 2k.E_1.E_2$$

Where E_1 and E_2 are the electric fields at a point due to the sources.

c) The interference term averaged over many cycles is zero if
   i) The sources have different frequencies or
   ii) The sources have the same frequency but no stable phase difference.

d) For such coherent sources,

$$I = I_1 + I_2$$

e) According to the superposition principle when two or more wave motions traveling through a medium superimpose one another, a new wave is formed in which resultant displacements due to the individual waves at that instant.

f) The average of the total intensity will be

$$\overline{I} = \overline{I_1} + \overline{I_2} + 2\sqrt{\left(\overline{I_1}\right)\left(\overline{I_2}\right)} \cos\phi$$

Where ϕ is the inherent phase difference between the two superimposing waves.

g) The significance is that the intensity due to two sources of light is not equal to the sum of intensities due to each of them.

h) The resultant intensity depends on the relative location of the point from the two sources, since changing it changes the path difference as we go from one point to another.

i) As a result, the resulting intensity will vary between maximum and minimum values, determined by the maximum and minimum values of the cosine function. These will be

$$\bar{I}_{MAX} = \bar{I}_1 + \bar{I}_2 + 2\sqrt{(\bar{I}_1)(\bar{I}_2)} = \left(\sqrt{\bar{I}_1} + \sqrt{\bar{I}_2}\right)^2$$

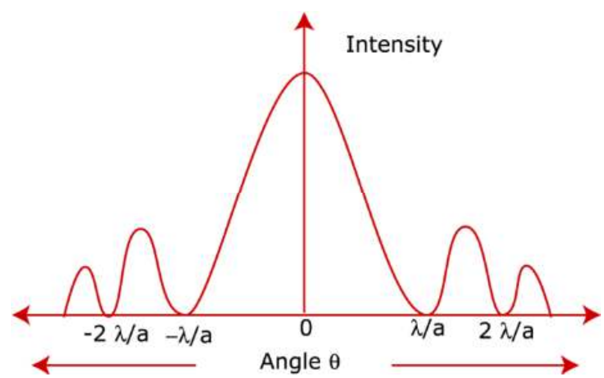
$$\bar{I}_{MIN} = \bar{I}_1 + \bar{I}_2 - 2\sqrt{(\bar{I}_1)(\bar{I}_2)} = \left(\sqrt{\bar{I}_1} - \sqrt{\bar{I}_2}\right)^2$$

- **Young's Experiment**
  Two parallel and very close slits S_1 and S_2 (illuminated by another narrow slit) behave like two coherent sources and produce on a screen a pattern of dark and bright bands – interference fringes.
  For a point P on the screen, the path difference
  $$S_2P - S_2P = \frac{y_1 d}{D_1}$$
  Where d is the separation between two slits, D_1 is the distance between the slits and the screen and y1 is the distance of the point of *P* from the central fringe.
  For constructive interference (bright band), the path difference must be an integer multiple of λ , i.e.,
  $$\frac{y_1 d}{D_1} = n\lambda \text{ or } y_1 = n\frac{D_1\lambda}{d}$$
  The separation Δy1 between adjacent bright (or dark) fringes is,
  $$\Delta y_1 = \frac{D_1\lambda}{d}$$
  using which λ can be measured.
- **Young's Double Slit Interference Experiment:**
  Fringe width, $w = \dfrac{D\lambda}{d}$
  where D is the distance between the slits & the screen d is the distance between the two slits
- **Constructive Interference:**
  a) Phase difference : $\Delta\phi = 2\pi n$ where n is an integer
  b) Path difference: $\Delta X = n\lambda$ where n is an integer
- Destructive interference:
  a) Phase difference : $\Delta\phi = \left(n + \frac{1}{2}\right)2\pi$, where n is an integer
  b) Path difference: $\Delta X = \left(n + \frac{1}{2}\right)\lambda$, where n is an integer
- **Diffraction due to Single Slit:**
  a) Angular spread of the central maxima $= \dfrac{2\lambda}{d}$
  b) Width of the central maxima: $\dfrac{2\lambda D}{d}$
  Where D is the distance of the slit from the screen d is the slit width

- **Condition for the Minima on the either side of the Central Maxima:**
  - $d\sin\theta = n\lambda$, where n = 1,2,3,....

- **Relation between phase difference & path difference:**
  - $\Delta\phi = \frac{2\pi}{\lambda}.\Delta X$

  Where $\Delta\phi$ is the phase difference & ΔX is the path difference
- **Diffraction:**
  a) It refers to light spreading out from narrow holes and slits, and bending around corners and obstacles.
  b) The single-slit diffraction pattern shows the central maximum $(at\theta = 0)$, zero intensity at angular separation
  $\theta = \pm(n+1/2)\lambda......(n \neq 0)$
- **Different Parts of the Wave Front at the Slit act as Secondary Sources:**
  a) Diffraction pattern is the result of interference of waves from these sources.
  b) The intensity plot looks as follows, with there being a bright central maximum, followed by smaller intensity secondary maxima, with there being points of zero intensity in between, whenever
  $d\sin\theta = n\lambda, n \neq 0$



- **Emission, Absorption and Scattering:**
  a) These are the three processes by which matter interacts with radiation. In emission, an accelerated charge radiates and loses energy.
  b) In absorption, the charge gains energy at the expense of the electromagnetic wave.
  c) In scattering, the charge accelerated by incident electromagnetic wave radiates in all direction.
- **Polarization:**
  a) It specifies the manner in which electric field E oscillates in the plane transverse to the direction of propagation of light. If E oscillates back and forth in a straight line, the wave is said to be linearly polarized. If the direction of E changes irregularly the wave is unpolarized.
  b) When light passes through a single polaroid P_1 light intensity is reduced to half, independent of the orientation of P_1. When a second Polaroid P_2 is also included, at one specific orientation w.r.t P_1, the net transmitted intensity is reduced to zero but is transmitted fully when P_1 is turned 90^0 from that orientation. This happens

because the transmitted polarization by a polaroid is the component of E parallel to its axis.

c) Unpolarized sunlight scattered by the atmosphere or reflected from a medium gets (partially) polarized.

- **Optical Activity:**
  Linearly polarized light passing through some substances like sugar solution undergoes a rotation of its direction of polarization, proportional to the length of the medium traversed and the concentration to the substance. This effect is known as optical activity.
- **Intensity of the Light due to Polarization:**

  $$I = I_0 \cos^2 \theta$$

  Where I is the intensity of light after polarization Io is the original intensity, θ is the angle between the axis of the analyzer & the polarizer
- **Brewster's Law:**
  When an incident light is incident at the polarizing angle, the reflected & the refracted rays are perpendicular to each other. The polarizing angle, also called as Brewster's angle, is

  $$\tan \theta_p = \mu$$
- **Polarization by Scattering:**
  a) Light is scattered when it meets a particle of similar size to its own wavelength. The scattering of sunlight by dust particles is an example of polarization by scattering.
  b) Rayleigh showed that the scattering of light is proportional to the fourth power of the frequency of the light or varies as $\frac{1}{\lambda^4}$ where λ is the wavelength of light incident on the air molecules of size 'd' where $d << \lambda$. Hence blue light is scattered more than red. This explains the blue colour of the sky.