PHYSICS 101

PAPER 181101

MODULE 2 – OPTICS

Aberration in lenses, Spherical and Chromatic Aberration, methods of minimization.

Interference of light by division of wavefront (brief discussion) and division of amplitude. Interference due to reflected light in plane parallel film. Interference in variable thickness (wedge shaped) film. Newton’s ring.

Books:

1. Principles of Optics. By B. K. Mathur.
2. A text book on Light for Degree Students. By K. G. Mazumdar.
3. Applied Physics for Engineers. by Neeraj Mehta.
4. Optics. by Ajoy Ghotok.
5. Engineering Physics. by Gaur &Gupta.

Introduction: The branch of physics which deals with the phenomena associated with light is known as **OPTICS.**

Optics is one of the branches of physics in which the nature and properties of light are studied. It is divided into 3 different branches.

1.Geometrical Optics.

2. Physiological Optics.

3.Physical Optics.

Defect of Image and their remedy.

The simple formulae for mirrors and lenses are true only when the rays are incident very close to the axis, however the rays are incident at a large angle of incidence at a point far away from the axis and hence the simple formulae are inapplicable there.

Thus, the image formed by reflection or refraction is defective. This defect of the image arising out of the wide angles of incidence of rays of a particular wavelength is called **Monochromatic Aberration.**

There are 5 such monochromatic aberrations which are known as

Seidal Aberrations.

They are

1) Spherical aberration
2) Coma
3) Astigmatism
4) Curvature
5) Distortion.

Again, when the image is formed by refraction of white light, they become colored due to dispersion of white light and this defect of image is called **Chromatic Aberration.**

Monochromatic Spherical Aberration:

A wide beam of parallel light is made incident on the refracting surface.

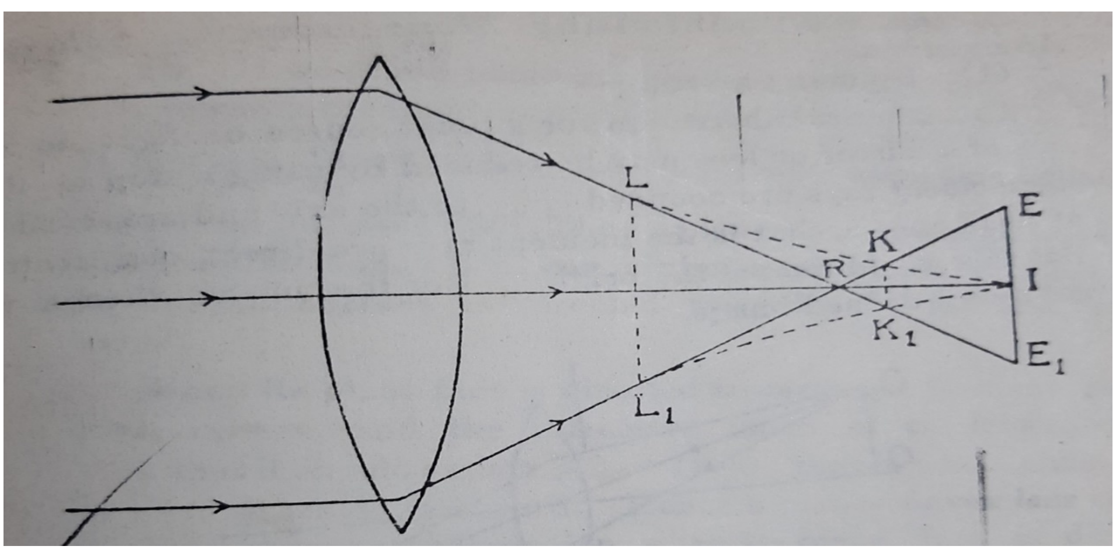
The rays which are incident very close to the axis (paraxial rays) after reflection (in case of mirror) or refraction pass through(I).

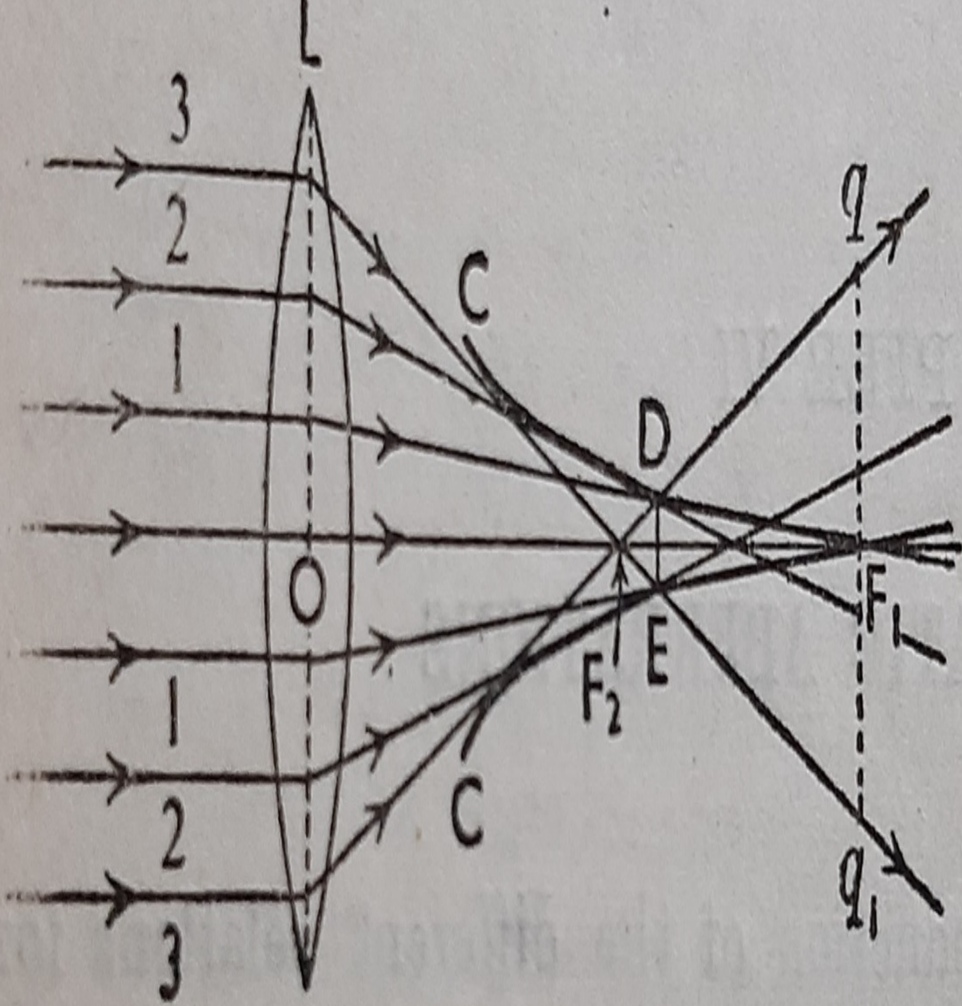
The rays which are incident on the peripheral region, after reflection or refraction passes through(R).

Thus, there is no sharp point image for an object at infinity. This defect of the image, in which the central and peripheral incident rays form images at different points on the axis is called **spherical aberration.**

If a screen is placed perpendicular to the axis at LL_1, a bright circular edge and a faint center is appear. And on putting a screen at EE_1, a bright center with faint edge will appear. But when the screen is at $KK_{1,}$ a circular patch of almost uniform illumination appears. This circle is called circle of least confusion. The distance RI is a measure of **Longitudinal Spherical Aberration** while IE measures **Lateral Spherical Aberration.**

Fig 1

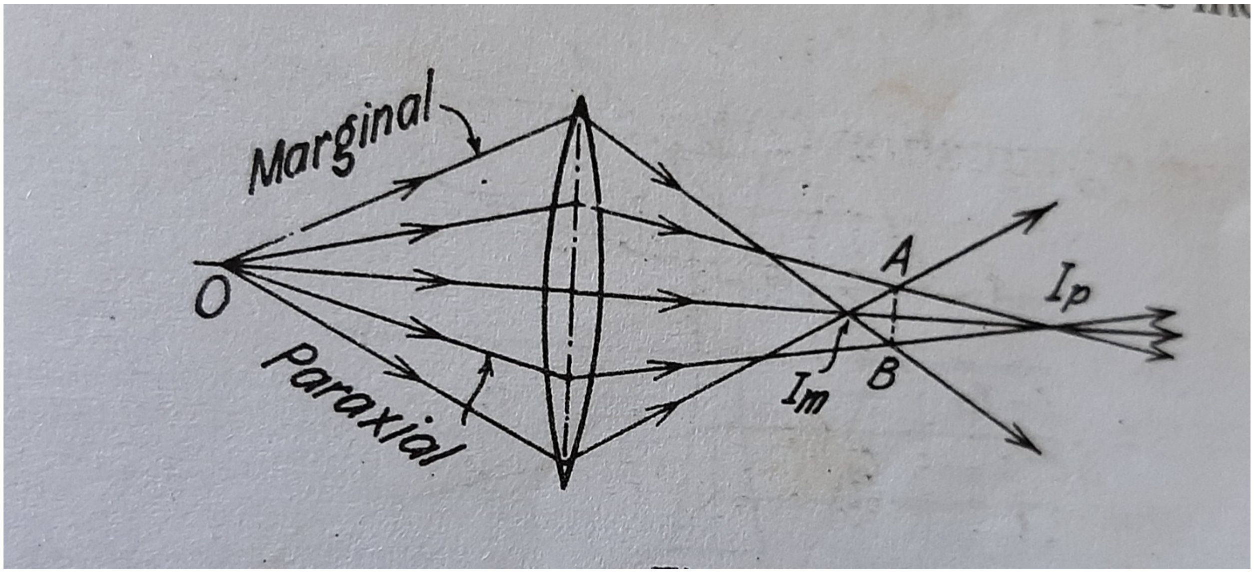



L
3
2
1
O
1
2
3
C
C
D
E
F_2
F_1
q_1
q_1

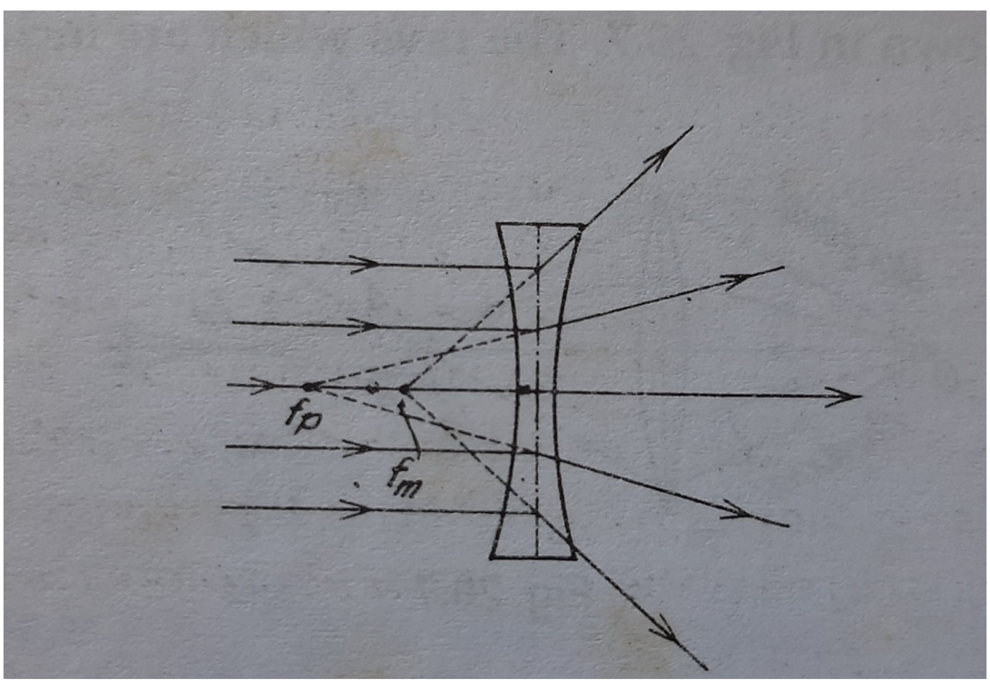
SPHERICAL ABERRATION:

A point source **O** of monochromatic light placed on the axis of a large aperture convex lens fig(i). The rays which are incident near the axis called paraxial rays come to focus at while the ray incident near the rim of the lens called the marginal or peripheral rays come to focus at**.**

The intermediate rays are brought to focus between and . It is clear from the figure that the paraxial rays form the image at a point distance than the marginal rays. Thus, the image is not sharp at any point on the axis. Thus, the failure or inability of the lens to form a point image of an axial point object is called **Spherical Aberrations.**



Fig(i)



Fig(ii)

The reason of spherical aberration is as follows:

Let the lens be divided into circular zones. It can be proved mathematically that the focal lengths slightly vary with the radius of the zones. i.e. different zones have different focal lengths. The focal length of marginal zone is lesser than the paraxial zone. Hence the marginal rays are focused first.

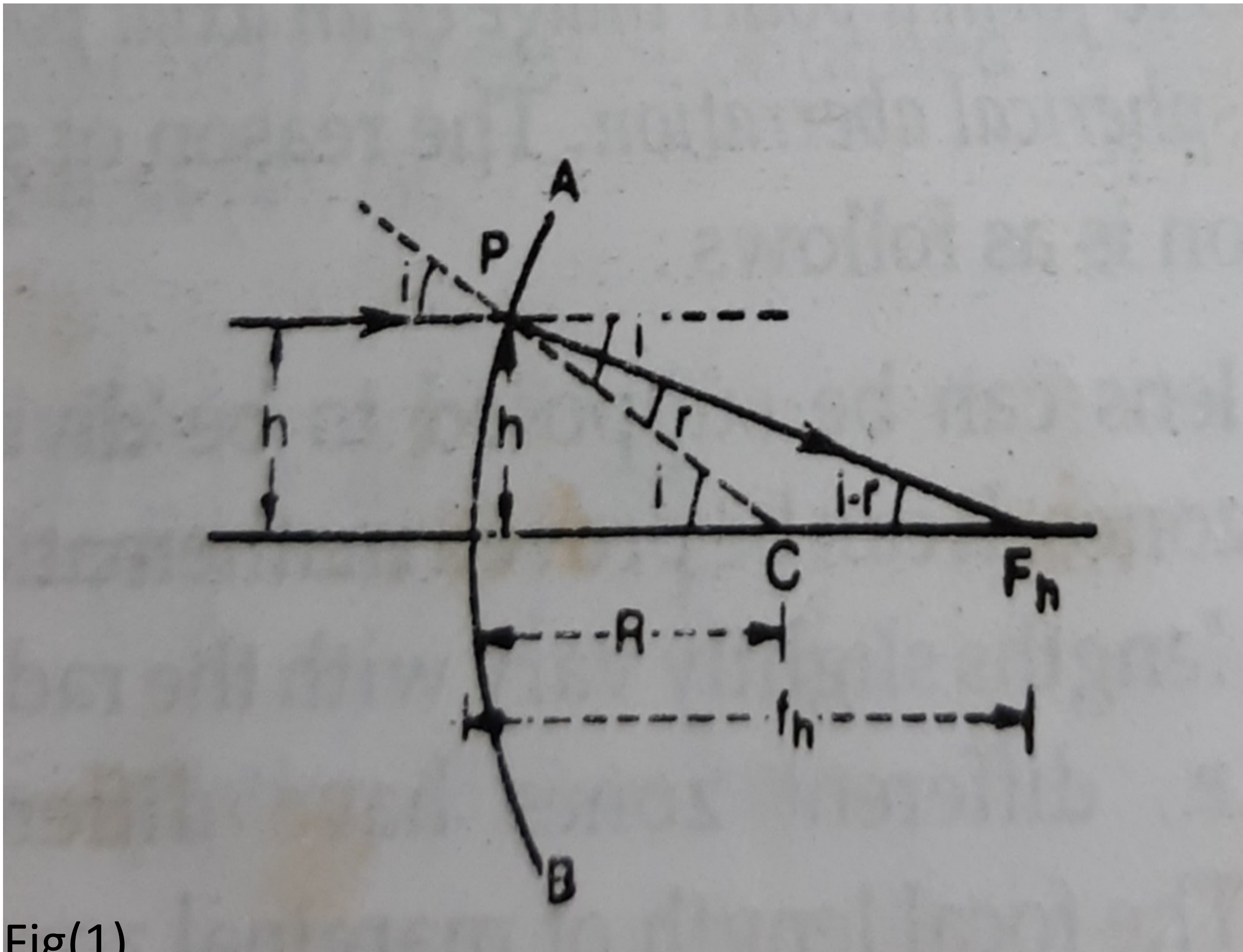
The spherical aberration can also be explained by saying that the marginal rays suffer greater deviation than the paraxial rays because they are incident at a greater height than the later.

The distance between and is the measure of **longitudinal or axial spherical aberration.**

If a screen is placed normal to the principal axis at , then the image on the screen consists of circular disc. The disc would be sharply focused at the center but diffused near the outer edge. A disc image would again be obtained if the screen is placed at . If the screen is moved between and then the size of the disc is minimum in position AB where the paraxial and marginal rays cross.

Due to the smallest cross section, this is known as **circle of least confusion**. This is the nearest approach to a point image. i.e. if the screen is placed in the position AB, then it is the best possible image of uniform sharpness. The radius of the circle of least confusion is called the **lateral spherical aberration.**

Spherical aberration due to spherical surface:



Fig(1)

AB is a spherical surface of radius of curvature R. Let an incident ray parallel to the principal axis meet the spherical surface at a height *h* from the axis.

The refracted ray intersects the axis at a point Therefore O = for rays in zone *h*.

From fig 1

= R +

From CP

==

C=

= ,

=

=

Since,

=R +

= R [1 +]

For paraxial rays, when *h* tends to 0

and tends to 1.

Therefore,

=

focal length of paraxial rays.

Now, the change of focal length for h zone as compared to axial zone is given by,

-= -R [1+]

= R [-]

This represents the **Longitudinal Spherical Aberration.**

The approximate value of spherical aberration can be calculated as follows:

Since sin i = from fig1

Or   sin r =   ,   since = μ

Now, i) = (1 -)

(1 -)

And

Cos r =(1- r) =(1 -)

(1 -)

Therefore,

= R[-

Solving,

=

Where

=

This gives the approximate value of the spherical aberration due to a spherical surface.

Deviation produced by a thin lens:

The angle between the incident light ray and the corresponding refracted ray from a thin lens is known as angle of **deviation**.

From fig L is the converging lens, O is a point object, LO=u. A ray OX meets the lens at a height h above the principal axis. A deviation is produced and meets the principal axis at a point I at a distance LI=v, it is the real image point object O.

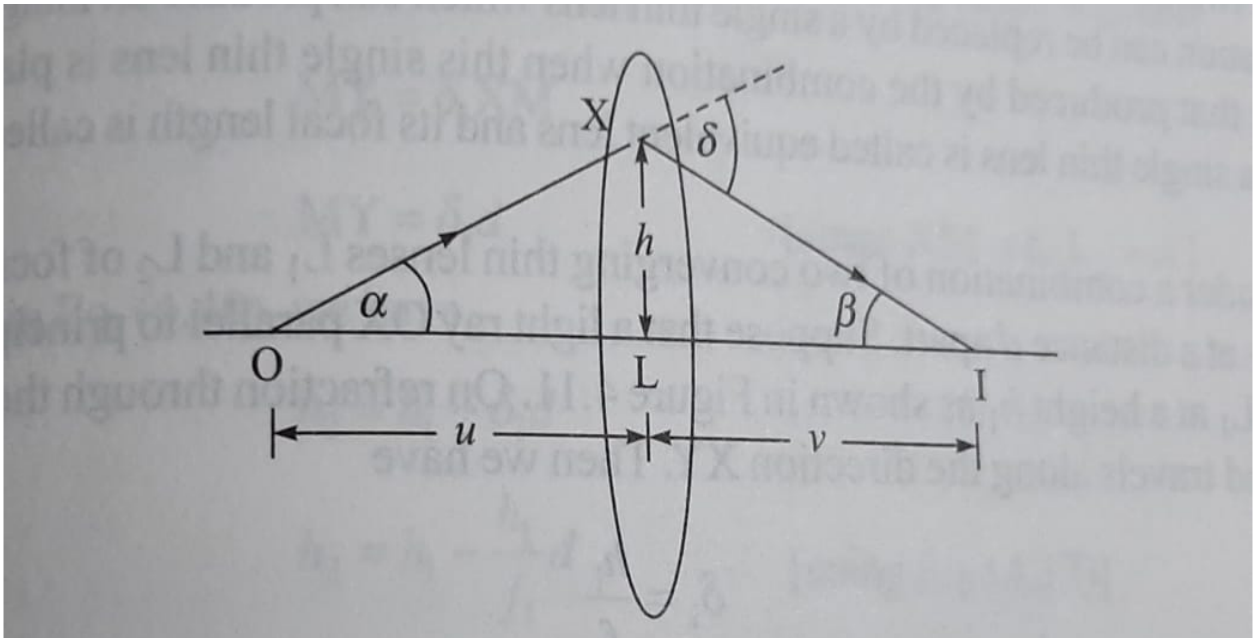


Figure 4.10 Deviation produced by a thin lens.

Let angle XOL= α & angle XIL=β

Therefore,

$= \alpha + \beta$

For paraxial rays the angles α & β are very small.

In right angle triangle

ΔXLO & ΔXLI

$\alpha = \tan \alpha =$

$\beta = \tan \beta =$

therefore

$=$

Or,

Lens formula for thin lens is

Comparing, we get, $=$

this is the expression for deviation produced by a thin lens._

Minimization of Spherical Aberration:

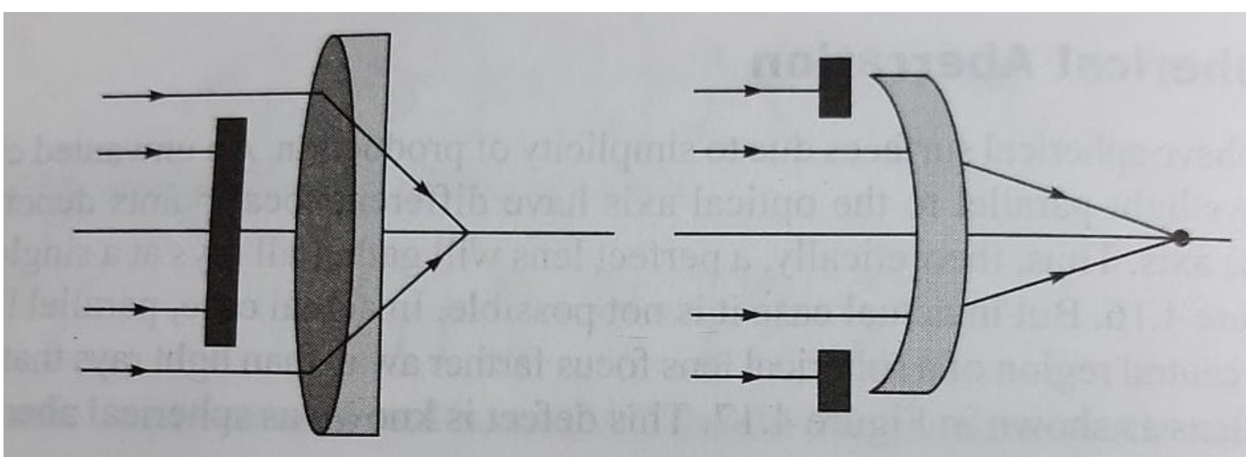
The different methods are

1) By means of stop
2) By the use of planoconvex lens or by dividing the deviation equally.
3) By using two suitable lenses in contact
4) By using crossed lens
5) By using two planoconvex lenses separated by a distance.

1) **By means of stop:**

In this method either the marginal or paraxial rays are cut off by using stop method. Then the rest rays converge practically to a common focal point as shown in fig (1).

In telescope objectives this method is used to cut off paraxial light rays while in case of camera lenses this method is used to cut off marginal light rays.



(a) Elimination of paraxial rays (b) Elimination of marginal rays

(2)By using planoconvex lens or by dividing the deviation equally:

The spherical aberration may be minimized by using planoconvex lens. It as been observed that the spherical aberration is proportional to the square of the total deviation produced by the lens.

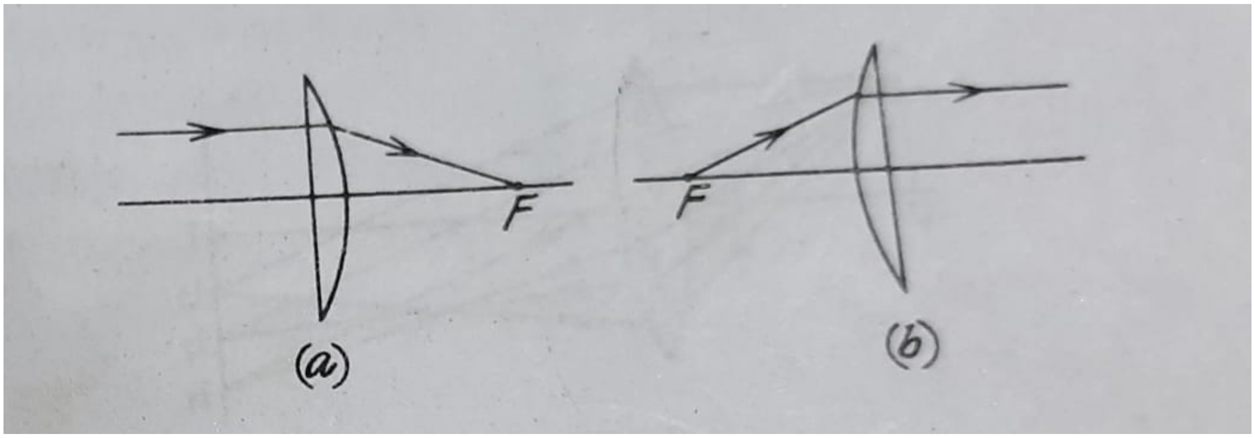
If be the total deviation produced by the lens and and be the deviation produced at the two surfaces of the lens, then spherical aberration

+ 4

It is obviously minimum when

i.e. the deviation is equally divided at the two surfaces.

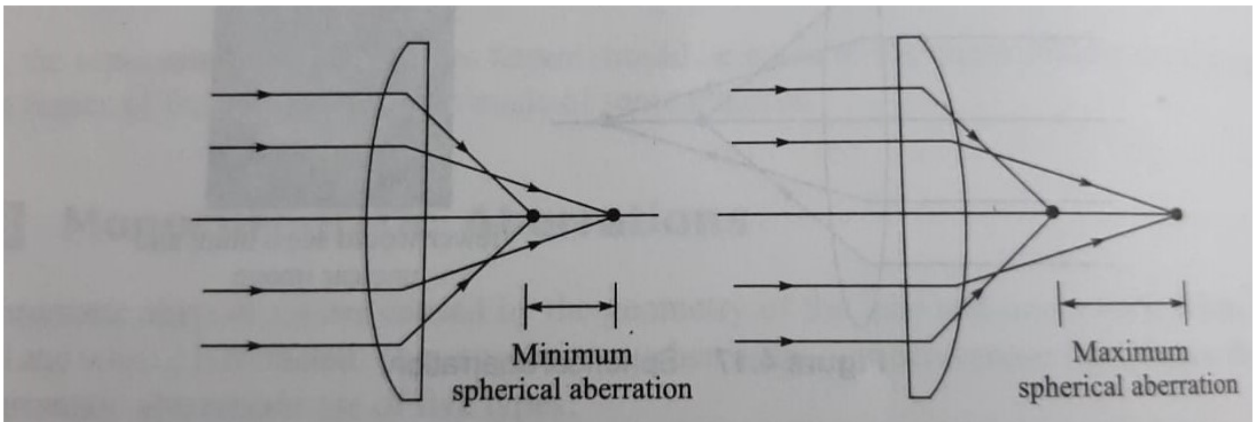
It is important to note that if a ray parallel to the principal axis is incident on the plan surface of a Plano Convex Lens fig(a) then there will be no deviation at plane surface and the whole deviation will be on the 2nd surface i.e. the convex surface. so, there are no question of equal deviation at the two surfaces.



Similarly, when the object is at focus towards the curve surface fig(b). Therefore, to minimize the spherical aberration how a plano-convex lens is placed is important.

If the plane side is placed towards the object, the deviation would be only at the 2^{nd} surface. i.e. the convex lens.so the longitudinal spherical aberration will be as fig (II). Spherical aberration is maximum in the 2^{nd} case.

Fig(I) & Fig (II)



(a) Convex surface facing the distant object (b) Plane surface facing the distant object

The general rule is to minimize the spherical aberration in a plano-convex lens is that the convex side should be face the incident or emergent beam whichever is more parallel to the axis.

(3) By using two suitable lenses in contact:

In case of a convex lens, the marginal image lies towards the left of paraxial image while in case of a concave lens, the marginal image lies towards the right of paraxial image

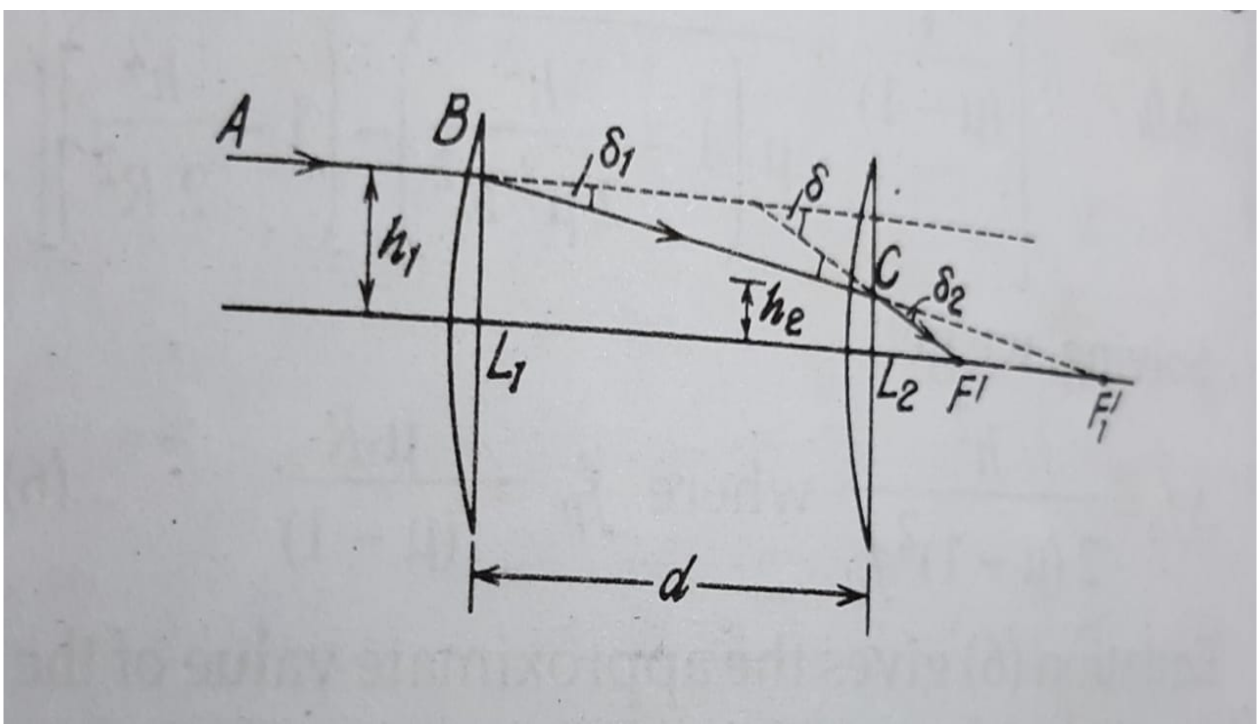
Thus, by a suitable combination of two lenses the spherical aberration may be minimized.

(4) by using crossed lens:

(5)By using two planoconvex lenses separated by a distance:

The spherical aberration can be minimized by using two planoconvex lenses of the same material placed at a distance equal to the difference of their focal lengths.

In this case the deviation produced in a ray is spread over four surfaces and is shared equally by two lenses.



fig(1)

Let, and be two planoconvex lenses of focal lengths and separated by a distance ***d*** as shown in

fig (1).

Let a ray of light AB parallel to the axis meet the first lens at height and suffer a deviation

= .

This is directed towards , and 2nd focal point of , the refracted ray BC strikes the lens , at height and suffers a deviation

=

The emergent ray meets the axis at

The 2nd focal point of the combination.

For minimum spherical aberration

=

Therefore, = =

From similar triangles

and

= = =

Since,

=

Therefore,

=

[=

=[

This is the required condition for minimizing spherical aberration.

Dispersion and dispersive power:

Let PQ be a ray of light (white) incident on the principal section ABC of a prism. The ray after emergence from the prism will be deviated and its constituent colors will be separated or dispersed. The less refrangible red ray proceeds along LR while the most refrangible violet light proceed along MV.

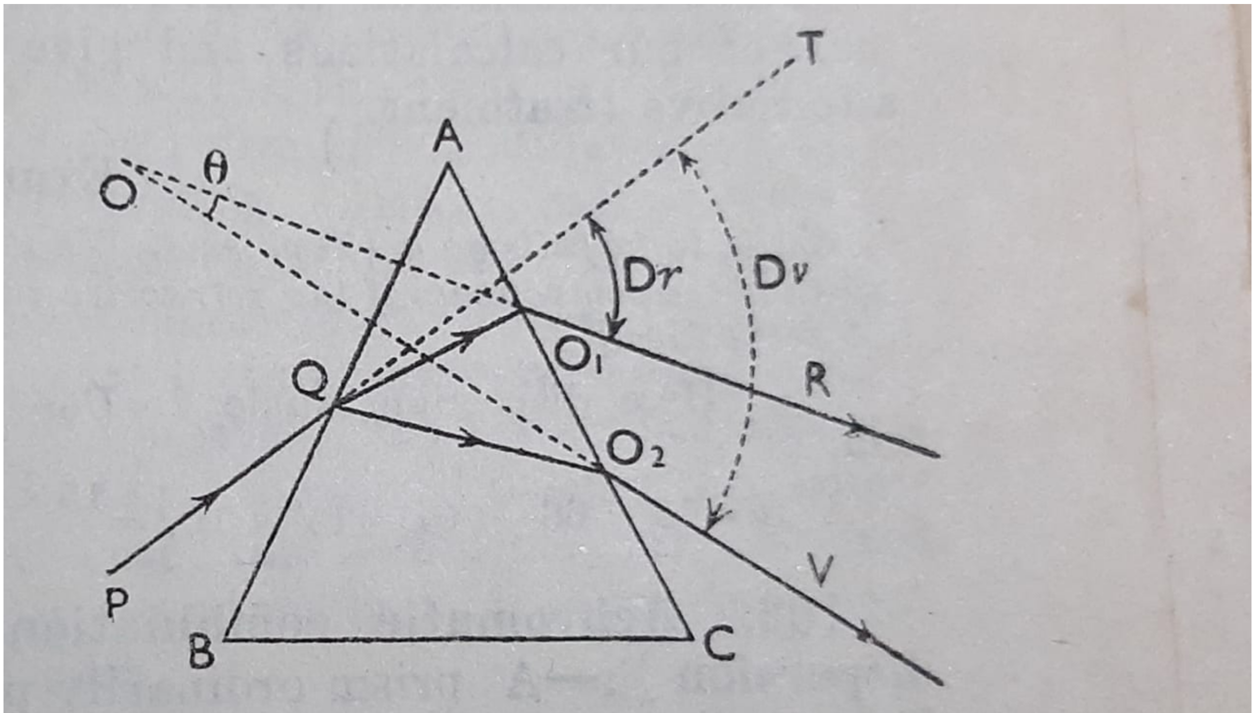


Fig. 163

Let, the red and violet rays be produced backward to meet at O. Then the angular separation between red and violet rays, angle ROV is called **Dispersion** between red and violet rays.

Let be a straight line through O drawn parallel to PQ, the direction of the incident ray. Then angle XOR=is the deviation for red light while the angle XOV=is the deviation for violet rays.

Thus, Dispersion=angle ROV= ()

If the prism be thin, then

= ()A

()A

Therefore Dispersion = ()

=-)A

Again if and

Be the refractive indices of a material for the two given colors say red and violet then there is an intermediate color between the two given colors so the refractive index of the material for that intermediate color will be equal to

This intermediate color is called the mean color between the two given colors.

The dispersive power of the material of the prism is defined as

Dispersive power:

=

=

=

=

=

=

Where,

Change of refractive index of the material when the color changes from violet to red.

It should be remembered that the dispersive power of a material is different from its refractive power. The refracting power is greater when the refractive index is higher.

Thus, for example diamond has low dispersive power though its refracting power is higher due to high refractive index.

Chromatic Aberration in lenses:

A lens may be looked upon as a number of thin prisms.so when abeam of white light is incident on any zone of a lens in a direction parallel to the principal axis of the lens it is not brought to a point focus after refraction because each of the ray s will be dispersed by the lens into its constituent colors.

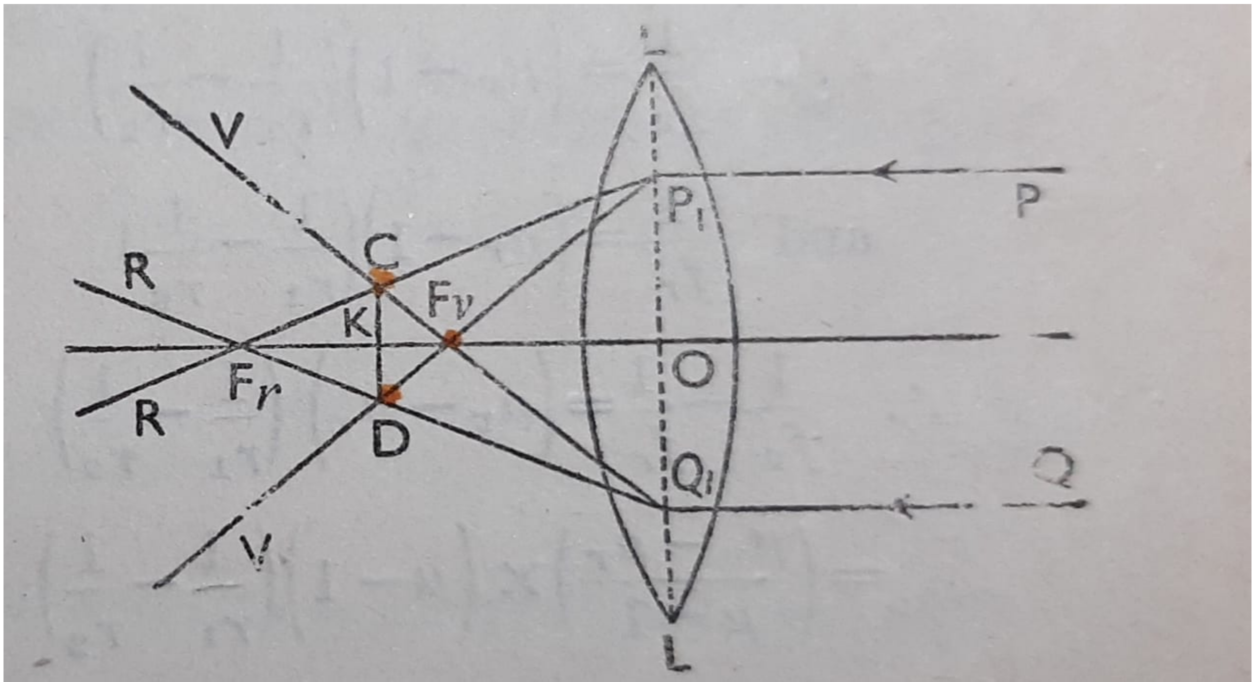


Fig.

The red components being least refrangible will be focused at on the principal axis. This is the principal focus for the red rays and the violet components will be more deviated and the corresponding principal focus for the violet rays will be at a point which is much closes to the lens surface than .

This wandering of the principal focus along the axis of the lens due to the composite nature of the incident beam is known as the **axial or longitudinal chromatic aberration** of the lens.

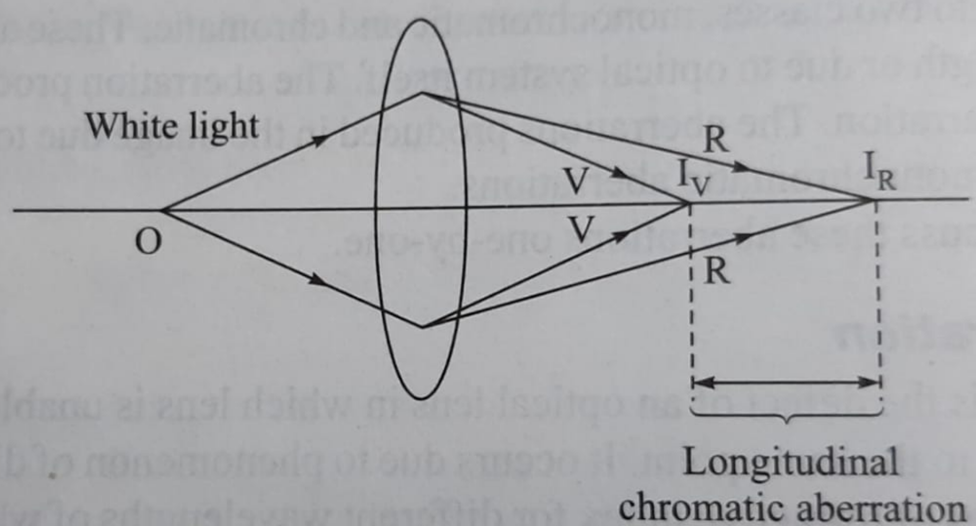


Figure Longitudinal chromatic aberration.

If the screen is placed at the center of the colored patch will be intensely violet with the outer edge colored red. and if the screen is shifted on to the position the center of the colored patch will be intensely red and with its outer edge colored violet. If the screen is placed at CD the patch will be more or less uniformly illuminated and color effect will be minimum there. this patch is known as the **circle of least confusion** or of least chromatic aberration. And diameter of this circular patch at CD is a measure of the **lateral or chromatic**

aberration.

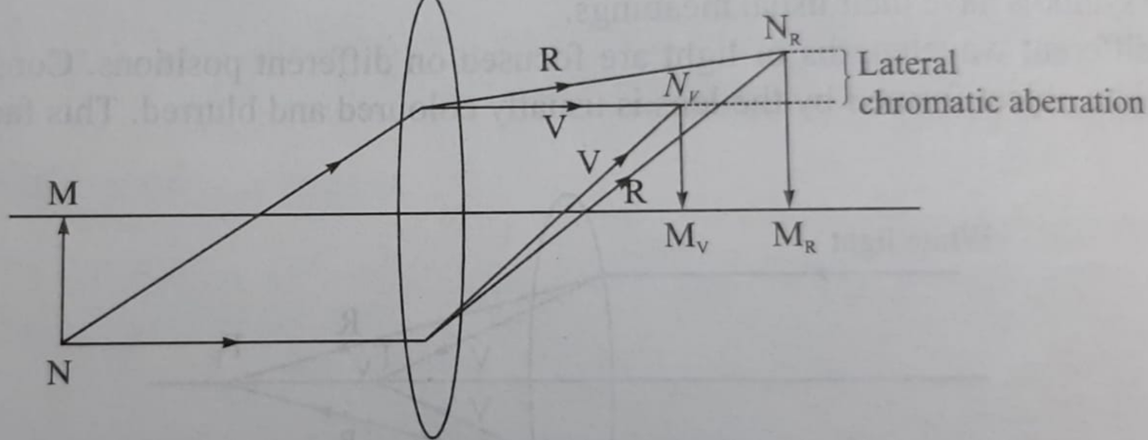


Figure 4.15 Lateral chromatic aberration.

The Lateral chromatic aberration is actually the difference in magnification of the two extreme color images formed due to the chromatic error in a lens.

The longitudinal chromatic aberration is measured by the difference in the focal lengths of the two extreme color components and is initially associated with the position of the images formed by the lens while the lateral chromatic aberration is associated with the question of magnification of the images. It is due to chromatic aberration that a real image produced by an incorrected single lens is found to be fringed with the colors of the spectrum.

Calculation of chromatic aberration:

(a) **<u>Longitudinal chromatic aberration:</u>**
The longitudinal chromatic aberration is measured by the difference in the focal lengths of the two extreme color components of the incident composite beam. i.e; the longitudinal chromatic aberration is -.

Since, = ()[]

f is the mean focal length.

= ()[] and

= ()[]

Therefore,

= ()[]

= () []

Therefore,

=

But

= for all practical purposes.

=

-------------------(1)

This is the expression for the dispersive power of a lens. and

) =

From eq (1)

) is the longitudinal chromatic aberration which is equal to .

(b) Lateral or Transverse Chromatic Aberration:

The lateral chromatic aberration is measured by the diameter of the circle of least chromatic aberration. i.e.by CD.

To deduce an expression for CD in terms of the constants of the lens, let us from fig(1),

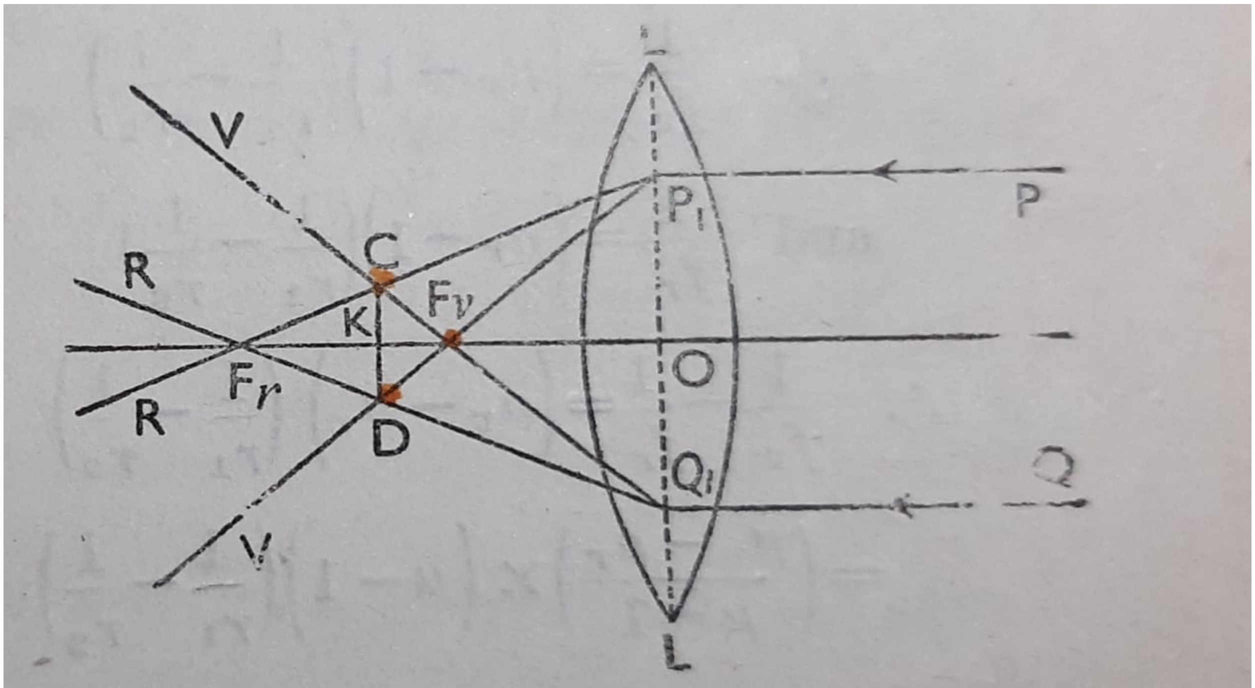


Fig.

where the similar triangle,

and

= = -----------------(i)

Again, the similar triangles

and

= = -------------------(ii)

From (i) and (ii)

=

=

Here,

) =

And

) = 2f (approx..)

And = d the effective aperture of the lens. Therefore,

=

CD = --------------(iii)

This is the expression for the lateral chromatic aberration of a lens.

Achromatic system:

An ideal case of achromatism in a system of lenses is that in which all the colored images are of the same size

(when) and at the same place (when).

By the superposition of different colors the coloring effect of the image is destroyed. In this ideal case, the overlapping of different colored image should occur not for one position of the object but for its every position. This ideal condition is very difficult to attain.

In practice, partial achromatism is obtained for different colored images either they have different magnification but of same image distance or of equal magnification but of different image distances. Again, when partial achromatism is obtained for one distance of the object, it will not remain same for other distances of the object.

Thus, for achromatism w.r.t size *I* or magnification m of the image, should have

And for achromatism w.r.t position or image distance v, then dv=0.

Achromatism in lenses:

(a) Single lens:

In a single lens of mean focal length f, the chromatic aberration is given by so the lens to make achromatic, the principal focus for the red rays must be made coincident with the principal focus for the violet rays. For achromatism ()=0

Since,

[=

The condition of achromatism demands the () should also be zero.

According to the convention of calculus, the condition for achromatism as *d*() = 0,

The differentiation w.r.to λ.

Therefore,

$= (\mu - 1)$ []

$d() = d\mu$ []

$(\mu - 1)$ []

Since, is the dispersive power.

For achromatism of a single lens

$d()==0$ but therefore the condition demands that f

So, **no single lens of finite focal length can be made achromatic.**

(b)**Two lenses in contact**:

when two lenses are in contact, the equivalent focal length is given by F, where ----------(1)

here are the focal lengths of component lenses.

Due to the chromatic aberration the principle foci for the red and the violet components will be different and for achromatism of the system the difference between the focal lengths of the red and the violet components must vanish.

Therefore, the condition of achromatism is that

Again, =

The condition of achromatism demands that,

d()=0

but,

d()=d()+d()

since

d() = d

=

=

whereis the dispersive power of the lens C of focal length .

Similarly,

d()=

is the dispersive power of the lens of focal length .

Therefore

d()= +

for achromatism of the combination

d()=0

[+] = 0 -----------------(1)

When relation (1) is satisfied for a combination of two lenses in contact, it becomes achromatic for the two extreme colors with refence to which and have been defined from (1) we have, Here,and are positive. Hence, must be of opposite signs.

If refers to a convex lens andwould refer a concave lens and let both the lenses are of same material numerically. (since=).

This would make =0

So the purpose of the lens combination is not served here.

So, .

If refers to a crown glass and refers to a flint glass, being greater than so must be greater than .

Thus, in order to make a conveying achromatic combination of two lenses in contact.

A convex lens of crown glass of smaller focal length is to be placed in contact with a concave lens of flint glass of greater focal length so that the above relation (1) satisfied.

In **achromatic doublet** generally the flint glass lens is made planoconcave, the concave surface of which is placed in contact with a suitable convex lens of crown glass. If the convex surface face the incident ray, this achromatic doublet also sufficient reduce the

spherical aberration.

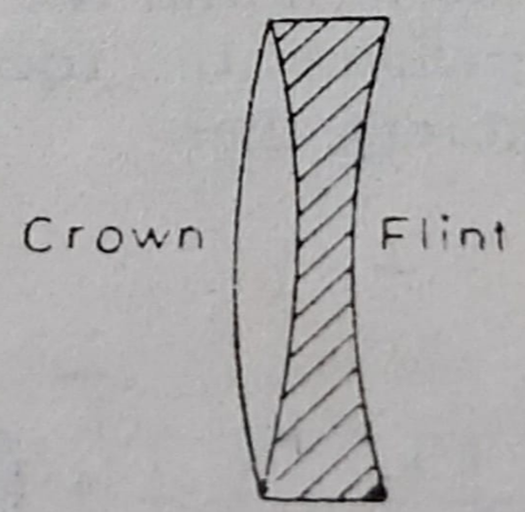


Fig. 4.2 An achromatic doublet.

If a number of lenses are put in contact to form an achromatic combination, the condition is given by .

Where summation () extends over all component lenses.

Two lenses separated by a distance:

the equivalent focal length F in this case is given by

is the separation between the two component lenses.

For achromatism d()=0

The differentiation being w.r.t .

But d()=d()+d()+a()d()+a()d()

And d() =()

d()=()

substituting in the expression for d(), we have

d()= ()+()+()+()

Therefore,

for achromatism,

()+()+=0 --------(α)

If the lenses are of the same material

=

Therefore,

()+()+ = 0 -------------(β)

(for achromatism).

If the component lenses are convex the condition would be

=

=

-------------------------------(γ)

Thus, the relation (α)gives the condition of achromatism for two lenses separated by a distance when the lens materials are not necessarily the same.

The relation (γ) gives the condition of achromatism for the two lenses of the same material separated by a distance. This principle is utilized in the construction of the Huygens eyepiece.

In relation (γ) being absent this condition of achromatism is valid for all colors but it must be remembered that the equivalent focal length F is used here indicates that the achromatism of magnification is only ensured and not necessarily that of position. It can be easily shown that for complete achromatization of the system both for the magnification as well as for the position, each of the component lenses must itself be achromatic.
