Kunthavai Naachiyar Government Arts College for Women, Thanjavur.

Department of Physics

OPTICS AND LASER PHYSICS

18K3P04

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UNIT-I - LENS AND ABERRATIONS

Refraction through lenses –Sign Convention-Defects of images – Spherical aberration- Reducing spherical aberration (qualitative study) – Coma (qualitative study) - Chromatic aberration – Chromatic aberration in a lens-Achromatic combination of lenses-Condition for achromatism – Lenses in contact-Lenses separated by a distance "d" apart.

Introduction

A lens is a portion of a transparent medium bounded by two regular curved surfaces; or by one spherical surface and a plane surface.Spherical surfaces are easy to make therefore most lenses are made of spherical surfaces and have a wide range of curvature. Other transparent materials such as Quartz,used Silica and plastics are also used in making lenses. A single lens with two refracting surfaces is a simple lens.

Refraction through Lenses

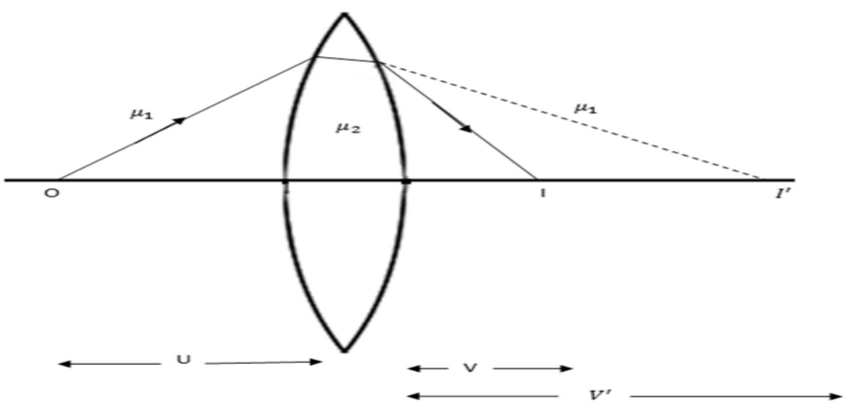
A lens is an image-forming device. It forms an image by refraction of light at its bounding surfaces, one spherical surface and a plane surface.The line joining the centres of curvature of the two spherical surfaces is known as the principal axis. If one of the surface is plane, the axis is a straight line normal to the surface drawn throughout the centre of curvature of the other surface.A plane through the axis is called the principal section of the lens.Optical centre of a lens is a point on the principal axis through which all the rays will pass, when the incident and emergent paths are parallel to each other.

Thin Lens

A thin lens is a lens with a thickness (distance along the optical axis between the two surfaces of the lens) that is negligible compared to the radii of curvature of the lens surfaces

Thin Lens Equation

Consider a thin lens of refractive index μ_2 placed in a medium of refractive index μ_1.



Let R_1 and R_2 be the radii of curvature of the two co-axial spherical surfaces and O is a point-object situated on the principal axis. An image I' is formed at a distance of v' from the pole of the first surface.

Then, $\frac{\mu_2}{v'} - \frac{\mu_1}{u} = \frac{\mu_2-\mu_1}{R_1}$----------(1)

If the distance from of the final image from the pole of the second surface is equal to v,

then, $\frac{\mu_1}{v} - \frac{\mu_2}{v'} = \frac{\mu_1-\mu_2}{R_2}$ -----------(2)

In this case the rays are passing from the medium of refractive index μ_2 to medium of refractive index μ_1

Adding equations (1) and (2)

$\frac{\mu_1}{v} - \frac{\mu_1}{u} = (\mu_2 - \mu_1)\left[\frac{1}{R_1} - \frac{1}{R_2}\right]$----------(3)

Dividing equation 3 by μ_1,

$\frac{1}{v} - \frac{1}{u} = (\frac{\mu_2}{\mu_1} - 1)\left[\frac{1}{R_1} - \frac{1}{R_2}\right]$----------(4)

If the lens is placed in air $\mu_1 = 1$ and $\frac{\mu_2}{\mu_1} = \mu$, where μ is the refractive index of material of the lens.

Then equation (4) becomes,

$$\frac{1}{v} - \frac{1}{u} = (\mu - 1)\left[\frac{1}{R_1} - \frac{1}{R_2}\right]$$ -----

Equation 5 is known as the thin lens equation.

Equation of a thin lens is

$\frac{1}{v} - \frac{1}{u} = (\mu - 1)\left[\frac{1}{R_1} - \frac{1}{R_2}\right]$----------(1)

If the object is at infinity, the image is formed at the *principal focus* of the lens. When $u = \infty, \frac{1}{u} = 0$ and $v = f$. then equation [1] becomes,

$$\frac{1}{f} - \frac{1}{\infty} = (\mu - 1)\left[\frac{1}{R_1} - \frac{1}{R_2}\right]$$

$$\frac{1}{f} = (\mu - 1)\left[\frac{1}{R_1} - \frac{1}{R_2}\right]$$ ---------

Equation (2) is known as the lens maker's formula, since it enables one to calculate f from the known properties of the lens. It can also be used to determine the values of R_1 and R_2 needed for a desired focal length of a lens of a given index of refraction.

Magnification

The magnification of a lens means how large or small, an object can be reproduced on the image plane.

If an object of length X forms an image of length Y in the image, the magnification of the lens is defined to be Y/X. This is the lateral or transverse magnification (m) of a lens.

If a small object of length du placed along the axis, produces an image of length dv along the axis, then Longitudinal magnification L = dv/du.

Power

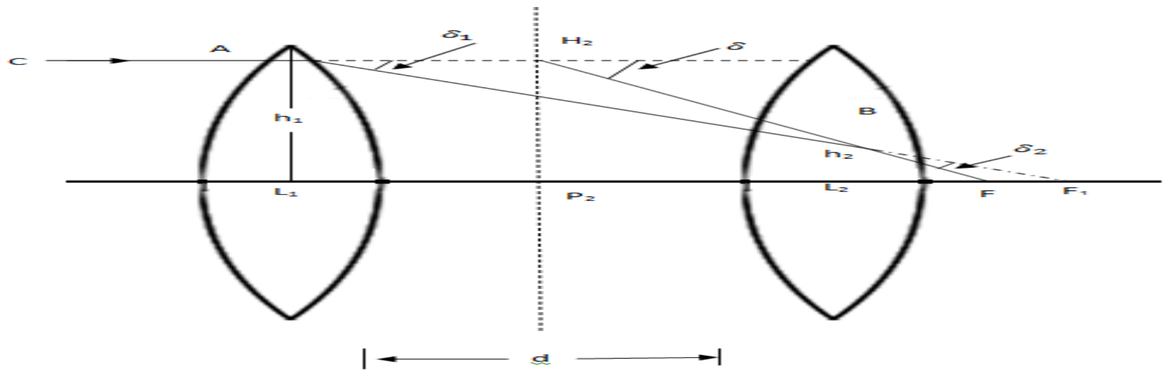
The power of a lens is defined as the measure of its ability to produce convergence of a parallel beam of light. The unit in which the power of a lens is measured is called dioptre (D). Convex lens converges the light, so its power is taken as +ve. Concave diverge the light; hence its power is taken as –ve.

Mathematically,

$$\text{Power} = \frac{1}{focallengthinmetres}$$

Equivalent Focal Length Of Two Thin Lenses

Let f_1 and f_2 be the focal lengths of two thin lenses L_1 and L_2 placed co-axially and separated by a distance d in air.



Let a ray IA of monochromatic light parallel to the common axis be incident on the first lens L_1 at a height h_1 above the axis. This ray, after refraction through the first lens, is directed towards F_1 which is the second principal focus of L_1. Then the deviation δ_1, produced by the first lens is given by,

$$\delta_1 = \frac{h_1}{f_1}$$

The emergent ray from the first lens is refracted by the second lens L_2 at a height h_2 and finally meets the axis at F. Since the incident ray IA is parallel to the principal axis and after refraction through the combination meets the axis at F, F must be the second principal focus of the combination. The deviation δ_2, produced by the second lens is given by

$$\delta_2 = \frac{h_2}{f_2}$$

The incident and the final emergent rays, when produced, intersect at E. It is clear that a single lens placed at P_2 will produce the same deviation as the two constituent lenses together. The lens of focal length P_2F placed at P_2 is termed as the **equivalent lens** which can replace the two lenses L_1 and L_2. The deviation produced by the equivalent lens is

$\delta = \frac{h_1}{f}$ where f is the focal length of the equivalent lens.

$$\delta = \delta_1 + \delta_2$$

$$\frac{h_1}{f} = \frac{h_1}{f_1} + \frac{h_2}{f_2} \text{-------------}(1)$$

Δs AL_1F_1 and BL_2F_1 are similar

$$\therefore \frac{AL_1}{L_1F_1} = \frac{BL_2}{L_2F_1} \text{ or } \frac{h_1}{f_1} = \frac{h_2}{f_1 - d}$$

$$h_2 = \frac{h_1(f_1-d)}{f_1} \text{-----------} (2)$$

Substituting this value of h_2 in equation (1)

$$\frac{h_1}{f} = \frac{h_1}{f_1} + \frac{h_1(f_1-d)}{f_1f_2}$$

$$\frac{1}{f} = \frac{1}{f_1} + \frac{(f_1-d)}{f_1f_2}$$

$$\frac{1}{f} = \frac{1}{f_1} + \frac{1}{f_2} - \frac{d}{f_1f_2}$$

$$\therefore f = \frac{f_1f_2}{f_1+f_2-d}$$

$$\boxed{f = \frac{-f_1f_2}{\Delta}}$$

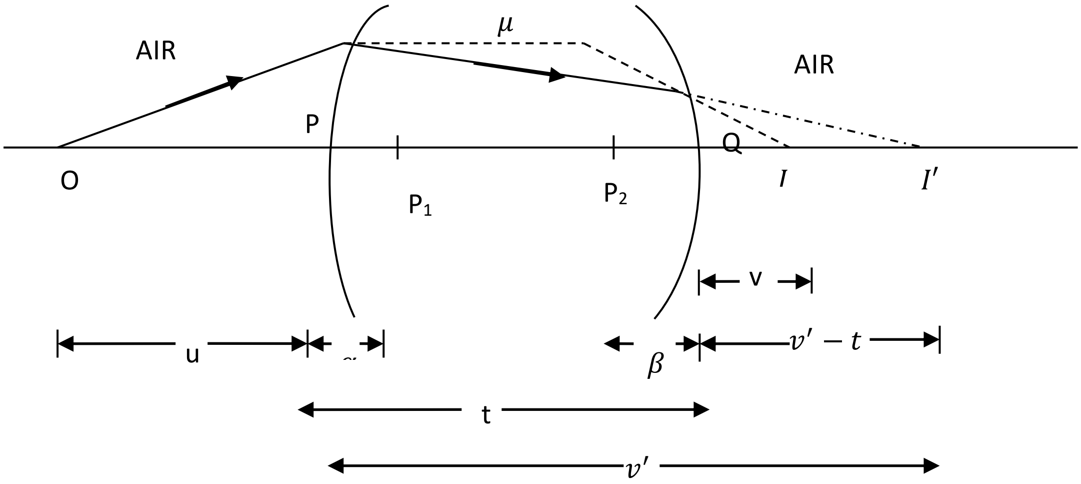
where $\Delta = d - (f_1 + f_2)$ and is known as the optical separation or optical interval between the two lenses. It is numerically equal to the distance between the second principal focus of the first lens and the first principal focus of the lens.

Thick Lens

A thick lens is a physically large lens having two spherical surfaces separated by a distance, which is not negligible in comparison to the radii of curvature of the spherical surfaces.

Thick Lens Formula

Consider a lens of thickness t and of a refractive indexμ, placed in air. The radii of curvature are R1 and R2.



A point object O is situated on the axis at a distance u from the first refracting surface and forms an image I′ at a distance v1 from P.

$$\frac{\mu}{v_1} - \frac{1}{u} = \frac{\mu - 1}{R_1}$$

$v_1 = \frac{R_1 u\mu}{R_1 + u(\mu - 1)}$-----------(1)

The image formed by the first surface acts as the object for the second surface and the final image is formed at I.

$$\frac{1/\mu}{v} - \frac{1}{(v_1 - t)} = \frac{1/\mu - 1}{R_2}$$

$(v_1 - t) = \frac{\mu v R_2}{R_2 + v(\mu - 1)}$-------(2)

Substituting the value of v_1 from equation (1) in equation (2), we obtain

$$\frac{R_1 \mu u}{R_1 + u(\mu - 1)} - t = \frac{\mu v R_2}{R_2 + v(\mu - 1)}$$

On simplification of the above expression, we obtain

$uv[\mu(\mu - 1)(R_1 - R_2) - (\mu - 1)^2 t] + u[\mu R_1 R_2 - tR_2(\mu - 1)] + v[-\mu R_1 R_2 - tR_1(\mu - 1)] - tR_1 R_2 = 0$----------(3)

The equation is of the form

$$uvA + uB + vC + D = 0$$

$uv + u\frac{A}{B} + v\frac{C}{A} + \frac{D}{A} = 0$----------(4)

Where A, B, C, and D coefficients.

Let us take $V = v - \beta$ and $U = u - \alpha$ and the focal length=f

$\frac{1}{v-\beta} - \frac{1}{u-\alpha} = \frac{1}{f}$----------(5)

Simplifying and rearranging the terms, we obtain

$uv + (-\beta - f)u + (-\alpha + f)v + (-\beta f + \alpha f + \alpha\beta) = 0$---------(6)

Comparing equation (5) and (6), we have

$-\beta - f = \frac{B}{A}$-----------(7)

$-\alpha + f = \frac{C}{A}$-----------(8)

and$-\beta f + \alpha f + \alpha\beta = \frac{D}{A}$-----------(9)

From equation (7) to (9), we get

$$f^2 = \frac{D}{A} - \frac{BC}{A^2} = \frac{AD - BC}{A^2}$$

Substituting the values of A, B, C and D in the above expression and after simplification, we get

$$f = \frac{\mu^2 R_1^2 R_2^2}{[\mu(\mu-1)(R_1 - R_2) - (\mu-1)^2 t]^2}$$

$$f = \pm \frac{\mu R_1 R_2}{[\mu(\mu-1)(R_1 - R_2) - (\mu-1)^2 t]}$$

$\frac{1}{f} = (\mu - 1)\left[\frac{1}{R_1} - \frac{1}{R_2} + \frac{(\mu-1)t}{\mu R_1 R_2}\right]$--------(10)

For a thin lens, t=0 and form equation (10) we see that

$\frac{1}{f_1} = (\mu - 1)\left[\frac{1}{R_1} - \frac{1}{R_2}\right]$---------(11)

Power Of Thick Lens

The power of a thick lens is given by

$P = P_1 + P_2 - P_1 P_2 . \frac{t}{\mu}$----------(1)

The power of the first refracting surface P_1 is

$$P_1 = \frac{(\mu - 1)}{R_1}$$

and the power of the second refracting surface P_2 is

$$P_2 = -\frac{(\mu - 1)}{R_2}$$

Substituting P_1 and P_2 in equation 1, we get

$$P = \frac{1}{f} = \frac{(\mu - 1)}{R_1} - \frac{(\mu - 1)}{R_2} + \frac{(\mu - 1)^2}{R_1 R_2} . \frac{t}{\mu}$$

Nodal Points

Nodal points are defined as a pair of conjugate points on the axis having unit positive angular magnification.

Defects Of Images

The departure of real images from the ideal images, in respect of the actual size, shape and position are called aberrations.Inotherwords, the failure of the lens to bring all rays from a point object to focus at the same point.

Aberrations

In an ideal optical system, all rays of light from a point in the object plane would converge to the same point in the image plane, forming a clear image. The influences which cause different rays to converge to different points are called aberrations.

Definition

The deviations from the actual size, shape and position of an image are called aberrations.

Types

The two types of aberrations are

i) Chromatic aberrations

ii) Monochromatic aberrations.

The aberrations produced by the variation of refractive index with wavelength of light are called chromatic aberrations. The aberrations caused even if monochromatic light is used are called monochromatic aberrations.

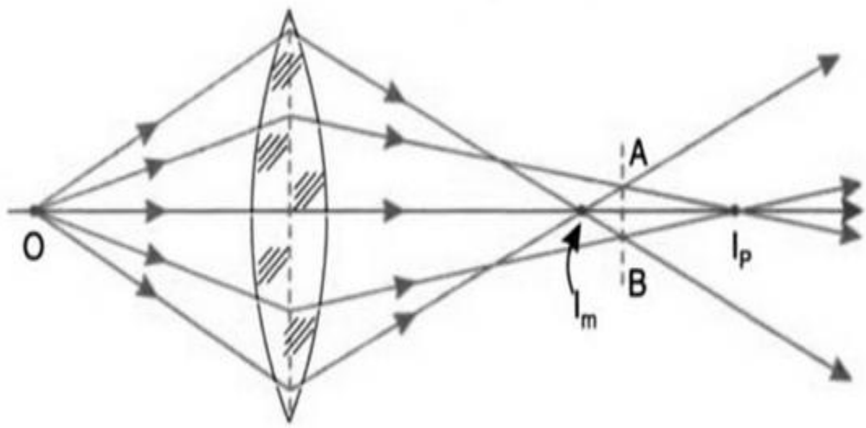
Monochromatic aberrations:

Spherical aberration, coma, astigmatism, curvature of field and distortion are called monochromatic aberrations.

Spherical aberration due to thin lens

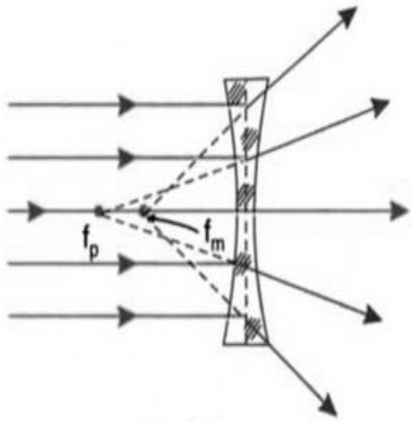
It is defined as failure of the lens to bring all rays from a point object situated on the axis to focus at the same point.

The presence of spherical aberration in the image formed by a single convex lens is illustrated in the figure.



O is a point object on the axis of the lens and $I_p$and $I_m$are the images formed by the paraxial and marginal rays respectively. The paraxial rays of light form the image at a longer distance from the lens than the marginal rays. The image is not sharp at any point on the axis. But at C, the image appears to be a circular patch of diameter AB. On either side of AB, the image patch has a larger diameter. The circular patch at C with diameter AB is the position of the best image and is called **circle of least confusion**. The distance between $I_m$and $I_p$is the longitudinal spherical aberration and the radius of the circle of least confusion is the lateral spherical aberration.

For lenses made with spherical surfaces, rays which are parallel to the optic axis but at different distances from the optic axis, fail to converge to the same point. Thus, for an object point O on the axis, the image extends over the length I_mI_p. This aberration arises due to the fact that different annular zones of the lens have different focal length. The spherical aberration produced by a concave lens is shown below.



The spherical aberration produced by a convex lens is positive and by a concave lens is negative.

Methods of reducingSphericalAberration

Spherical aberration can be minimised or eliminated by using

i) Stops
ii) Crossed lens

iii) Single Plano-convex lens and
iv) Two Plano-convex lens separated by a small distance
v) Combination of convex and concave lenses

i) Using stops

When the aperture of the lens is relatively large compared to the focal length of the lens, the cones of the rays of light refracted through the different zones of the lens surface are not brought to focus at the same point, resulting in spherical aberration. This can be minimised by using stops which reduce the effective lens aperture. Stops permit either the paraxial rays or marginal rays of light as shown.

The image appears less bright because the intensity of the incoming light is reduced by stops.

ii) Using crossed lens

The longitudinal spherical aberration produced by a thin lens for parallel incident beam is given by

$$x = \frac{\rho_2}{f_2}\left[\frac{k^2\mu^2 + k(\mu+2\mu^2+2\mu^3)+\mu^3-2\mu^2-2}{2\mu(\mu-1)^2(1-k^2)}\right] \text{------------(1)}$$

where x is the longitudinal spherical aberration, ρ is the radius of the lens aperture and f_2 is the second principal focal length.

$$k = \frac{R_1}{R_2}$$

where R_1 and R_2 are the radii of curvature. For given values of μ, f_2 and ρ, the condition for minimum spherical aberration is $\frac{dx}{dk} = 0$.

Differentiating equation (1) and equating the result to zero

$$k = \frac{R_1}{R_2} = \frac{\mu(2\mu-1)-4}{\mu(2\mu+1)} \text{------------(2)}$$

from equation 2, if μ = 1.5, then $k = -\frac{1}{6}$. Thus the lens which produces minimum spherical aberration is biconcave.

A lens whose $\frac{R_1}{R_2} = -\frac{1}{6}$ is called a crossed lens. Crossed lens can be used to minimize the spherical aberration.

iii) Using Plano- convex lenses

Plano- convex lenses are used in optical instrument so as to reduce the spherical aberration. When the curved surface of the lens faces the incident or emergent light whichever is more parallel to the axis, the spherical aberration is minimum. The spherical aberration in a crossed lens is only 8% less than that of a Plano-convex lens having the same focal length and radius of the lens aperture. Hence Plano-convex lens can also be used to minimise the spherical aberration.

iv) Using two Plano-convex lenses

Spherical aberration can be minimised by using two Plano-convex lenses separated by a small distance. The separation should be equal to the difference in their focal length. If f_1 and f_2 are the focal lengths of the two Plano-convex lenses, then the separation d = $f_1 - f_2$. The total deviation is equally shared by both the lenses and the spherical aberration is minimum.

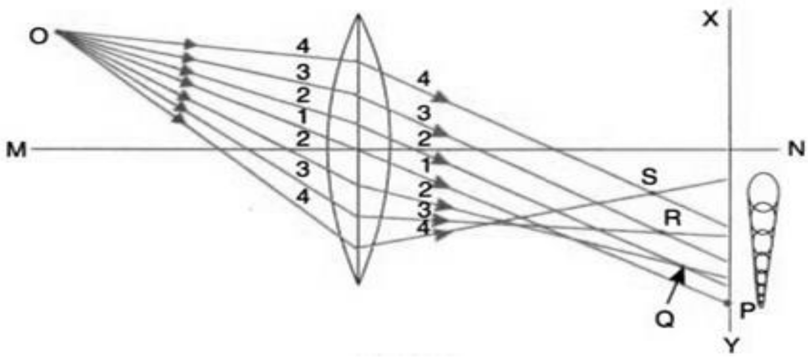
V) Combination of convex and concave lenses

Spherical aberration for a convex lens is +ve and that of a concave lens is –ve. By a suitable combination of convex and concave lenses, spherical aberration can be made minimum.

Coma

It is defined as failure of the lens to bring all rays from a point object not situated on the axis to focus at the same point.

The effect of rays from an object point not situated on the axis of the lens results in an aberration called coma. In spherical aberration, the point object is situated on the axis and the image is a circle of varying diameter along the axis. In case of comatic aberration, the point object is situated off the axis and the image is comet-shaped (circle of varying diameter normal the axis) and hence the name coma. The figure illustrates the presence of coma in the image due to a point object situated off the axis of the lens.



Rays of light getting refracted through the centre of the lens (ray 1) meet the screen XY at the point P. Rays 2,2; 3,3; etc., getting refracted through the outer zones of the lens come to focus at point Q, R, S etc., nearer the lens and on the screen overlapping circular patches of gradually increasing diameter are formed. The resultant image of the point is comet-shaped. Coma is the result of varying magnification for rays refracted through different zones of the lens. If the magnification of outer zone is lesser than inner zone, then coma is said to be +ve.

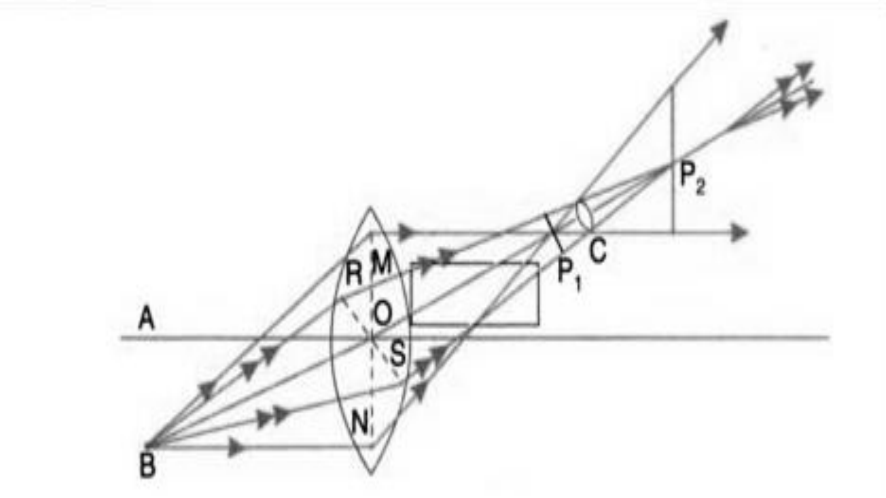
Elimination of coma:

Comatic aberration produced by a single lens can be corrected by properly choosing the radii of curvature of the lens surface. Coma can be altogether eliminated for a given pair of object and image points whereas spherical aberration cannot be completely corrected. Further, a lens corrected for coma will not be free from spherical aberration and the one corrected for spherical aberration will not be free from coma. Use of a stop or a diaphragm at the proper position eliminates coma.

Astigmatism

Astigmatism is the aberration formed by a lens in the image of object points off the axis.

It is similar to coma (object is situated off the axis). However, in coma, the spreading of the image takes place in a plane perpendicular to the lens axis and in astigmatism the spreading takes place along the lens axis. Fig. illustrates the defect of astigmatism in the image of a point B.



The cone of rays of light refracted through the tangential (vertical) plane BMN comes to focus at point P_1 nearer the lens and the cone of rays refracted through the sagittal (horizontal) plane BRS comes to focus at the point P_2 away from the lens. All rays pass through a horizontal line passing through P_1 called the primary image and also through a vertical line passing through P_2 called the secondary image.

The refracted beam has an elliptical cross-section which ends to a horizontal line at P_1 and a vertical line P_2 as shown in the fig.

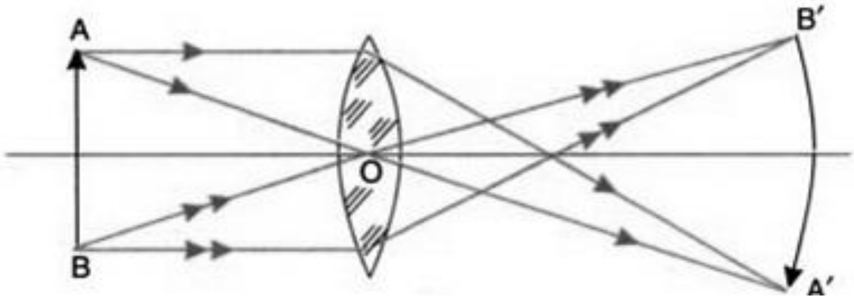
The cross section of the refracted beam is circular at some point between the primary and the secondary images and this is called the circle of least confusion.

The focus of all the primary images of all points is called the primary image surface and locus of the secondary images gives the secondary image surface. If the primary image surface is to the left of the secondary image surface, astigmatism is said to be positive, otherwise negative.

By using a convex and a concave lens of suitable focal lengths and separated by a distance, it is possible to minimise the astigmatic difference and such a lens combination is called an anastigmatic.

Curvature

The image of an extended plane object due to a single lens is not a flat one but will be a curved surface and this defect of a lens is known as curvature of field. Curvature of field causes a planar object to project a curved (non planar) image. It can be thought of arising from a "power error" for rays at a large angle. The central portion of the image nearer the axis is in focus but the outer regions of the image away from the axis are blurred. This is due to the fact that the paraxial focal length is greater than the marginal focal length. Fig. illustrates the presence of curvature of field in the image formed by a convex lens.



This aberration is present even if the aperture of the lens is reduced by a suitable stop.

Elimination: For a system of thin lenses, the curvature of the final image is given by

$$\frac{1}{R} = \Sigma \frac{1}{\mu_n f_n}$$

where R is the radius of curvature of the final image, μ_n and f_n are the refractive index and focal length of the n^{th} lens. For the image to be flat, R must infinity. If two lenses are used which are placed in air, the condition for no curvature is

$$\frac{1}{\mu_1 f_1} + \frac{1}{\mu_2 f_2} = 0$$

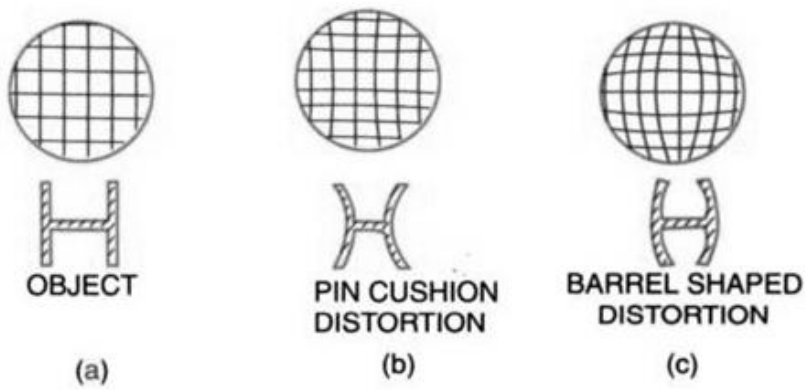
This is known as Petzwal's condition for no curvature. The above condition will be satisfied if the lenses are of opposite sign. If one of the lenses is convex the other must be concave.

Distortion

The variation in the magnification produced by a lens for different axial distances results in an aberration called distortion.

Distortion is of two types namely a) Pin – cushion distortion and b) Barrel shaped distortion.

In pin cushion distortion, the magnification increases with increasing axial distance and the image of an object appears as shown below in fig (b).



If the magnification decreases with increasing axial distance, it results in barrel shaped distortion and the image appears as shown in fig (c).

Elimination: If a stop is placed before the lens the distortion is barrel-shaped and if a stop is placed after the lens, the distortion in pin-cushion type. To eliminate distortion, a stop is placed in between two symmetrical lenses, so that the pin-cushion distortion produced by the first lens is compensated by the barrel-shaped distortion produced by the second lens.

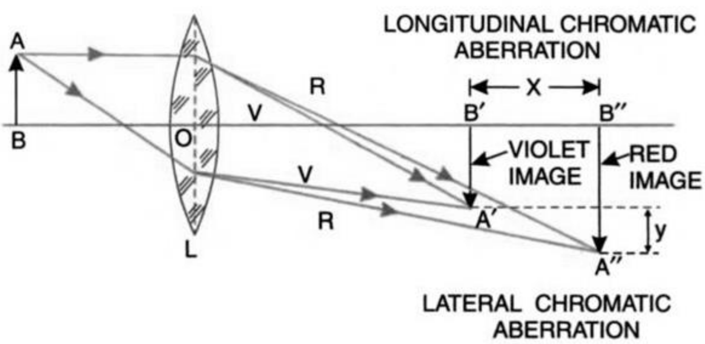
Chromatic Aberration

A lens will not focus different colours in exactly the same place because the focal length depends on refraction and the refractive index of the material of a lens is different for different wavelengths of light. Hence the focal length of a lens is different for different wavelengths.

The index of refraction for blue light (short wavelengths) is larger than that of red light (long wavelengths). Further, as the magnification of the image is dependent on the focal length of a lens, the size of the image is different for different wavelengths (colours). The amount of chromatic aberration depends on the dispersion of the glass.

It is defined as an aberration where a single lens produces a coloured image of an object illuminated by white light.

Chromatic aberration present in an image formed by a single lens is illustrated in the Fig.



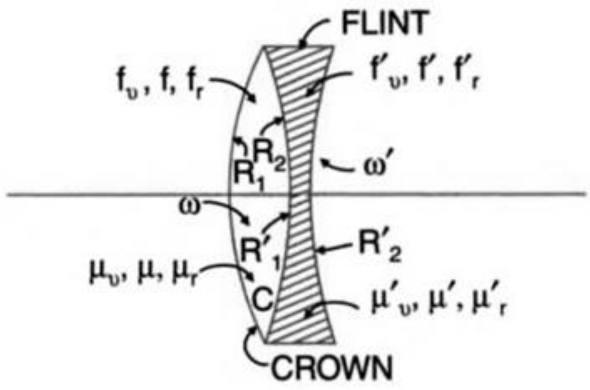
The violet image is formed nearer the lens than the red image. The distance x measures the axial or longitudinal chromatic aberration and the distance y measures the lateral chromatic aberration.Elimination of this defect in a combination of lenses is called achromatism.

Condition for Achromatism

Chromatic aberration cannot be eliminated by using a single lens. Hence more than one lens is used. One way to minimize this aberration is to use glasses of different dispersion in a doublet or other combination.

Condition for achromatism of two lenses placed in contact:

The use of a strong positive lens made from a low dispersion glass like crown glass coupled with a weaker high dispersion glass like flint glass can correct the chromatic aberration for two colours, e.g., red and blue. A convex lens of crown glass and a concave lens of flint glass are placed in contact as shown.



Let μ_b, μ, μ_r and μ_b', μ', μ_r' be the refractive indices for blue, yellow and red rays of light of the two materials. f_b, f, f_r and f_b', f' and f_r' are the corresponding focal lengths of the two lenses and ω and ω' are the dispersive powers for crown and flint glass respectively.

The focal length of a lens is given by

$\frac{1}{f} = (\mu-1)\frac{1}{R_1} - \frac{1}{R_2}$---------------(1)

$\frac{1}{f_b} = (\mu_b-1)\frac{1}{R_1} - \frac{1}{R_2}$---------------(2)

$\frac{1}{f_r} = (\mu_r-1)\frac{1}{R_1} - \frac{1}{R_2}$---------------(3)

$\frac{1}{f'} = (\mu'-1)\frac{1}{R_1'} - \frac{1}{R_2'}$---------------(4)

$\frac{1}{f_b'} = (\mu_b'-1)\frac{1}{R_1'} - \frac{1}{R_2'}$----------------(5)

$\frac{1}{f_r'} = (\mu_r'-1)\frac{1}{R_1'} - \frac{1}{R_2'}$--------------(6)

From equations (1) and (4)

$\frac{1}{R_1} - \frac{1}{R_2} = \frac{1}{(\mu-1)f}$ ------------ (7)

and$\frac{1}{R_1'} - \frac{1}{R_2'} = \frac{1}{(\mu'-1)f'}$----------(8)

Substituting these values in equations (2), (3), (5) and (6) we get

$$\frac{1}{f_b} = \frac{(\mu_b-1)}{(\mu-1)f}$$
$$\frac{1}{f_r} = \frac{(\mu_r-1)}{(\mu-1)f}$$
$$\frac{1}{f_b'} = \frac{(\mu_b'-1)}{(\mu'-1)f'}$$
$$\frac{1}{f_r'} = \frac{(\mu_r'-1)}{(\mu'-1)f'}$$

Let F_b and F_r be the focal lengths of the combination for blue and red rays of light. Then

$$\frac{1}{F_b} = \frac{1}{f_b} + \frac{1}{f_b'} = \frac{(\mu_b-1)}{(\mu-1)f} + \frac{(\mu_b'-1)}{(\mu'-1)f'} \quad \text{and}$$

$$\frac{1}{F_r} = \frac{1}{f_r} + \frac{1}{f_r'} = \frac{(\mu_r-1)}{(\mu-1)f} + \frac{(\mu_r'-1)}{(\mu'-1)f'}$$

For the combination to be achromatic, the focal lengths F_b and F_r must be equal.

$F_b = F_r$ or $\frac{1}{F_b} = \frac{1}{F_r}$

$$\therefore \frac{(\mu_b-1)}{(\mu-1)f} + \frac{(\mu_b'-1)}{(\mu'-1)f'} = \frac{(\mu_r-1)}{(\mu-1)f} + \frac{(\mu_r'-1)}{(\mu'-1)f'}$$

$$\frac{(\mu_b-\mu_r)}{(\mu-1)f} + \frac{(\mu_b'-\mu_r')}{(\mu'-1)f'} = 0$$

$\frac{\omega}{f} + \frac{\omega'}{f'}$ 0 or $\frac{\omega}{f} = -\frac{\omega'}{f'}$ $\left(\because \frac{(\mu_b-\mu_r)}{(\mu-1)} = \omega\right)$

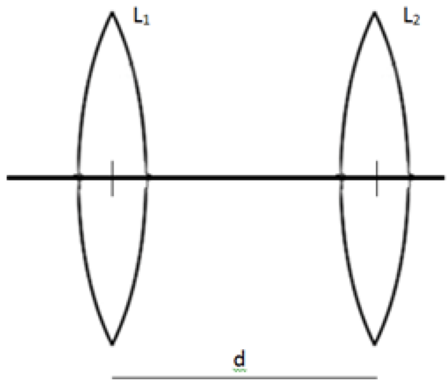
$$f' = -f\frac{\omega'}{\omega}$$

Since ω and ω' are positive quantities, f' is negative if f is positive, i.e., if the crown glass is convex, then the flint glass lens is concave.

Thus, the condition for achromatism is that **the ratio of the dispersive powers of the materials of the lenses must be equal to ratio of the focal lengths of the two lenses.**

ii) **Condition for achromatism of two thin lenses separated by a finite distance**

Let f_1 and f_2 be the focal lengths of two lenses separated by a distance d as shown in fig.



The two lenses are made of the same material and μ, μ_b and μ_r are the refractive indices for the mean rays, blue rays and red rays respectively for both the lenses. f_r, f_r' and f_b , f_b' are the focal lengths of the two lenses for red and blue rays of light. Then,

$$\frac{1}{F} = \frac{1}{f_1} + \frac{1}{f_2} - \frac{d}{f_1 f_2}$$

$$\frac{1}{F_r} = \frac{1}{f_r} + \frac{1}{f_r'} - \frac{d}{f_r f_r'}$$

and $$\frac{1}{F_b} = \frac{1}{f_b} + \frac{1}{f_b'} - \frac{d}{f_b f_b'}$$

where F, F_r and F_b are the focal lengths of the combination for the mean rays, red rays and blue rays.

But

$$\frac{1}{f_r} = \frac{(\mu_r - 1)}{(\mu - 1) f_1} \quad , \quad \frac{1}{f_r'} = \frac{(\mu_r - 1)}{(\mu - 1) f_2} \text{ and}$$

$$\frac{1}{f_b} = \frac{(\mu_b - 1)}{(\mu - 1) f_1} \quad , \quad \frac{1}{f_b'} = \frac{(\mu_b - 1)}{(\mu - 1) f_2}$$

$$\therefore \frac{1}{F_r} = \frac{(\mu_r - 1)}{(\mu - 1) f_1} + \frac{(\mu_r - 1)}{(\mu - 1) f_2} - \frac{(\mu_r - 1)^2}{(\mu - 1)^2} \frac{d}{f_1 f_2} \text{ and}$$

$$\frac{1}{F_b} = \frac{(\mu_b - 1)}{(\mu - 1) f_1} + \frac{(\mu_b - 1)}{(\mu - 1) f_2} - \frac{(\mu_b - 1)^2}{(\mu - 1)^2} \frac{d}{f_1 f_2}$$

For the combination to be achromatic, the focal lengths F_b and F_r must be equal.

$$F_b = F_r \text{ or } \quad \frac{1}{F_b} = \frac{1}{F_r}$$

$$\frac{(\mu_r - 1)}{(\mu - 1) f_1} + \frac{(\mu_r - 1)}{(\mu - 1) f_2} - \frac{(\mu_r - 1)^2}{(\mu - 1)^2} \frac{d}{f_1 f_2} = \frac{(\mu_b - 1)}{(\mu - 1) f_1} + \frac{(\mu_b - 1)}{(\mu - 1) f_2} - \frac{(\mu_b - 1)^2}{(\mu - 1)^2} \frac{d}{f_1 f_2}$$

Rearranging the above equation we get

$$\frac{(\mu_r - 1)}{(\mu - 1)} \left(\frac{1}{f_1} + \frac{1}{f_2}\right) - \frac{(\mu_r - 1)^2}{(\mu - 1)^2} \frac{d}{f_1 f_2} = \frac{(\mu_b - 1)}{(\mu - 1)} \left(\frac{1}{f_1} + \frac{1}{f_2}\right) - \frac{(\mu_b - 1)^2}{(\mu - 1)^2} \frac{d}{f_1 f_2}$$

$$\text{Or } \frac{(\mu_b-\mu_r)}{(\mu-1)}\left(\frac{1}{f_1}+\frac{1}{f_2}\right)= \frac{d}{(\mu-1)^2 f_1 f_2}[(\mu_b-1)^2 - (\mu_r-1)^2]$$

$$= \frac{d}{(\mu-1)^2 f_1 f_2}[(\mu_b-\mu_r)(\mu_b+\mu_r-2)]$$

$$= \frac{d(\mu_b-\mu_r)}{(\mu-1)^2 f_1 f_2}(2\mu-2) \quad (\text{taking } \mu_b+\mu_r = 2\mu)$$

$$= \frac{d(\mu_b-\mu_r)}{(\mu-1)^2 f_1 f_2}\, 2(\mu-1)$$

$$\therefore \frac{(\mu_b-\mu_r)}{(\mu-1)}\left(\frac{1}{f_1}+\frac{1}{f_2}\right) = \frac{2d(\mu_b-\mu_r)}{(\mu-1) f_1 f_2}$$

$$\frac{1}{f_1}+\frac{1}{f_2} = \frac{2d}{f_1 f_2}$$

$$\therefore d = \frac{f_1+f_2}{2}$$

Thus, the condition for achromatism of two thin co-axial lenses of same material separated by a distance is that **the distance between the two lenses must be equal to the mean focal length of the two lenses.**

SUMMARY OF ABERRATIONS

Aberration	Character	Correction
1. Spherical aberration	Monochromatic, on- and off- axis, image blur	Bending, high index, aspheric, gradient index, doublet
2. Coma	Monochromatic, off-axis only, blur	Bending, spaced doublet with central stop
3. Oblique astigmatism	Monochromatic, off-axis blur	Spaced doublet with stop
4. Curvature of field	Monochromatic, off-axis	Spaced doublet

5. Distortion	Monochromatic, off-axis	Spaced doublet with stop
6. Chromatic aberration	Heterochromatic, on- and off-axis, blur	Contact doublet, spaced doublet

Model Questions

Part – A

1. Define magnification of a lens?
2. Define principal axis of a lens?
3. What is a thick lens?
4. What are nodal points?
6. What is meant by aberration?
7. What are the two types of aberration?
8. Mention any four monochromatic aberrations?
9. What is spherical aberration?
10. Write any two methods of reducing spherical aberration?
11. What is coma?
12. Differentiate spherical and comatic aberration?
13. Give the similarity and difference between coma and astigmatism?
14. What are the types of distortion?
15. What do you mean by chromatic aberration?
16. What is achromatism?
17. In what ways chromatic aberration can be eliminated?

Part – B

1. Explain spherical aberration in detail.
2. Explain how spherical aberration can be minimized.
3. Briefly explain about coma.

4. Explain chromatic aberration.

5. Write a short note on Aberration.

6. Explain any one method of eliminating chromatic aberration.

Part – C

1. What is spherical aberration? Describe the methods of minimizing spherical aberration.

2. Write a short note on i) coma ii) astigmatism.

3. Explain the following with necessary diagrams i) chromatic aberration and ii) Coma.

4. Derive the condition for acromatism when two lenses are in contact.

5. Explain what is meant by chromatic aberration. Deduce the condition for achromatism of two lenses separated by a distance?Derive it.

6. Enumerate the various defects of image formation by an optical system.Explain the methods of removing them.

Kunthavai Naachiyar Government Arts College for Women, Thanjavur.

Department of Physics

OPTICS AND LASER PHYSICS (18K3PO4)

Unit-5 LASER

Laser- Characteristics - spontaneous and stimulated emission – Einstein's Co-efficient - Energy levels – Population inversion – Meta stable state – Active medium – Pumping – Optical resonator – Types of LASER – Nd-YAG LASER – CO_2 LASER – Semiconductor LASER – Applications - Industrial – LASER welding and cutting – Medical – LASER Surgery.

Introduction about LASER

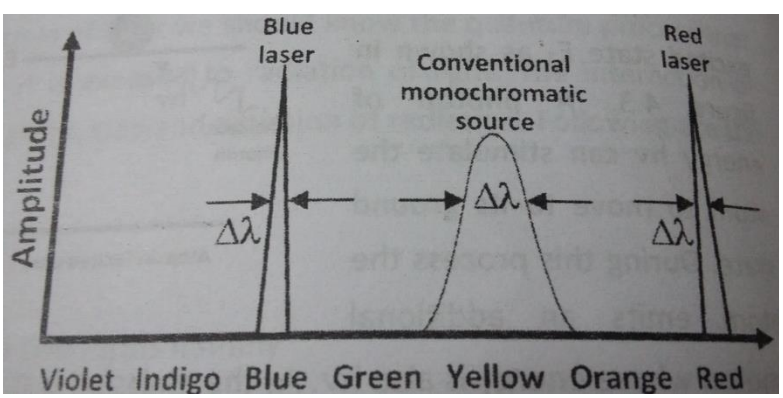
The word LASER is an acronym for "Light Amplification by Stimulated Emission of Radiation". It is a powerful monochromatic light source of collimated beam in which the light waves are highly coherent. The laser light has many superior features compared to conventional light source. Einstein introduced this concept in 1917. Dr. T.H. Maiman demonstrated the first laser namely the ruby laser in the year 1960.

Laser characteristics

Laser differs from the ordinary light with respect to some properties. They are

- Monochromaticity
- Directionality
- Coherence
- Intensity

Monochromaticity

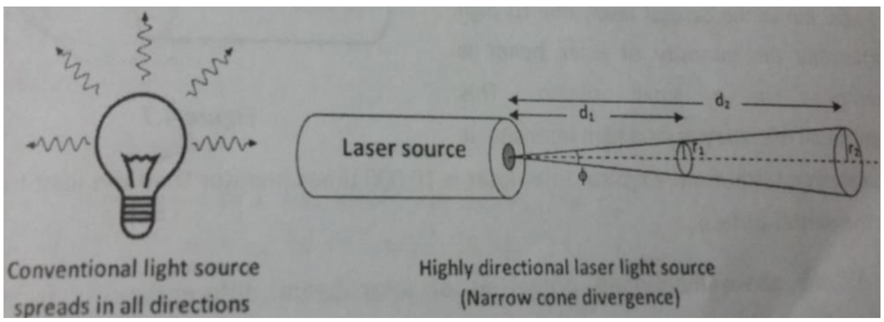


Laser beam is highly monochromatic. It emits single wavelength (one colour). i.e, it possesses good spectral purity since range of laser beam wavelength ($\Delta\lambda$) is very narrow. But ordinary light emits combination of wide range of wavelength (colours).

Directionality

The ordinary source emits light in all directions and its angular spread is 1 metre/metre. But the laser is highly directional and its angular spread is 1mm/metre. The angular spread (ϕ) or divergence is given by,

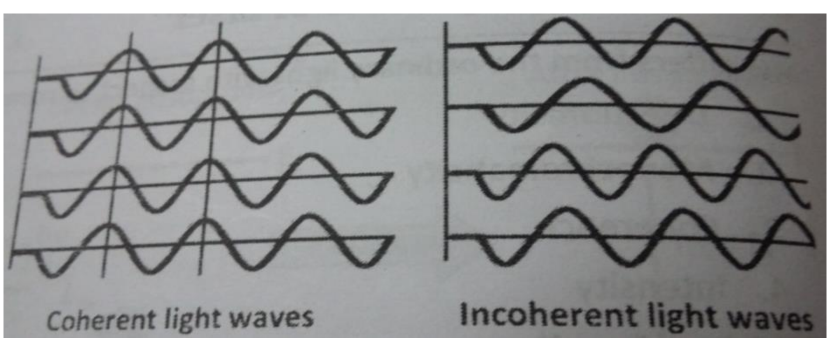
$$\phi = \frac{r_2 - r_1}{d_2 - d_1} \text{ degree}$$



where d_1, d_2 are any two distances from the laser source emitted and r_1, r_2 are the radii of the beam spots at a distance d_1 and d_2, respectively.

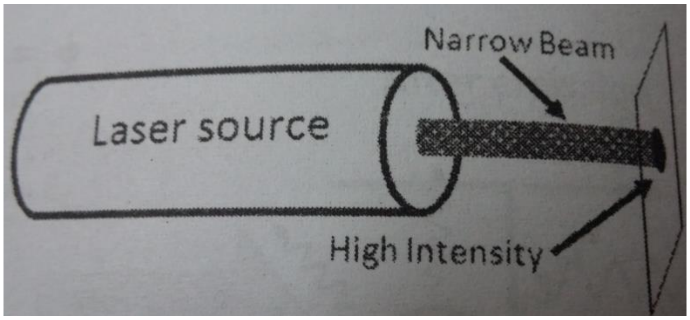
Coherence

The light from a source consists of wave pattern. These wave patterns when identical in phase and direction are called coherent. Laser has a high degree of coherence than the ordinary sources. The coherence of laser emission results in an extremely high power of 5×10^6 watt/m^2. A laser beam can be focused to a very small area of about 0.7 μm diameter.



Intensity

The ordinary light spreads in all directions, so the intensity reaching the target is very less. But in the case of laser, due to high directionality the intensity of laser beam is concentrated in a small region. This concentration of energy gives a high intensity. It is estimated that light from a typical 1mW laser is 10,000 times brighter than the light from the sun at the earth's surface.



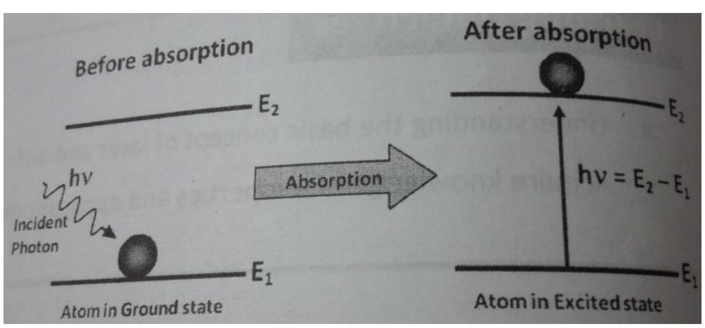
Ground state and Excited states:

Laser emission is shaped by the rules of quantum mechanics, which limit atoms and molecules to having discrete amounts of stored energy that depend on the nature of the atom or molecule. The lowest energy level for an individual atom occurs when its electrons are all in the nearest possible orbits to its nucleus (*see* electronic configuration). This condition is called the **ground state**. When one or more of an atom's electrons have absorbed energy, they can move to outer orbits, and the atom is then referred to as being "**excited.**" Excited states are generally not stable; as electrons drop from higher-energy to lower-energy levels, they emit the extra energy as light.

Principles of laser

Absorption of radiation

An atom is in the ground state with energy E_1 absorbs a photon of energy hν and goes to the excited state with energy E_2 as shown in Fig. This transition is known as stimulated absorption or induced absorption or simply absorption. Here the energy difference is given as $(E_2 - E_1) = h\nu$.



If there are many number of atoms in the ground state then each atom will absorb the energy from the incident photon and goes to the excited state then,

The rate of absorption (R_{12}) is proportional to the following factors

(i.e) $R_{12} \propto$ Energy density of incident radiation (ρ_v)

$\propto$ No. of atoms in the ground state (N_1)

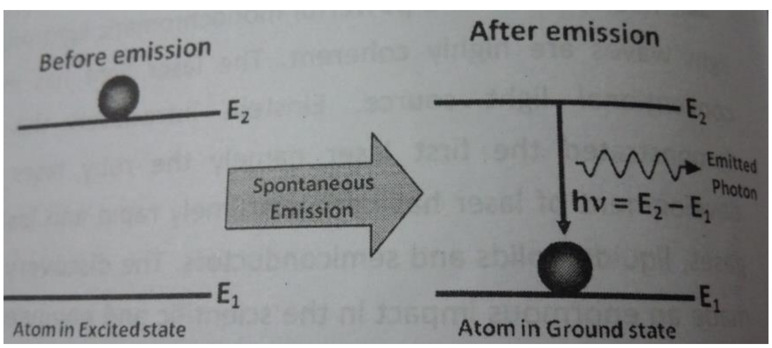
$$R_{12} = B_{12} \rho_v N_1$$

$$R_{12} \propto \rho_v N_1$$

where B_{12} is a constant which gives the probability of absorption transition per unit time

Spontaneous emission

The natural tendency of an atom is to seek out the lowest energy configuration. The excited atoms do not stay in the excited state for longer time but tend to return to the lower state by giving up the excesses energy hν as shown in fig. The atom in the excited state E_2 returns to the ground state E_1 by emitting a photon of energy hν without any external energy. Such emission of radiation not initiated by any external influence is called spontaneous emission. This emission is uncontrollable.



The rate of spontaneous emission R_{21} (Sp)

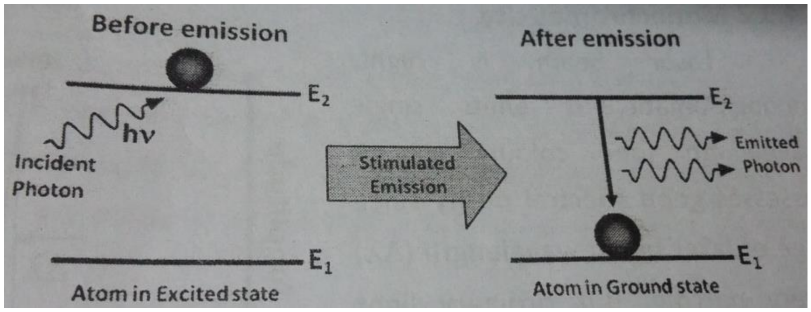
(i.e) R_{21} (Sp) $\propto N_2$

$$R_{21} (Sp) = A_{21}N_2$$

where A_{21} is a constant which gives the probability of spontaneous emission transitions per unit time

Stimulated emission

The atom in the excited state E_2 as shown in fig.--. A photon of energy hν can stimulate the atom to move to its ground state. During this process the atom emits an additional photon whose energy is also hν. As the emission is stimulated by external photon, this process is known as stimulated emission.



The rate of stimulated emission R_{21} (St) is given by

(i.e) $R_{21}\,(St) \propto \rho_\nu N_2$

$$R_{21}\,(St) = B_{21}\,\rho_\nu\,N_2$$

where B_{21} is a constant which gives the probability of stimulated emission transitions per unit time

Einstein's theory of stimulated emission

Einstein's theory of absorption and emission of light by an atom is based on Planck's theory of radiation. Also under thermal equilibrium, the population of energy levels obeys the Bolzmann's distribution law.

At thermal equilibrium,

The rate of absorption = The rate of emission

$$B_{12}\,\rho_\nu\,N_1 = A_{21}N_2 + B_{21}\,\rho_\nu\,N_2 \quad \text{--------------------------} \quad (1)$$

$$\rho_\nu\,[B_{12}\,N_1 - B_{21}\,N_2] = A_{21}N_2$$

$$\rho_\nu = \frac{A_{21}N_2}{B_{12}N_1 - B_{21}N_2}$$

$$\rho_\nu = \frac{A_{21}}{B_{12}(N_1/N_2) - B_{21}} \quad \text{----------------------} \quad (2)$$

We know from Bolzmann distribution law

$N_1 = N_0\, e^{-E1/K_BT}$

$N_2 = N_0\, e^{-E2/K_BT}$

Where, K_B is the Bolzmann constant,

T is the absolute temperature and

N_0 is the number of atoms at absolute zero

At equilibrium, we can write the ratio of population as follows,

$$\frac{N_1}{N_2} = e^{(E2 - E1)/K_BT}$$

since $E_2 - E_1 = h\nu$, we have

$$\frac{N_1}{N_2} = e^{h\nu/K_BT} \text{ -- } (3)$$

Sub (3) in (2) we have,

$$\rho_\nu = \frac{A_{21}}{B_{12}(e^{h\nu/K_BT}) - B_{21}}$$

$$\rho_\nu = \frac{A_{21}}{B_{21}} \frac{1}{(B_{12}/B_{21}\, e^{h\nu/K_BT}) - 1} \text{ ------------------------------ } (4)$$

This equation has a very good agreement with Planck's energy distribution radiation law,

$$\rho_\nu = \frac{8\pi h\nu^3}{c^3} \frac{1}{e^{h\nu/K_BT} - 1} \text{ --------------------------------- } (5)$$

Therefore comparing equations (4) and (5),

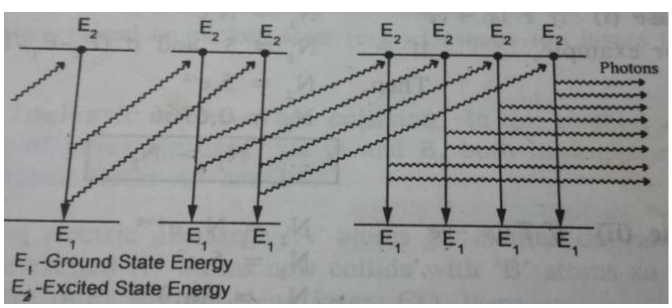
$$B_{12} = B_{21} = B \quad \text{and} \quad \frac{A_{21}}{B_{21}} = \frac{8\pi h\nu^3}{c^3}$$

Taking $A_{21} = A$, *The constants A and B are called as Einstein coefficients.*

S. No	Stimulated emission	Spontaneous emission
1.	An atom in the excited state is induced to return to ground state, thereby resulting in two photons of same frequency and energy is called stimulated emission.	The atom in the excited state returns to ground state thereby emitting a photon, without any external inducement is called spontaneous emission.
2.	The emitted photons move in same direction and are highly directional.	The emitted photons move in all directions and are random.
3.	The radiation is high intense, monochromatic and coherent.	The radiation is less intense and is incoherent.
4.	The photons are in phase.	The photons are not in phase.
5.	The rate of transition is given by R_{21} (St) = $B_{21} \rho_\nu N_2$	The rate of transition is given by R_{21} (Sp) = $A_{21}N_2$

Light amplification

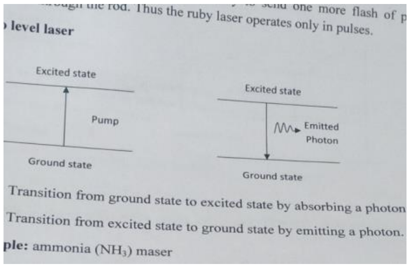
Let us consider many numbers of atoms in the excited state. We know the photons emitted during stimulated emission have same frequency, energy and are in phase as the incident photon. Thus results in 2 photons of similar properties. These two photons induce stimulated emission of 2 atoms in excited state thereby resulting in 4 photons. These 4 photons induce 4 more atoms and give rise to 8 photons etc., as shown in Fig.

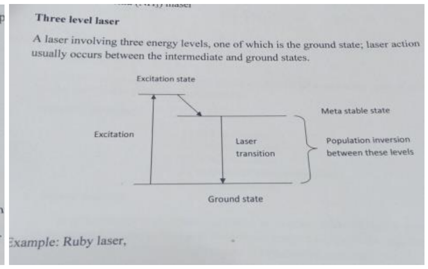


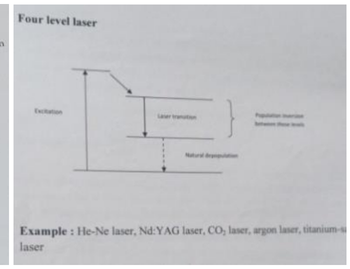
Principle: Due to stimulated emission the photons multiply in each step giving rise to an intense beam of photons that are coherent and moving in the same direction. Hence the Light is Amplified by Stimulated Emission of Radiation, termed as LASER.

Energy levels:

A population inversion can be produced in a laser through two basic mechanisms, either by creating an excess of atoms or molecules in a higher energy state, or by reducing the population of a lower energy state. This topic explores meta-stable states for both three-level and four-level laser systems.







Population inversion:

When a system is in thermal equilibrium, the distribution of energy states at a given temperature follows the Boltzmann's law as

$$N = N_0 e^{\left(\frac{-E}{KT}\right)}$$

where,

N_0 is the population in the ground state

N is the population in the given energy state

K is the Boltzmann's constant

T is the absolute temperature

From the above equation, it is clear that the population is maximum in ground state and decreases exponentially as one goes to higher energy state as shown in fig. 4(a). ie., $N_1 > N_2$.

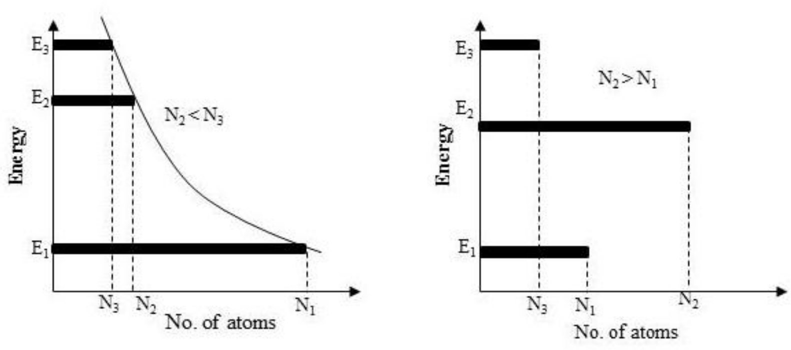


Fig. 4 (a) population at different energy states of atoms (b) population inversion through pumping process

If the situation is just reverse, ie there are more atoms in an excited state than the ground state as shown in fig 4 (b), a net emission of photons can result. **This condition is called population inversion. In this case $N_2 > N_1$.**

Meta stable state

It is an excited state of an atom with a longer life time than the other excited states. However it has a shorter life time than the stable ground state. Atoms in the metastable state remain excited for a considerable time in the order of 10^{-6} to 10^{-3} s.

Active Medium

The active laser medium consists of a collection of atoms, molecules or ions. The excited state of the active laser medium has a meta stable state having longer lifetime ($\approx 10^{-8}$ sec) compared to excited states which usually have short life times.

Conditions required for Laser action:

(a) Population inversion should be achieved.

(b) Stimulated emission should be predominant over spontaneous emission.

Pumping methods

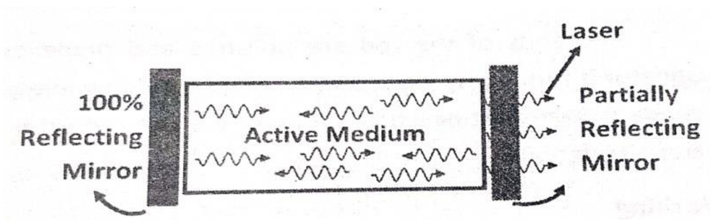
The process of achieving population inversion is called pumping. Pumping can be classified into the following types based on the type of source of pumping.

1. **Optical pumping**: Here the atoms are excited with the help of photons emitted by an optical source. The atoms absorb energy from the photons and raises to excited state. (e.g.) Ruby Laser, Nd-YAG Laser
2. **Electrical pumping**: The electrons are accelerated to very high velocities by strong electric field and they collide with gas atoms and these atoms are raised to excited state. (e.g.) Argon Laser, CO_2 Laser
3. **Direct Conversion**: Due to electrical energy applied in direct band gap semiconductor like GaAs etc., the combination of electrons and holes takes place and electrical energy is converted into light energy directly. (e.g) Semiconductor Laser.
4. **Inelastic collision between atoms**: During electric discharge "A" atoms get excited due to collision with electrons. The excited A* atoms now collide with "B" atoms so that B goes to excited state B* (e.g.) He – Ne Laser.

5. **Chemical pumping**: Due to some chemical reactions, the atoms may be raised to excited state. (e.g.) Dye Laser.

Optical resonator

The optical resonator contains a pair of reflecting surfaces of which one is fully reflecting and the other partially reflecting. The active material is kept in between the two reflecting surfaces. Photons(light) emitted due to transitions between the energy states of the active material are bounced back and forth between the two reflecting surfaces, so the intensity of the light is increased enormously. Finally the intense amplified beam called laser is coming out through the partial mirror as shown in the diagram.



Types of LASERS

1. Solid state laser : It is classified into two types (a) 3 level laser (e.g) Ruby laer, (b) 4 level laser (e.g) Nd-YAG laser
2. Gas laser: Egs. : CO2 laser, He-Ne laser
3. Semiconductor laser : Egs. GasAs
4. Liquid laser : Eg; Europium benzoyl acetone dissolved in alcohol.
5. Dye laser and chemical lasers.

Nd:YAG LASER (The Neodymium: yttrium- aluminium- garnet (Nd:YAG) laser)

Nd:YAG laser is a solid state laser in which lasing medium is obtained by embedding Nd^{3+} ions in YAG ($Y_3Al_5O_{12}$) crystal. The crystalline host, in general, is doped with around 1 % of neodymium by atomic percent. Krypton flash lamp is used for optical pumping. Instrumentation arrangement is shown in fig (1). Laser operation of Nd:YAG was first demonstrated by Geusic et.al. at Bell laboratories.

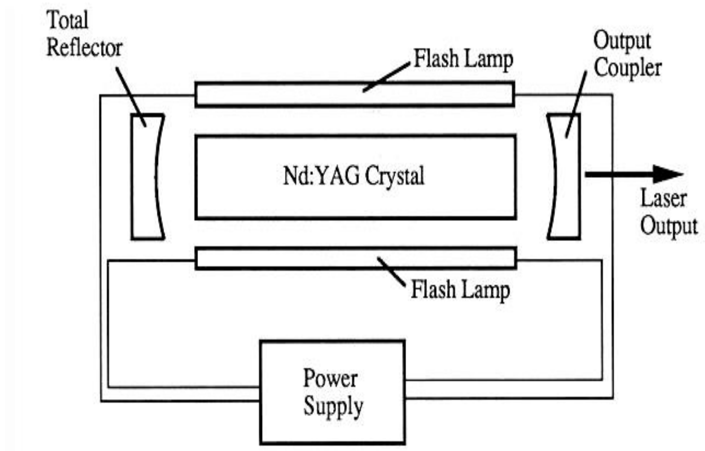


Fig. (1) schematic diagram of Nd:YAG laser

The energy level structure and laser transition in Nd:YAG laser are shown in fig (2). Nd:YAG laser is optically pumped using a flash lamp or laser diodes. Flash lamp pumping is possible due to the broadband pump absorption mainly in the 0.8 μm region and the four level characteristics. The krypton flash lamp emits most of its output light in the infrared region and of the absorption bands of Nd:YAG and, therefore, it is the best spectral match.

Nd^{3+} ions in the ground state absorb photons and are raised in energy to one of the pump bands. The state of lifetimes of the order of 10^{-8}sec, and the atoms quickly drop to the upper lasing level by radiation less transition. The upper lasing level, has a fluorescent lifetime of about 0.3ms. The population inversion develops and lasing occurs, with the atoms dropping to the lower lasing level. This level is very close to the ground state, and excited atoms rapidly return to the ground state by another radiationless transition. So, laser action is usually obtained between the levels E_3 and E_2 at a wavelength of about 1.06 μm in the infrared region.

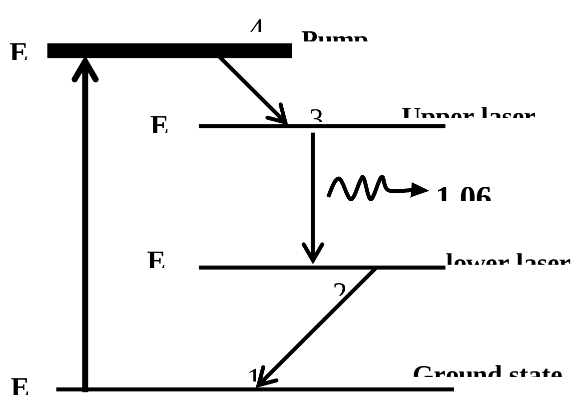


Fig.(2) energy level diagram of Nd:YAG laser

Advantages:

- Output energy is very high
- Repetition rate is very high
- Population inversion is easily achieved
- Excitation can be easily achieved by lower threshold energy.

Disadvantage:

- The electron energy level structure of Nd^{3+} in YAG is complicated

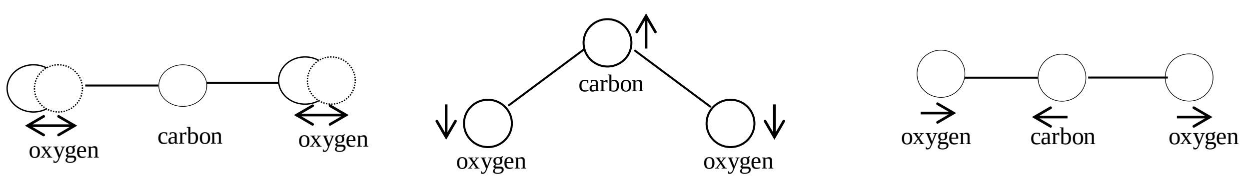
Applications:

Nd:YAG laser have wide range of applications.

- In industry they are used for material processing: drilling, spot welding and laser marking
- Medical applications include many types of surgery, such as memberane cutting, gall – bladder surgery
- It is used to study laser induced fusion reactions

Carbon dioxide laser

CO_2 laser is one of the molecular lasers. A molecule is made up of two or more atoms bound together. Thus, in addition to the electronic motions, atoms in the molecule may vibrate in different modes and rotate about various axes. Three modes of vibration of CO_2 molecule *viz.* i) symmetric stretch mode ii) asymmetric stretch mode and iii) bending mode are shown in fig (1).



Symmetric stretch mode Bending mode Asymmetric stretch mode

Fig (1) fundamental modes of vibration of CO_2

Symmetric stretch mode: ($10^0 0$)

In this mode, the oxygen atoms oscillate along the axis of the molecule simultaneously departing or approaching the carbon atom which is stationary.

Asymmetric stretch mode: ($00^0 1$), ($00^0 2$)

In this mode, all the three atoms oscillate, but while both oxygen atoms move in one direction, carbon atom moves in the opposite direction.

Bending mode: ($01^0 0$), ($02^0 0$)

In this mode, all the three atoms are vibrating perpendicular to the molecular axis.

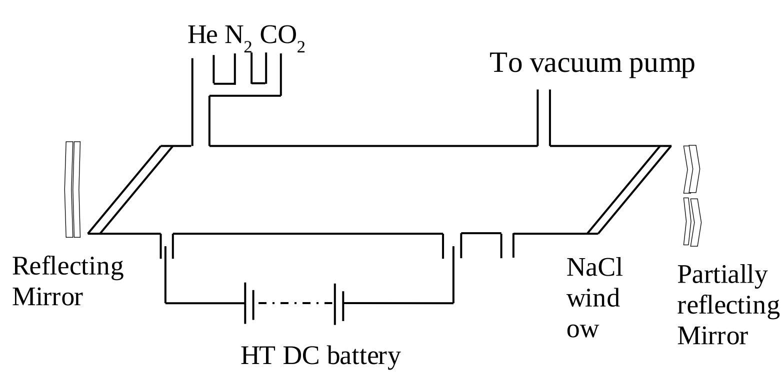
Principle:

It is a four level molecular gas laser**.** The mixture of CO_2, He, N_2 gases used as active medium. Laser transition takes place between the vibrational states of CO_2 molecule. Inelastic atom-atom collision method is used to achieve the population in active medium. A laser beam of wavelength 10.6 μm and 9.6 μm are emitted.

Construction

Fig shows the schematic diagram of CO_2 laser. It consists of a quartz discharge tube 5m long and 6.5 cm in diameter. This discharge tube is filled with the gaseous mixture of CO_2 (active medium), helium and nitrogen with suitable partial pressures. The terminals of the discharge tube are connected to a DC power supply.

The ends of this tube are fitted with NaCl Brewster windows so that the laser light generated will be polarized. The optical resonator is formed with two concave mirrors one fully reflecting and other partially reflecting.



Working

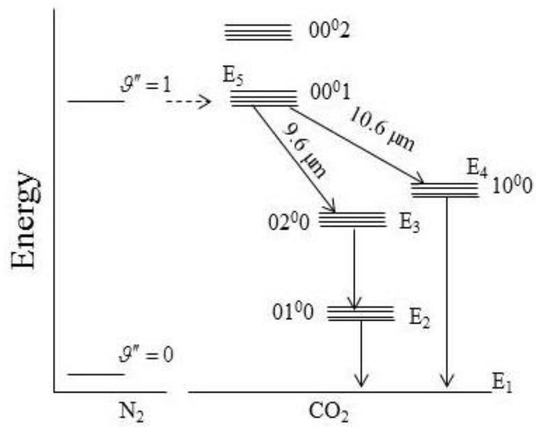


Fig. (3) energy transition level diagram of CO_2 ions in CO_2 laser

Fig (3) shows the vibrational energy level diagram for the electronic ground state of CO_2 and N_2 molecules. When the electrical discharge occurs in the gas, the electrons collide with nitrogen molecules and they are raised to excited states. This process is represented by the equation.

$$N_2 + e^* \longrightarrow N_2^* + e$$

state

E*-- Electron with kinetic energy

N_2^* -- Nitrogen molecule in excited state

E -- Same electron with lesser energy

Now, N_2 molecules in excited state collide with CO_2 atoms in ground state and excite them to higher electronic, vibrational and rotational levels. This process is represented by the equation

$$N_2^* + CO_2 \longrightarrow CO_2^* + N_2$$

N_2^* -- Nitrogen molecule in excited state

CO_2-- Carbon dioxide atoms in ground state

CO_2^* -- Carbon dioxide atoms in excited state

N_2 – Nitrogen molecule in ground state

Since the excited level of nitrogen is very close to E_5 level of CO_2 atoms, the resonant transfer of energy takes place from N_2 molecule to CO_2 molecule. The population in E_5 level increases by radiation less transition from upper excited levels. As soon as population inversion is reached, any of the spontaneously emitted photon will trigger laser action in the tube. The transition from the level E_5 to E_4 and E_5 to E_3 takes place which leads to the laser oscillations near 10.6 μm and 9.6 μm.

Advantages

- The construction is simple.
- High efficiency.
- High output power.

Disadvantages

- The corrosion may occur at the reflecting plates.
- Accidental exposure may damage our eyes, since it is invisible to our eyes.
- The contamination of oxygen by carbon monoxide will have some effect on laser action.

Applications

- High power CO_2 laser finds application in materials processing, welding, drilling, cutting, soldering, etc.
- It is used in remote sensing
- It is used in the treatment of liver and lung diseases.
- It is used to perform microsurgery and bloodless operations.

SEMICONDUCTOR LASER

A semiconductor is a typically fabricated p-n junction diode which emits coherent light when it is forward biased. The active medium in a semiconductor laser is formed by heavily doping p and n type material hence the semiconductor laser is also called diode laser or injection laser. There are two types of semiconductor lasers,

1.Homojunction Laser : P and N regions are made upof the same semiconductor.

Example: Gallium Arsenide(Ga As)

2.Heterojunction Laser : One side of the junction differs from the other side of the junction.

Example: Ga Al As is grown on Ga As

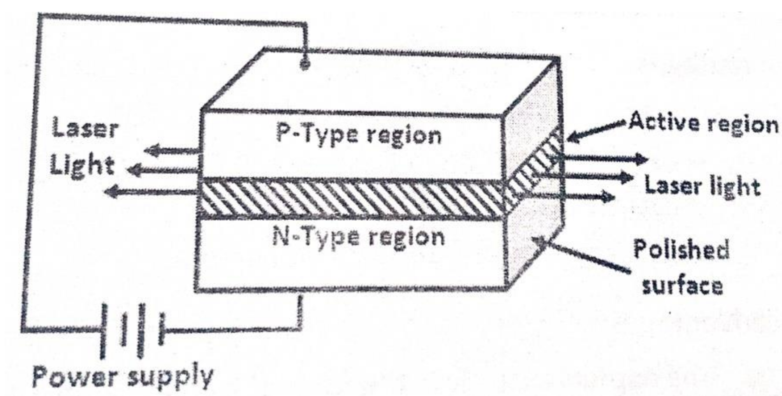
Homo junction Semiconductor Laser

A semiconductor diode is a specifically fabricated pn-junction device that emits laser light when it is a forward biased.In a certain semiconductor like Ga As,when the junction is forward biased electron from n-region and holes from p- region recombines with each other at the junction.

During recombination process, light energy is released form this radiation of energy is called recombination radiation and the corresponding energy is called activation energy. The wavelength of the light emitted depends on the activation energy. The photon emitted during recombination stimulates other charges and as a result, stimulated emission takes place.

Construction

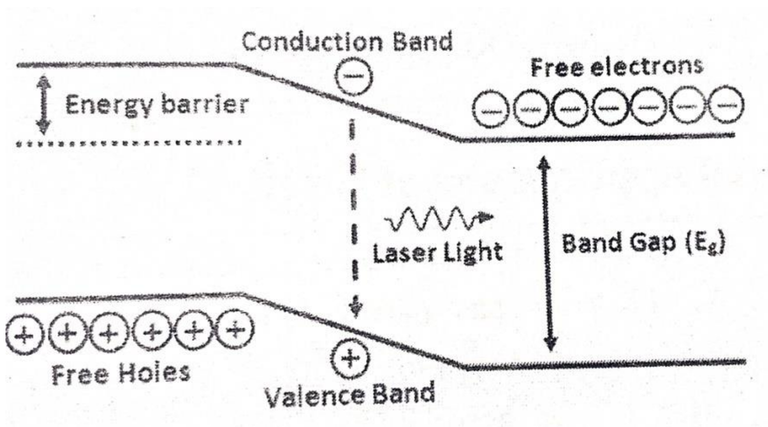
The basic construction of the semiconductor laser is shown in figure. The active medium is a pn-junction diode made from a single crystal of gallium arsenide (Ga As). It is cut in the form of a plate having narrow thickness (0.5mm) so that the emitted laser radiation has larger divergence. The end faces of the junction diode are well polished and parallel to each other. Since the refractive index of Ga As is high it acts as optical resonator through which the emitted light will come out. The upper and lower electrodes fixed in the "p" and 'n' region helps to supply current to the diode.



Working

The energy level diagram of the semiconductor laser is shown in the diagram. The p-n junction is forward biased with large applied voltage. The electrons and holes are injected into junction region. The region around the junction contains large amount of electrons within the conduction band and large amount of holes in the valence band. If the population density is high, the population inversion is achieved. The electron and holes recombine each other and produce radiation in the form of light.

When forward biased voltage is increased, more and more light protons are emitted and light instantly becomes stronger. These photons can trigger a chain of stimulated recombination resulting in the release of photons in phase. The photon moving at the plane of junction travels back and forth by reflection between the two polished sides. After gaining enough strength, it comes out as th user beam. The output wavelength is given by



$$\chi = \frac{hc}{E_g}$$

Where, for Ga As, Eg=1.44 ev and the output wavelength emitted by a diode made up of

$$\chi = \frac{6.626\times 10{-}34\times 3\times 10^{8}}{1.44\times 1.6\times 10^{19}} = 8626Å$$

The wavelength is near IR region.

Advantages

1. It is very small in size.
2. It exhibits high efficiency.
3. It consumes low power.
4. It requires very little auxiliary equipment.

Disadvantages

1. The output is usually in the form of a wide beam
2. It is mostly monochromatically is poorer than the other types of laser.

Applications

1. It is mostly used in fibre optic communications.
2. It is used to heal the wounds by means of infrared radiation.
3. It is used in computer printers and CD drives.

LASER Cutting

Laser is used as a tool to cut thin metal sheets by properly focusing the laser onto any particular area to be cut, for a longer time. Thus due to thermal effect the sheet is cut.

LASER Welding

In ordinary welding process the heat will be made to fall on the area to be welded, so that the material in that area will go to molten state. This on cooling will join the material. In this process the heat will spread all over the surroundings and will affect the other area of the material and hence the material gets damaged. This damage can be avoided by using laser welding. In laser welding the beam is focused onto the area to be welded and other areas remain unaffected. Without affecting the material the area to be welded alone melted and joined.

LASERS in Industry

Using high power lasers we can weld or melt any material. We can produce very small holes that cannot be done by mechanical drilling. Lasers can be used for cutting and for testing the quality of the materials. During laser welding and drilling there is no damage the structure of the materials. Lasers can be used for surface hardening techniques.

MEDICAL APPLICATIONS OF LASERS

Laser cosmetics surgery is used for removing tattoos, scars, stretch marks, sunspots, wrinkles and hairs.

1. Laser types used in dermatology:

It include Ruby (694nm), pulsed diode arrays (810nm), Nd: YAG (1064nm) and Er : YAG (2940nm)

2. Laser eye surgery:

   Laser eye surgery is a medical procedure that uses a laser to reshape a surface of the eyes. This is done to correct short sightedness, long sightedness and astigmatism (uneven curvature of the eye surface).

3. Soft- Tissue surgery:
   a. In soft tissue laser surgery, a highly focused laser beam vapourises the soft tissue with the high water content
   b. Soft tissue laser surgery is used in a variety of applications which include general surgery, neuro surgery, ENT, dentistry and oral surgery.
   c. Soft tissue laser surgery is also used in veterinary surgical fields.

4. Laser light therapy

   Laser light therapy involves exposure to laser light of specific variant. The light is administered for a prescribed amount of light. This is commonly used for skin diseases and disorders.

5. Laser is widely used for no-touch removal of tumors, especially of the brain and spinal cord
6. In dentistry, laser is used for tooth whitening and carries removal.

LASER SURGERY

A type of surgery that uses the cutting power of a laser beam to make bloodless cuts in tissue or remove a surface lens such as a skin tumor. There are a number of different types of lasers that differ in emitted light wavelengths and power ranges and in their ability to clot, cut or vapourise tissue. Among the commonly used lasers are pulsed dye laser, the YAG laser, the CO_2 laser and the argon laser.

Model Questions

1. What are coherent sources?
2. Distinguish between spontaneous and stimulated emission?
3. List out the characteristics of LASER.
4. What is meant by Spontaneous emission?
5. What is meant by stimulated emission?

6. What is meant by population inversion?
7. What is meant by pumping?
8. What are different methods of pumping?
9. What are the conditions required for laser action?
10. What are Einstein's coeffecients?
11. Define active medium.
12. Explain inelastic atom-atom collision.
13. What is meant by Optical resonator or Resonance cavity?
14. Give some applications of laser in medical field.
15. Give the applications of laser in industry.
16. Describe the construction and working of Nd: YAG.
17. What are the medical applications of lasers?
18. Explain the modes of vibrations of CO_2 molecule. Describe the construction and working of CO_2 laser with necessary diagrams.
19. Derive Einstein's relation for stimulated emission and hence explain the existence of stimulated emission.
20. Discuss with theory the construction and working of homojunction semiconductor laser.
21. Discuss the applications of laser in various fields.

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