ANNAI WOMEN'S COLLEGE
KARUR.

Code : 16SCCPH5

Optics.

ABERRATIONS IN LENSES

1.15. Introduction

The deviations in the size, shape, position and colour in the actual images produced by a lens in comparison to the object are called aberrations produced by a lens. Chromatic aberrations are distortions of the image due to the dispersion of light in the lenses of an optical system when white light is used. *The defect of coloured image formed by a lens with white light is called chromatic aberration.* If monochromatic light is used, then such defects are automatically removed. Besides these defects, there are defects which are present even when monochromatic light is used. Such defects are called *monochromatic aberrations*. These aberrations are the result of (i) the large aperture of the optical system, (ii) the large angle subtended by the rays with the principal axis and (iii) the large size of the object. As a result of these aberrations, (i) a point is not imaged as a point, (ii) a plane is not imaged as a plane and (iii) equidistant points are not imaged as equidistant points. Following are the monochromatic aberrations: (i) Spherical aberration, (ii) Astigmatism, (iii) Coma, (iv) Curvature of field and (v) Distortion.

1.16. Spherical Aberration in a Lens

This aberration is due to large aperture of the lenses. The lens of large aperture may be thought to be made up of zones. The marginal and paraxial rays form the images at different places. Fig. 1.19 shows that a monochromatic point source S on the axis is imaged as S_p and S_m. Here, S_m and S_p are the images formed by marginal and paraxial rays respectively. Thus the point object is not imaged as a point. Similarly the focus of marginal and paraxial rays do not coincide. The distance $S_m S_p$ on the axis measures longitudinal spherical aberration.

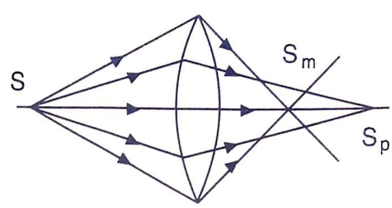

Fig. 1.19.

The failure of a lens to form a point image of a point object on the axis is called spherical aberration.

For rays parallel to principal axis, the distance between the foci of marginal and paraxial rays gives the extent of longitudinal spherical aberration. In Fig. 1.20*a*, F_p and F_m are the foci for the paraxial and the marginal rays respectively. Spherical aberration of a convergent lens is taken to be positive as the distance $(f_p - f_m)$, measured along the axis. The spherical aberration of a diverging lens is negative (Fig. 1.20*b*).

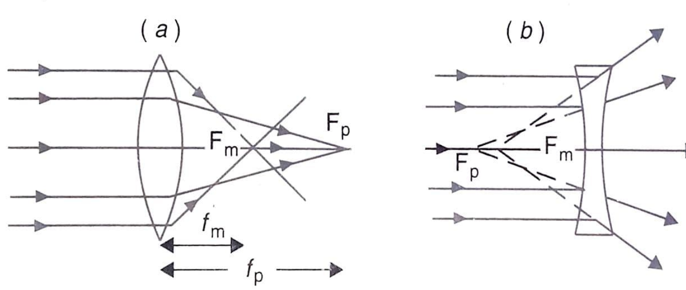

Fig. 1.20.

1.17. Methods of Minimising Spherical Aberration

The following methods are used to reduce spherical aberration.

(i) By using stops : By using stops, we can reduce the lens aperture. We can use either paraxial or marginal rays [Fig. 1.21]. Here, circular discs, called the stops, are used to cut off the unwanted rays. The stop in Fig. 1.21 *(a)* is a disc with a circular hole. It eliminates marginal rays. Fig. 1.21 *(b)* shows a stop to eliminate paraxial rays. But the use of stops reduces the intensity of the image and the resolving power of the instrument.

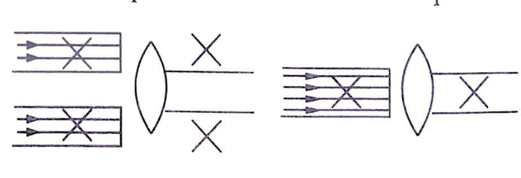

Fig. 1.21.

(ii) By using the two lenses separated by a distance. When two convex lenses separated by a finite distance are used the spherical aberration is minimum when the distance between the lenses is equal to the difference in their focal lengths. In this arrangement, the total deviation is equally shared by the two lenses. Hence the spherical aberration is minimum.

(iii) By using an aplanatic lens

(iv) By using a crossed lens. The radii of curvature R_1, R_2 of a thin lens satisfy the following relation:

$$\frac{1}{f} = (n-1)\left(\frac{1}{R_1} - \frac{1}{R_2}\right)$$

It, therefore, shows that spherical aberration depends upon *(i)* the refractive index of the lens medium (n) and *(ii)* the shape factor β, which is determined by the ratio $\beta = R_1/R_2$. If the refractive index of material of the lens is 1.5, the spherical aberration will be minimum when $\beta = R_1/R_2 = -1/6$. A convex lens whose radii of curvatures bear the said ratio is called as a *crossed lens*. It is essential to divide the deviation on two surfaces equally (Fig. 1.22). The axial and marginal rays of light come to focus with minimum of spherical aberration.

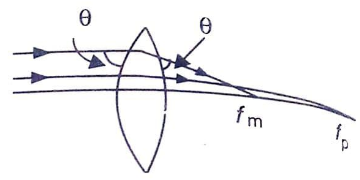

Fig. 1.22.

Example 1 : *Find the radii of curvature for a lens of f = 10 cm, n = 1.5 for which parallel incident light has minimum spherical aberration.*

Solution : Here, f = 10 cm; n = 1.5.

For minimum spherical aberration, $R_1/R_2 = -1/6$. ∴ $R_2 = -6R_1$.

Now, $$\frac{1}{f} = (n-1)\left(\frac{1}{R_1} - \frac{1}{R_2}\right) \text{ or } \frac{1}{10} = (15-1)\left(\frac{1}{R_1} + \frac{1}{6R_1}\right)$$

∴ $R_1 = 5.833$ cm; $R_2 = -6R_1 = -35$ cm.

1.18. Condition for Minimum Spherical Aberration of Two Thin Lenses-Separated by a Distance

Spherical aberration may be minimised by using two plano-convex lenses separated by a distance equal to the difference in their focal lengths.

Let two plano-convex lenses L_1 and L_2 of focal lengths f_1 and f_2 be placed coaxially separated by a distance a (Fig. 1.23). Consider a ray OA, parallel to principal axis, incident on lens L_1 at height h_1 above the principal axis.

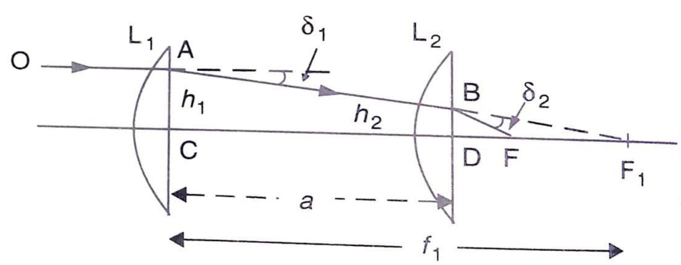

Fig. 1.23.

The deviation δ_1 produced by the lens L_1 is given by

$$\delta_1 = \frac{h_1}{f_1} \quad ...(1)$$

The refracted ray AB is incident at B at a height h_2 from the axis on lens L_2. The deviation, δ_2 produced by lens L_2 is given by

$$\delta_2 = \frac{h_2}{f_2} \quad ...(2)$$

The ray AB produced meets the axis at F_1 which is the principal focus of lens L_1. Hence $CF_1 = f_1$.

For minimum spherical aberration, the deviation produced by both the lenses should be equal, *i.e.*, $\delta_1 = \delta_2$

or
$$\frac{h_1}{f_1} = \frac{h_2}{f_2}$$

or
$$\frac{h_1}{h_2} = \frac{f_1}{f_2}. \qquad ...(3)$$

From similar triangles ACF_1 and BDF_1, we get
$$\frac{AC}{BD} = \frac{CF_1}{DF_1} = \frac{CF_1}{CF_1 - CD}$$

or
$$\frac{h_1}{h_2} = \frac{f_1}{f_1 - a} \qquad ...(4)$$

Comparing Eqs. (3) and (4), we get
$$\frac{f_1}{f_2} = \frac{f_1}{f_1 - a} \text{ or } f_2 = f_1 - a$$

$\therefore$
$$a = f_1 - f_2$$

This is the condition for minimum spherical aberration for two lenses separated by a distance.

1.19. Aplanatic Lens

A spherical lens which is free from the defects of spherical aberration and coma is called an *aplanatic lens*. The pair of conjugate points in the lens system free from spherical aberration and coma are called *aplanatic points*.

Aplanatic points are two conjugate points on the axis with respect to a spherical surface such that an object placed at one of these points produces at the second point an image which is free from spherical aberration and coma.

Aplanatic points of a spherical refracting surface : Let C be the centre of curvature of a spherical surface of radius of curvature R and refractive index n [Fig. 1.24]. Consider a point object O placed on the axis at a distance R/n from C. A ray of light OP making an angle θ_1 with the axis after refraction will bend away from the normal along PB. When produced back, it will meet the axis at I making an angle θ_2. The angles of incidence and refraction are i ($\angle OPC$) and r ($\angle NPB$) respectively.

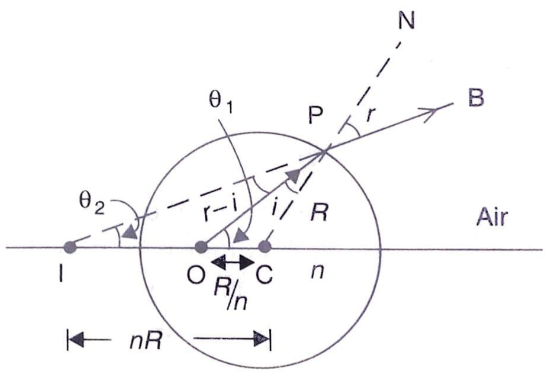

Fig. 1.24.

Then $\sin i / \sin r = 1 / n$

or
$$n \sin i = \sin r \qquad ...(1)$$

$$\Delta\, OPC, \frac{PC}{\sin \theta_1} = \frac{CO}{\sin i} \text{ or } \frac{R}{\sin \theta_1} = \frac{R/n}{\sin i}$$

or
$$n \sin i = \sin \theta_1 \qquad ...(2)$$

From Eqns. (1) and (2), $\sin \theta_1 = \sin r$

or
$$\theta_1 = r \qquad ...(3)$$

In $\Delta\, OPI$, $\theta_1 = \theta_2 + (r - i)$

or
$$\theta_2 = i \qquad ...(4)$$

From similar triangles OCP and PCI, $\frac{CI}{CP} = \frac{CP}{CO}$ or $CI = \frac{CP^2}{CO} = \frac{R^2}{R/n}$

$$\therefore \quad CI = Rn \quad ...(5)$$

This relation does not contain θ_1 and θ_2. This shows that if the object is placed at a distance R/n from C, then the image is formed at a distance nR irrespective of the slopes θ_1 and θ_2. Hence all the rays starting from O will appear to diverge from I. Therefore, the image formed is free from spherical aberration. O and I are aplanatic points of the spherical lens.

Use of aplanatic lens in high power oil immersion microscope objective. The aplanatic lens is used in high power microscopes to minimise spherical aberration and coma. A typical microscope objective is shown in Fig. 1.25. L_1 is a hemispherical lens of radius R with its plane face directed towards the object O. The object is immersed in cedar wood oil. The refractive index of cedarwood oil and the material of the lens L_1 is the same. The object O is placed in the oil at a distance R/n from the centre of the hemispherical lens. The image is formed at I_1 at a distance of nR from C. Now, I_1 is at the centre of the first surface of the meniscus lens L_2. Therefore, the rays enter the meniscus lens without any deviation. Further, the radius of curvature of the second surface of L_2 is such that I_1 is its first aplanatic point. Thus the rays after refraction through the second surface appear to come from the conjugate aplanatic point I_2. The virtual image I_2 is free from spherical aberration. In this way, a wide beam starting from O is changed into a small angled pencil diverging from I_2. The narrow beam of light from I_2 enters the achromatic combination of lenses which acts as objective of microscope.

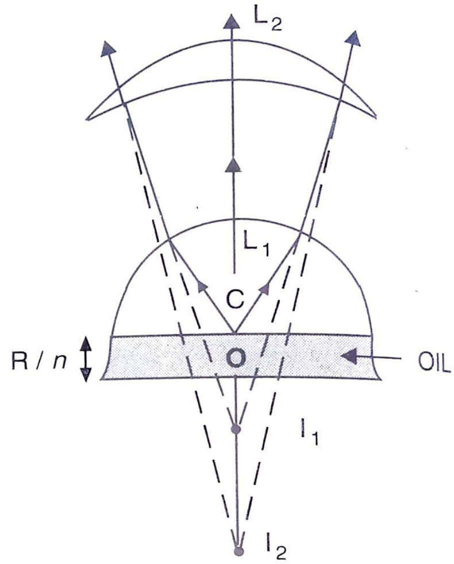

Fig. 1.25.

1.20. Chromatic Aberration in a Lens

The focal length of a lens is given by

$$\frac{1}{f} = (n-1)\left(\frac{1}{R_1} - \frac{1}{R_2}\right)$$

Since n changes with the colour of light, f must be different for different colours. This change of focal length with colour is responsible for chromatic aberration. It is classified into two types : (a) Longitudinal chromatic aberration, (b) Lateral chromatic aberration.

(a) Longitudinal chromatic aberration : A beam of white light is incident on a convex lens parallel to the principal axis [Fig. 1.26]. The dispersion of colours takes place due to prismatic action of the lens. Violet is deviated most and red the least. Red rays are brought to focus at a point farther than the violet rays. Evidently $f_r > f_v$. The difference $f_r - f_v$ is a measure of the axial chromatic aberration of a lens for parallel rays.

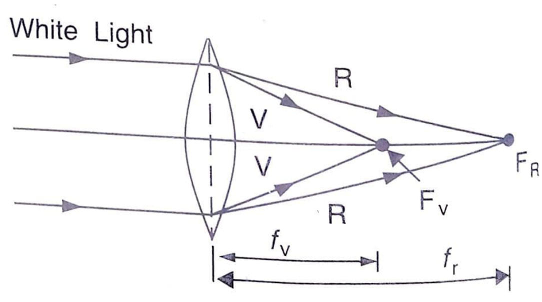

Fig. 1.26.

Expression for Longitudinal chromatic aberration

The focal length of a lens is given by

$$\frac{1}{f} = (n-1)\left(\frac{1}{R_1} - \frac{1}{R_2}\right)$$

Let f_v, f_r and f_y be the focal lengths of the lens for violet, red and yellow colours respectively. Also let n_v, n_r and n_y be the respective refractive indices. Then,

$$\frac{1}{f_v} = (n_v - 1)\left(\frac{1}{R_1} - \frac{1}{R_2}\right) \quad ..(1)$$

$$\frac{1}{f_r} = (n_r - 1)\left(\frac{1}{R_1} - \frac{1}{R_2}\right) \quad ...(2)$$

$$\frac{1}{f_y} = (n_y - 1)\left(\frac{1}{R_1} - \frac{1}{R_2}\right) \quad ...(3)$$

Subtracting Eq. (2) from Eq. (1),

$$\frac{1}{f_v} - \frac{1}{f_r} = (n_v - n_r)\left(\frac{1}{R_1} - \frac{1}{R_2}\right)$$

or

$$\frac{f_r - f_v}{f_v\, f_r} = \frac{n_v - n_r}{n_y - 1}\,(n_y - 1)\left(\frac{1}{R_1} - \frac{1}{R_2}\right)$$

Now, $\omega = (n_v - n_r) / (n_y - 1)$ = dispersive power of the material of the lens; $f_v f_r = f_y^2$.

$\therefore$
$$f_r - f_v = \omega f_y \quad ...(4)$$

(b) Lateral chromatic aberration : Fig. 1.27 shows a convex lens and an object AB placed in front of the lens. The lens forms the image of white object AB as B_vA_v and B_rA_r in violet and red colours respectively. The images of other colours lie in between the two. Evidently, the size of red image is greater than the size of violet image ($B_rA_r > B_vA_v$). The difference ($B_rA_r - B_vA_v$) is a measure of lateral or transverse chromatic aberration.

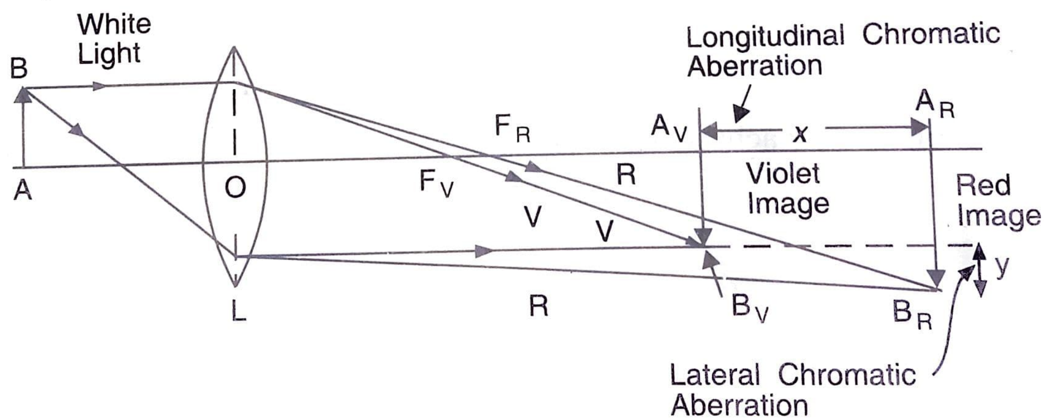

Fig. 1.27.

Chromatic aberration is eliminated by :

(i) keeping two lenses in contact with each other and

(ii) keeping two lenses out of contact.

Achromatic Combination of Lenses

When two or more lenses are combined together in such a way that the combination is free from chromatic aberration, then such a combination is called achromatic combination of lenses.

The minimisation or removal of chromatic aberration is called *achromatisation*. Chromatic aberration cannot be removed completely. Usually achromatism is achieved for two prominent colours.

1.23. Coma

When a lens is corrected for spherical aberration, it forms a point image of a point object situated on the axis. But *if the point object is situated off the principal axis, the lens, even corrected for spherical aberration, forms a comet-like image in place of point image. This defect in the image is called coma.*

Consider an off axis point A in the object (Fig. 1.30). The rays leaving A and passing through the different zones of the lens such as 11, 22, 33 are brought to focus at different points B_1, B_2, B_3, gradually nearer to the lens. The radius of these circles go on increasing with increase in radius of zone. Thus the resultant image is comet like.

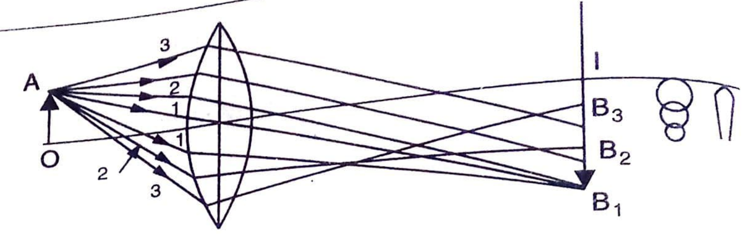

Fig. 1.30.

Removal of coma. The comatic aberration may be eliminated as follows:

1. By using a stop before the lens and so making the outer zones ineffective.
2. By properly choosing the radii of curvature of the lens surfaces. For example, for an object situated at infinity, the comatic aberration may be minimised by taking a lens of $n = 1.5$ and

$$k = \frac{R_1}{R_2} = -\frac{1}{9}.$$

3. **Abbe sine condition.** Abbe showed that coma may be eliminated if each zone of the lens satisfies the *Abbe sine condition*

$$n_1 h_1 \sin \theta_1 = n_2 h_2 \sin \theta_2.$$

Here, n_1 and n_2 are refractive indices of the object and image regions respectively. h_1 and h_2 are the heights of the object and the image. θ_1 and θ_2 are the angles which the incident and the conjugate emergent rays make with the axis (Fig.1.31).

If this condition is satisfied, the lateral magnification

$$\frac{h_2}{h_1} = \frac{n_1 \sin \theta_1}{n_2 \sin \theta_2}$$

will be same for all the rays of light, irrespective of the angles θ_1 and θ_2. Therefore, coma will be eliminated.

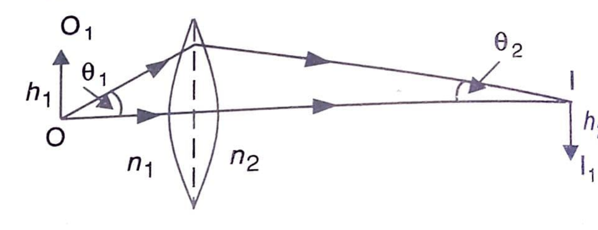

Fig. 1.31.

1.24. Astigmatism and its Minimization

Consider a point B situated off the axis in a line object which is vertically below the axis of the lens. When the cone of rays from B falls on full circumference of the lens, then after refraction all the rays do not meet at a single point (Fig. 1.32).

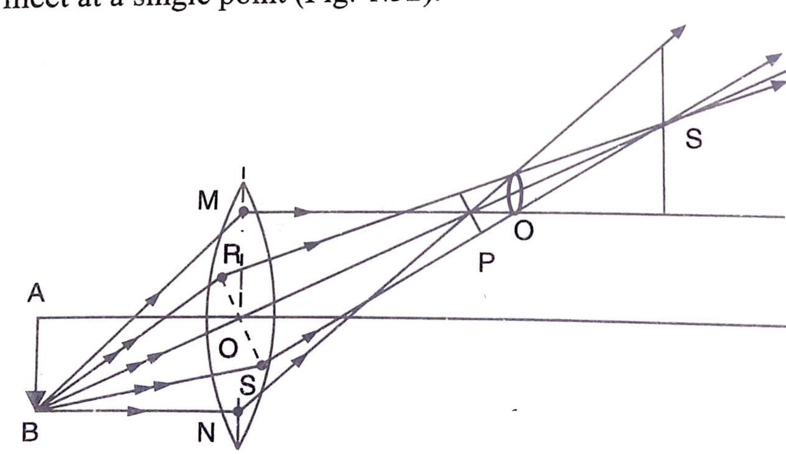

Fig. 1.32.

(a) The rays lying in the vertical plane BMN (called *meridional plane*) form the image as a horizontal line P.

(b) The rays lying in the horizontal plane BRS (called *sagittal plane*) form the image as a vertical line S. The *circle of least confusion* C lies in between P and S.The best image for the object point

is obtained here. This defect is called *astigmatism*. The distance between P and S is a measure of astigmatism and is called the *astigmatic difference*.

The astigmatic difference in the concave lens is in opposite direction to that produced by a convex lens. Hence astigmatism may be reduced by suitable combination of concave and convex lenses. Such a combination of lenses is called *anastigmatic combination*. It is used in the construction of objective lens in a photographic camera.

EYE-PIECES

1.25. Eye-piece

An *eye-piece* is a combination of lenses designed to magnify the image already formed by the *objective* of a telescope and microscope. An eye-piece consists of two plano-convex lenses. F is called the *field lens* and E the *eye lens* (Fig. 1.33). The field lens has large aperture to increase the field of view. The eye lens mainly magnifies the image. To reduce the spherical aberration, the lenses taken are plano-convex lenses. Further the focal lengths of the two lenses and their separation are selected in such a way as to minimise the chromatic and spherical aberrations.

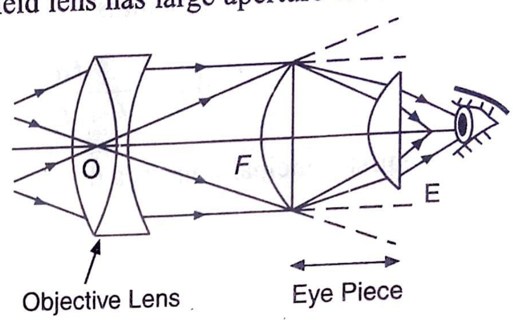

Fig. 1.33.

A combination of lenses is used in an eyepiece in place of a simple lens magnifier for the following reasons :

(i) The field of view is enlarged by using two or more lenses.

(ii) The aberrations can be minimised.

1.26. Huygens' Eye-piece

Construction: It consists of two plano-convex lenses of focal lengths $3f$ (field lens) and f (eye lens), placed a distance $2f$ apart [Fig. 1.34]. They are arranged with their convex faces towards the incident rays. The eye-piece satisfies the following conditions of minimum spherical and chromatic aberrations.

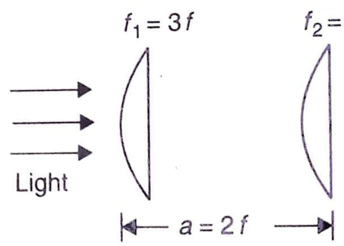

Fig. 1.34.

(i) The distance between the two lenses for minimum spherical aberration is given by $a = f_1 - f_2$. In Huygen's eyepiece, $a = 3f - f = 2f$. Hence this eye-piece satisfies the condition of minimum spherical aberration.

(ii) For chromatic aberration to be minimum $a = (f_1 + f_2)/2$. In Huygens' eyepiece, $a = (3f + f)/2 = 2f$. Hence this eyepiece satisfies the condition of minimum chromatic aberration.

Working : An eye-piece forms the final image at infinity. Thus the field lens forms the image I_2 in the first focal plane of eye-lens, *i.e.*, at a distance f to the left of eye-lens. Now the distance between the field lens and eye-lens is $2f$. Therefore, the image I_2 lies at a distance f to the right of field lens. The image I_1 formed by the objective of microscope or telescope acts as the virtual object for the field lens. Thus we treat I_1 as the virtual object for the field lens, and I_2 as the image of I_1 due to it (Fig. 1.35) or $v = f$, $F = 3f$, $u = ?$ We have

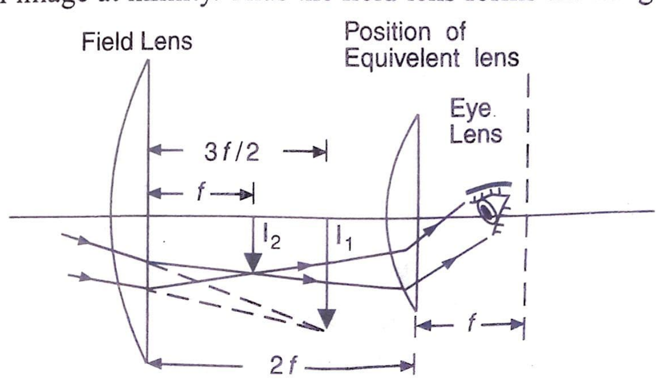

Fig. 1.35.

$$\frac{1}{v}-\frac{1}{u}=\frac{1}{F} \text{ or } \frac{1}{f}-\frac{1}{u}=\frac{1}{3f}$$

$$\therefore \quad u = 3f/2$$

i.e. I_1 should be formed at a distance $(3/2)f$ from the field lens. Therefore the rays coming from the objective which converge towards I_1, are focussed by the field lens at I_2. The rays starting from I_2 emerge from the eye-lens as a parallel beam.

Cardinal Points of Huygens Eyepiece

The equivalent focal length F of this eyepiece is

$$\frac{1}{F}=\frac{1}{f_1}+\frac{1}{f_2}-\frac{a}{f_1 f_2}=\frac{1}{3f}+\frac{1}{f}-\frac{2f}{3f\times f}=\frac{2}{3f}$$

$$\therefore \quad F = 3f/2.$$

The second principal point is at a distance β from the eye lens.

$$\beta = -\frac{f_2 a}{f_1+f_2-a}=\frac{-f\times 2f}{3f+f-2f}=\frac{-2f^2}{2f}=-f.$$

The first principal point is a distance α from the field lens.

$$\alpha = +\frac{f_1 a}{f_1+f_2-a}=\frac{3f\times 2f}{3f+f-2f}=\frac{6f^2}{2f}=3f.$$

The position of the principal points P_1 and P_2 and the principal foci F_1 and F_2 are shown in Fig.1.36. Since the system is in air, the nodal points coincide with the principal points.

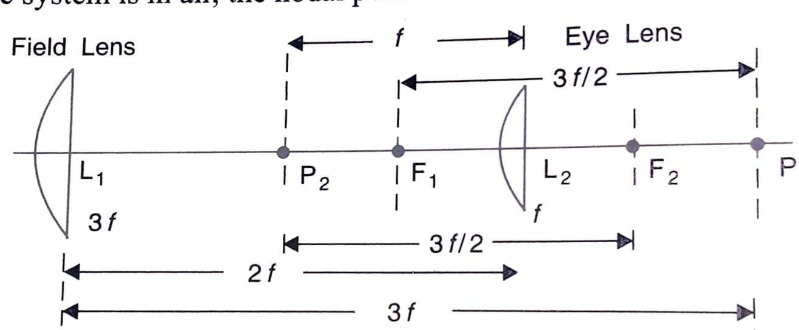

Fig. 1.36.

1.27. Ramsden's Eyepiece

Construction : It consists of two plano convex lenses each of focal length f. The distance between them is $(2/3)f$ [Fig.1.37]. For achromatism, the distance between the two lenses should be $a = (f_1 + f_2)/2 = \frac{(f+f)}{2} = f$. But here $a = (2/3)f$.

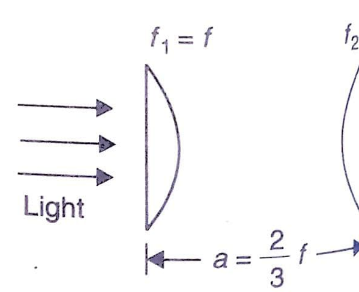

Fig. 1.37.

Thus in this eyepiece the chromatic aberration is only partly reduced. Similarly, for minimum spherical aberration, $a = f_1 - f_2 = f - f = 0$. Hence the spherical aberration is not at all reduced. This is a demerit of this eyepiece.

Working : I_1 is the image formed by the objective of the microscope or telescope. It serves as an object for eyepiece. The eyepiece is adjusted such that the image I_2 formed by the field lens in the first focal plane of the eyelens [Fig.1.38]. Then the eye-piece forms the final image at infinity. Since the focal length of the eye lens is f and $a = (2/3)f$, I_2 is at a distance $f/3$ from the field lens. Now, the image I_1 due to objective serves as the object for field lens. I_2 is the image of I_1 due to field lens. Or, $v = -f/3$, $F = f$, $u = ?$

$$\frac{1}{v} - \frac{1}{u} = \frac{1}{F} \text{ or } \frac{1}{-f/3} - \frac{1}{u} = \frac{1}{f} \text{ or } \frac{1}{u} = -\frac{4}{f}$$

$$\therefore \qquad u = -f/4.$$

Thus the eyepiece is so adjusted that the image (I_1) formed by the objective of telescope or microscope lies at a distance $f/4$ towards the left of field lens. The crosswire is placed at I_1. I_1 serves as the object for field lens and its image is formed at I_2.

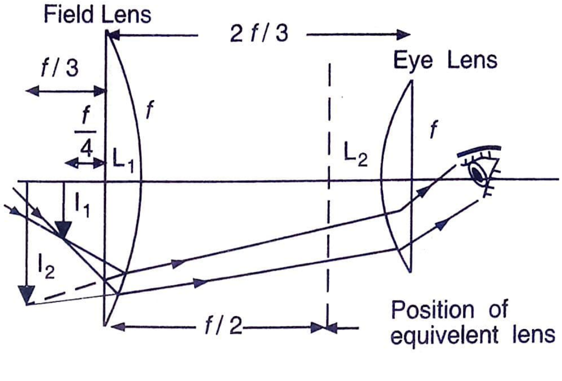

Fig. 1.38.

Cardinal points : The focal length F of the equivalent lens is

$$\frac{1}{F} = \frac{1}{f_1} + \frac{1}{f_2} - \frac{a}{f_1 f_2} = \frac{1}{f} + \frac{1}{f} - \frac{2f/3}{f^2} = \frac{4}{3f}.$$

$$\therefore \qquad F = 3f/4$$

$$\beta = \frac{-f_2 a}{f_1 + f_2 - a} = -\frac{f \times (2f/3)}{2f - (2f/3)} = -\frac{f}{2}$$

$$\alpha = \frac{f_1 a}{f_1 + f_2 - a} = -\frac{f \times (2f/3)}{2f - (2f/3)} = +\frac{f}{2}$$

The positions of the principal points P_1 and P_2 and the principal foci F_1 and F_2 are shown in Fig. 1.39. Since the system is in air, the nodal points coincide with the principal points.

Distance of the first principal focus from the field lens of the eyepiece $= F_1L_1 = F_1P_1 - \alpha = 3f/4 - f/2 = f/4$. Similarly the distance of the second principal focus from the eye lens is $L_2F_2 = P_2F_2 - \beta = 3f/4 - f/2 = f/4$.

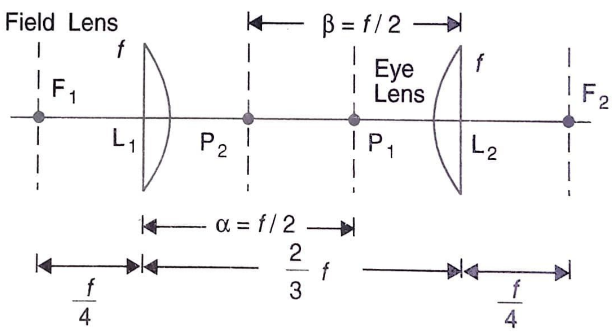

Fig. 1.39.

Example : *A Ramsden's eyepiece is to have an effective focal length of 3 cm. Calculate the focal lengths of the lens components and their distance of separation.*

Solution : We have, $\frac{1}{F} = \frac{1}{f_1} + \frac{1}{f_2} - \frac{a}{f_1 f_2}$.

Here, $f_1 = f, f_2 = f$, $a = 2f/3$ and $F = 3$cm.

$$\therefore \qquad \frac{1}{3} = \frac{1}{f} + \frac{1}{f} - \frac{2f/3}{f^2}$$

$$\therefore \qquad f = 4 \text{ cm, and } a = 2f/3 = 8/3 \text{ cm.}$$

for L_1. P_0 and P', E_0 and E', and L and L' are conjugate pairs for L_2. This makes points like P and P' conjugate for the whole system. If a point object is located on the axis at O, rays OP and OL limit the bundle that will get through the system. At L_1 these rays are refracted through P_0 and L_0. At L_2 they are again refracted in such directions that they appear to come from P' and L'.

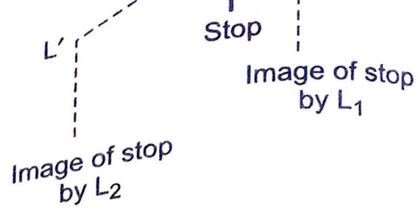

Fig. 1.43.

1.34. Curvature of the Field

Even if a lens is free from spherical aberration, coma and astigmatism, the image of an extended plane object OO' is curved (Fig. 1.44). If a screen is placed at I perpendicular to the axis the complete image II' will not be in focus. This defect is called '*curvature.*' It arises because the points away from the axis, such as O', are at a greater distance from the centre C of the lens than the axial point O. Hence the image I' is formed at a smaller distance than I.

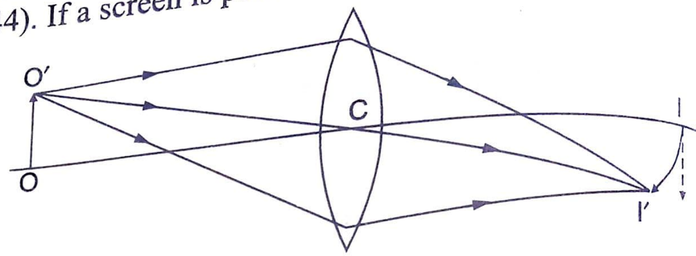

Fig. 1.44.

Removal of Curvature

(*i*) In case of a single lens, curvature can be minimised by using suitable stops.

(*ii*) For a combination of lenses, the condition for absence of curvature is

$$\Sigma \frac{1}{nf} = 0$$

Here n is the refractive index and f is the focal length of a lens.

For two lenses (whether in contact or separated by a distance) the condition reduces to

$$\frac{1}{n_1 f_1} + \frac{1}{n_2 f_2} = 0$$

or

$$n_1 f_1 + n_2 f_2 = 0.$$

This is known as *Petzval's condition.*

Since n_1, n_2 are positive, f_1 and f_2 must have opposite signs. Hence by combining a convex lens of a certain material with a concave lens of the suitable material and focal length, a flat field is obtained.

1.35. Distortion

When a stop is used with a lens to reduce the various aberrations, the image of a plane square-like object placed perpendicular to the axis is not of the same shape as the object. This defect is called '*distortion*'. This is because the chief rays forming images of different points on the object pass through different portions of the lens. Hence different parts of the object suffer different magnifications.

There are two types of distortion : (*i*) barrel-shaped, (*ii*) pin-cushion shaped.

(*i*) When the stop is placed on the object side of the lens (Fig. 1.45*a*), the magnification of the outermost part of the plane object is less than that of the central part, producing barrel-shaped distortion. If the stop is placed on the image side of the lens (Fig. 1.45*b*), then the outermost parts of the object are magnified more than the central parts, producing pin-cushion-shaped distortion.

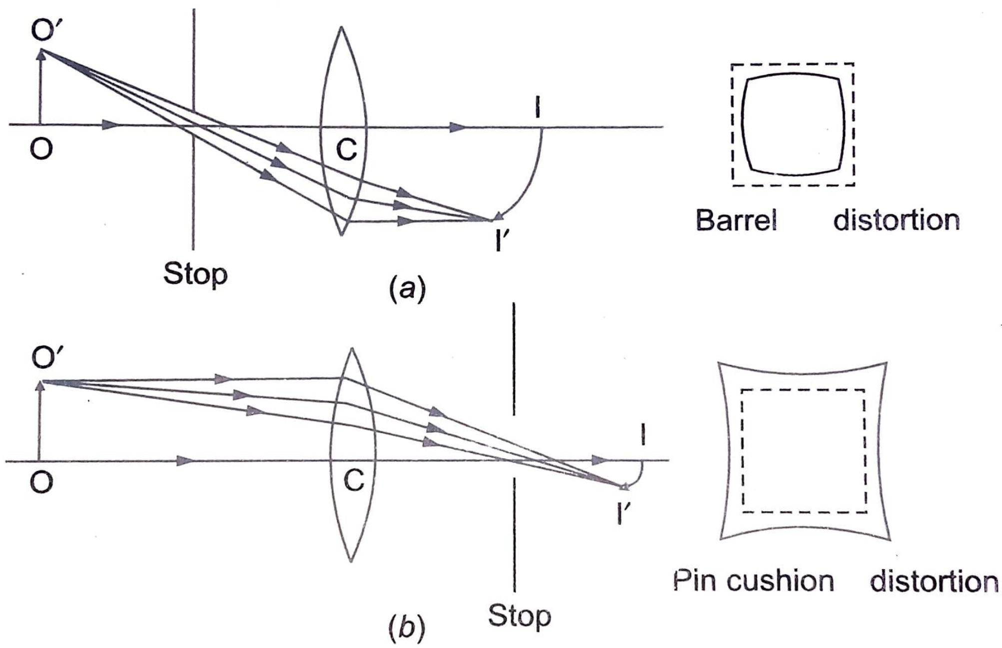

Fig. 1.45.

Removal of Distortion

A combination of two similar meniscus convex lenses, with their concave surfaces facing each other and having an aperture stop in the middle is free from distortion, when the object and image are symmetrically placed (Fig. 1.46). In this manner the pin-cushion-shaped distortion due to the first lens is exactly nullified by the barrel-shaped distortion due to the second lens.

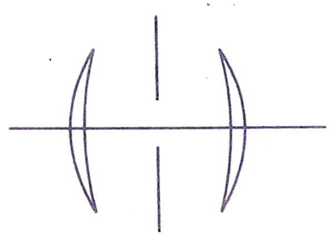

Fig. 1.46.