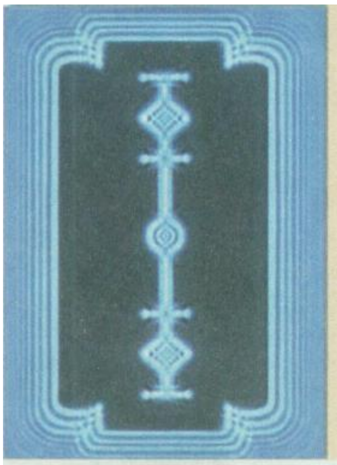
Chapter Five

Diffraction of Light

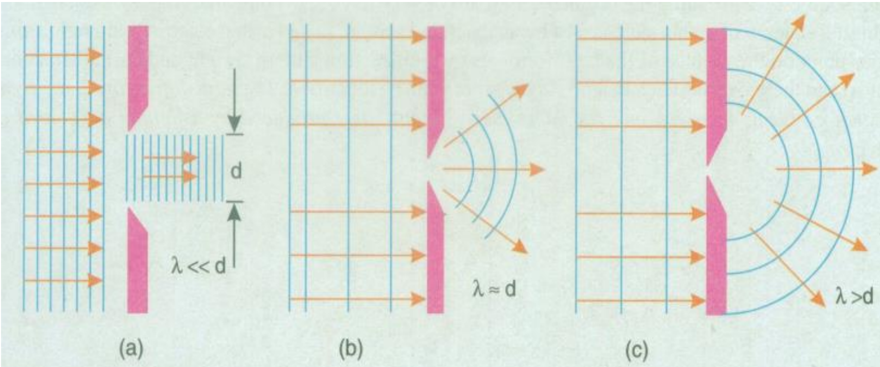
Fresnel & Fraunhofer Diffraction

5.1 Introduction

The bending of waves around the edges of an obstacle is called *diffraction.*

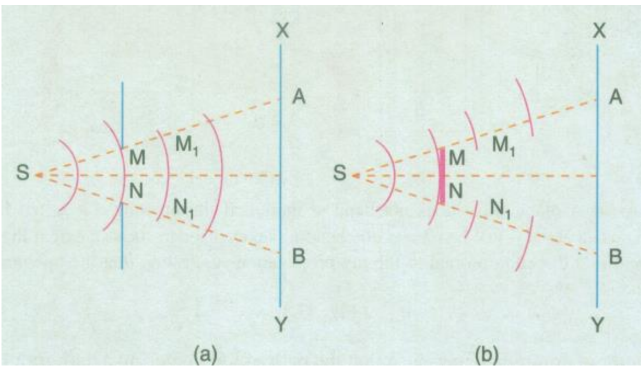


Light diffraction by a razor blade.

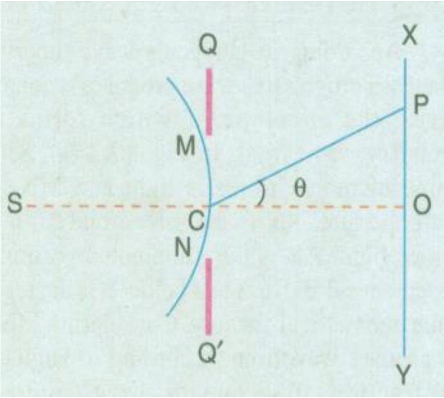


Diffraction–(*a*) A plane wave does not bend at the slit if the opening $d \gg \lambda$. (*b*) Bending is perceptible when $\lambda \approx d$ (*c*). When $\lambda > d$, the bending takes place to such an extent that light can be perceived in a direction normal to the ray propagation suggesting that the opening acts as a point source.

In general diffraction of waves becomes noticeable only when the size of the obstacle is comparable to a wavelength. It is a matter of common experience that the path of light entering a dark room through a hole in the window illuminated by sunlight is straight. Similarly, if an opaque obstacle is placed in the path of light, a sharp shadow is cast on the screen, indicating thereby that light travels in straight lines. Rectilinear propagation of light can be easily explained on the basis of Newton's corpuscular theory. But it has been observed that when a beam of light passes through a small opening (a small circular hole or a narrow slit) it spreads to some extent into the region of the geometrical shadow also. If light energy is propagated in the form of waves, one would expect bending of a beam of light round the edges of an opaque obstacle or illumination of the geometrical shadow.



5.2 FRESNEL'S ASSUMPTIONS




Augustin Jean Fresnel
(1788-1827)

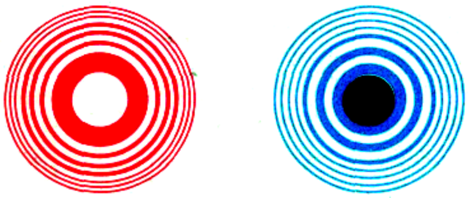
According to Fresnel, the resultant effect at an external point due to a wavefront will depend on the factors discussed below: In the Figure S is a point source of monochromatic light and MN is a small aperture. XY is the screen and SO is perpendicular to XY. MCN is the incident spherical wavefront due to the point source S. To obtain the resultant effect at a point P on the screen, Fresnel assumed the following:

(1) A wave front can be divided into a large number of strips or **zones** called Fresnel's zones of small area and the resultant effect at any point will depend on the combined effect of all the secondary waves emanating from the various zones.

(2) The effect at a point due to any particular zone will depend on the distance of the point from the zone.

(3) The effect at P will also depend on the obliquity of the point with reference to the zone under consideration, e.g. due to the part of the wavefront at C, the effect will be a maximum at O and decreases with increasing obliquity.

5.3 ZONE PLATE


(a) Zone Plate (b)

A zone plate is a specially constructed screen such that light is obstructed from every alternate zone. It can be designed so as to cut off light due to the even numbered zones or that due to the odd numbered zones. To construct a zone plate, concentric circles are drawn on white paper such that the radii are proportional to the square roots of the natural numbers. The odd numbered zones (i.e. 1st, 3rd, 5th, etc) are covered with black ink and a reduced photograph is taken. In the developed negative, the odd zones are transparent to incident light and the even zones will cut off light.

Zone Plate:

-A zone plate is a device used to focus light, zone plates use diffraction instead of refraction unlike lenses.

-It was Created by Fresnel ,they are sometimes called Fresnel zone plates.

-A zone plate consists of a set of radially symmetric rings, known as Fresnel zones ,which alternate between opaque and transparent .Light hitting the zone plate will diffract around the opaque zones .

-Zone plates produce equivalent diffraction patterns no matter whether the central disk is opaque or transparent.

Applications

1- Physics: There are many wavelengths of light outside of the visible area of the electromagnetic spectrum where traditional lens materials like glass are not transparent ,and so lenses are more difficult to manufacture. Zone plates eliminate the need for finding transparent, refractive, easy-to-manufacture materials for every region of the spectrum .

2- Photography: Zone plates are also used in photography in place of a lens or pinhole for a glowing, soft-focus image.

3- Gunsights: Zone plates have been proposed as a cheap alternative to more expensive optical sights or targeting laser.

4- **Lenses:** Zone plates may be used as imaging lenses with a single focus.

5.4 DIFFERENCE BETWEEN A ZONE PLATE AND A CONVEX LEN

1. a convex lens has only one focal length given by

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

In the case of a zone plate, there are a number of each focus and the focal length of the zone plate is given by

$$f_m = \frac{r_n^2}{(2m-1)n\lambda}$$

2. The focal length for violet light is more than for red light, which is reverse in the case of a convex lens.

3. The chromatic aberration in a zone plate is much more severe than in a convex lens.

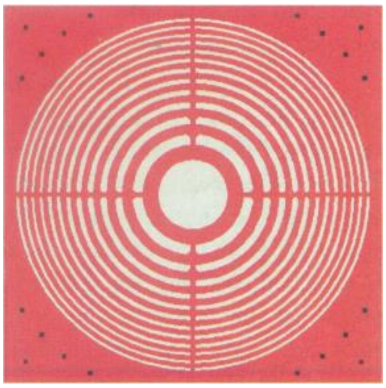
4. A zone plate acts simultaneously as a convex lens and as a concave lens. In addition to a real image, a virtual image is also formed simultaneously. A convex lens forms only a real image.

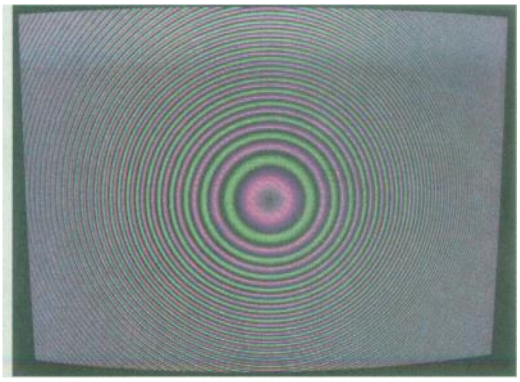
5. In case of zone plate the image is formed by the diffraction phenomenon. In case of a convex lens the image is formed due to refraction of light.

6. The zone plate has got multiple foci on either side of the plate. Hence, the intensity of the image formed will be much less. Convex lens has only one focus. As all the light is focused at one point, the intensity of the image will be more.

7. In a zone plate, waves reaching the image point through any two alternate zones differ in path by A, and in phase by 2 *n*. In case of a convex lens all the rays reaching the image point have zero path or phase difference.

8. A zone plate can be used over a wide range of wavelengths from microwaves to x-rays. Glass lens cannot be used beyond the visible region.





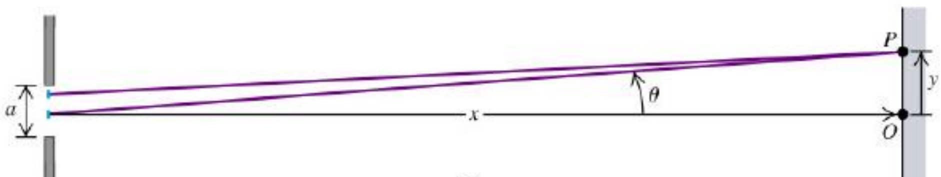
5.5 Distinction Between Interference and Diffraction

The main differences between interference and diffraction are as follows:

INTERFERENCE	DIFFRACTION
1. Interference is the result of the interaction of light coming from different wavefronts originating from	Diffraction is the result the of interaction of light coming from different parts of the same wavefront.
2. Interference fringes may or may not be of the same width.	Diffraction fringes are not of the same width.
3. Regions of minimum intensity are perfectly dark.	Regions of minimum intensity are not perfectly dark.
4. All bright bands are of same intensity.	The different maxima are of varying intensities with maximum intensity for central maximum.

Fraunhoffer Diffraction

Fraunhofer diffraction or **far-field diffraction**, is a form of wave diffraction that occurs when planar waves are passed through an aperture or slit causing only the size of an observed aperture image to change due to the far-field location of observation and the increasingly planar nature of outgoing diffracted waves passing through the aperture



(a)

The Fresnel number F: For an electromagnetic wave passing through an aperture and hitting a screen, the Fresnel number F is defined as

In case of F>>1 laws of geometrical optics are applied

$$F = \frac{a^2}{L\lambda}$$

Fresnel diffraction occurs when:

$$F = \frac{a^2}{L\lambda} \geq 1$$

Fraunhofer diffraction occurs when:

$$F = \frac{a^2}{L\lambda} \ll 1$$

a - aperture or slit size,

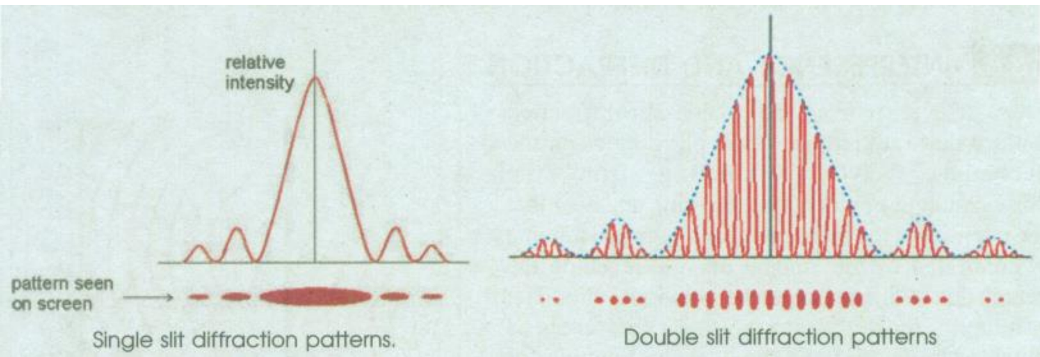
λ - wavelength, L - distance from the aperture

5.6 Comparison between Fresnel and Fraunhofer diffraction

1- In Fresnel diffraction the diffraction that takes place at a slit when the source of light is in finite distance from the slit but in Fraunhofer diffraction the diffraction that takes place at a slit when the source of light is at very large (or infinite) distance from the slit
2- **Fresnel Diffraction** (near-field diffraction) when incoming and outgoing waves are both non-planar. But Fraunhofer diffraction both incoming and outgoing wave contributions are considered as plane waves.
3- The Fresnel number for Fraunhofer diffraction $F<<1$ And for Fresnel diffraction $F\geq1$
4- Observation of Fresnel diffraction phenomenon does not require any lenses, but the conditions required for Fraunhoffer diffraction are achieved using two convex lenses
5- Fraunhoffer diffraction pattern can be easily observed in practice, Fresnel diffraction it is experimentally simple but the analysis proves to be very complex.

5.7 Distinction Between Single Slit and Double Slit Diffraction Patterns

The single slit diffraction pattern consists of a central bright maximum with secondary maxima and minima of gradually decreasing intensity. The double slit diffraction pattern consists of equally spaced interference maxima and minima with in the central maximum. The intensity of the central maximum in diffraction pattern due to a double slit is four times that of the central maximum in the diffraction pattern due to diffraction at a single slit. In the above arrangement, if one of the slits is covered with opaque screen, the pattern observed is similar to the one observed with a single slit.



The spacing of diffraction maxima and minima depends on *a*, the width of the slit and the spacing of the interference maxima and minima depends on the value of *a* and *b* where *b* is opaque spacing between the two slits. The intensities of the interference maxima are not constant but decrease to zero on either side of the central maximum. These maxima reappear two or three times before the intensity becomes too low to be observed.

5.8 PLANE DIFFRACTION GRATING

A diffraction grating is an extremely useful device and in one of its forms it consists of a very large number of narrow slits side by side. The slits are separated by opaque spaces. When a wave front is incident on a grating surface, light is transmitted through the slits and obstructed by the opaque portions. Such a grating is called a **transmission grating.** The secondary waves from the positions of the slits interfere with one another, similar to the interference of waves in Young's experiment. Joseph Fraunhoffer used the first grating which consisted of a large number of parallel fine wires stretched on a frame. Now, gratings are prepared by ruling equidistant parallel lines on a glass surface. The lines are drawn with a fine diamond point. The space in between any two lines is transparent to light and the lined portion is opaque to light. Such surfaces act as transmission gratings. If, on the other hand, the lines are drawn on a silvered surface (plane or concave) then light is reflected from the positions of the mirror in between any two lines and such surfaces act as *reflection gratings.*

If the spacing between the lines is of the order of the wavelength of light, then an appreciable deviation of the light is produced. Gratings used for the study of the visible region of the spectrum contain 10,000 lines per cm. Gratings, with originally ruled surfaces are only few. For practical purposes, replicas of the original grating are prepared. On the original grating surface, a thin layer of collodion solution is poured and the solution is allowed to harden. Then, the film of collodion is removed from the grating surface and then fixed between two glass plates. This serves as a plane transmission grating. A large number of replicas are prepared in this way from a single original ruled surface. angular spacing of the secondary maxima and minima is so small in comparison to the principal maxima that they cannot be observed. It results in uniform darkness between any two principal maxima.

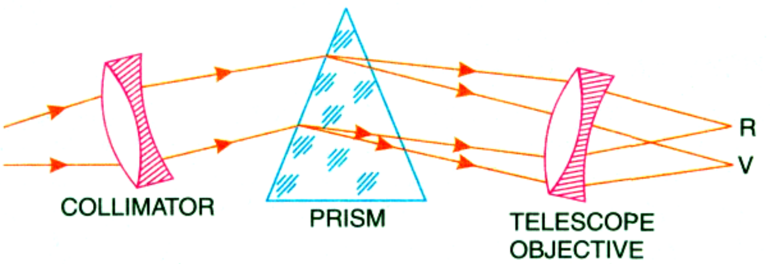
5.9 PRISM AND GRATING SPECTRA

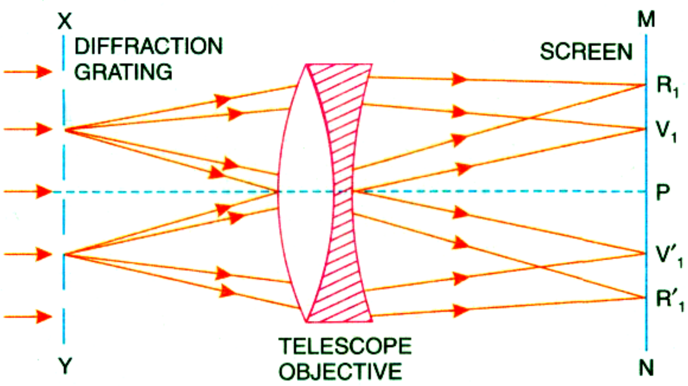
For dispersing a given beam of light and for studying the resultant spectrum, a diffraction grating is mostly used instead of a prism. The grating and prism spectra differ in the following points.

(1) With a grating, a number of spectra of different orders can be obtained on the two sides of the central maximum whereas with a prism only one spectrum is obtained.

(2) The spectra obtained with a grating are comparatively purer than those with a prism.

(3) With a grating, the diffraction angle for violet end of the spectrum is less than for red. With a prism the angle of deviation for the violet rays of light is more than for the red rays of light.





(4) The intensities of the spectral lines with a grating are much less than with a prism. In a grating spectrum, most of the incident light energy is associated with the undispersed central bright maximum and the rest of the energy is distributed in the different order spectra on the two sides of the central maximum. But in a prism most of the incident light energy is distributed in a single spectrum and hence brighter spectral lines are obtained.

(5) The dispersive power of a grating is given by

$$\frac{d\theta}{d\lambda} = \frac{nN'}{\cos\theta}$$

and this is constant for a particular order. Thus, the spectral lines are evenly distributed. Hence, the spectrum obtained with a grating is said to be **rational**. The refractive index of the material of a prism changes more rapidly at the violet end than at the red end of the spectrum. The dispersive power of a prism is given by

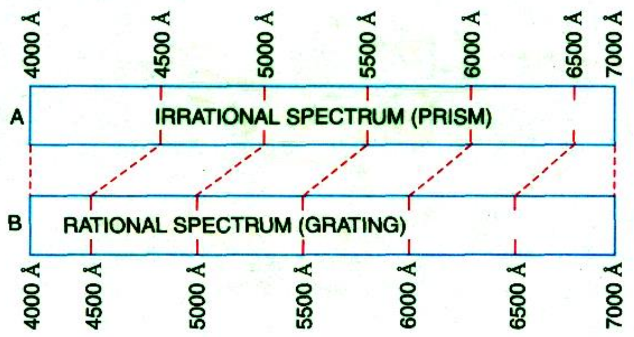
$$\frac{d\mu}{\mu - 1}$$

and this has higher value in the violet region than in the red region. Hence, there will be more spreading of the spectral lines towards the violet and the spectrum obtained with a prism is said to be **irrational**.

(6) The resolving power of a grating is given by ***nN*** whereas the resolving power of a prism is given by

$$t\,\frac{d\mu}{d\lambda}$$

Where *t* is the base of the prism. The resolving power of a grating is much higher than that of a prism. Hence the same two nearby spectral lines appear better resolved with a grating than with a prism.



(7) Lastly, the spectra obtained with different gratings are identical because the dispersive power and the resolving power of a grating do not depend on the nature of the material of the grating. But the spectra obtained with prisms made of different materials are never identical because both dispersive and resolving powers depend on the nature of the material of the prism.