Unit 1. Modern Optics

INTRODUCTION

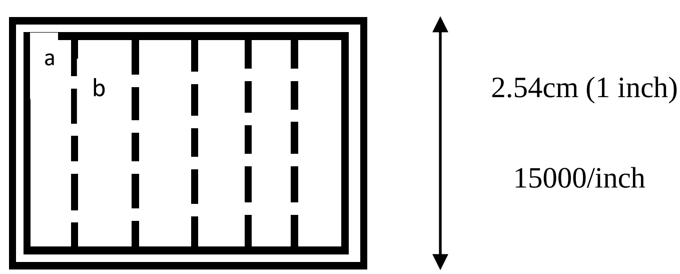
Optics is the branch of physics that studies the behavior and properties of light, including its interactions with matter and the construction of instruments that use or detect it. Basically in optics there are two sub-branches, **Geometric** (Ray) Optics and **Physical** (Wave) Optics. Geometric optics treats light as a collection of rays that travel in straight lines and bend when they pass through or reflect from surfaces. Physical optics is a more comprehensive model of light, which includes wave effects such as interference and diffraction.

- **Interference:** Interference is a phenomenon in which two or more waves superimpose to form a resultant wave called as interference. There are two types of interference, one is constructive and another is destructive.
- **Diffraction: Diffraction** is the phenomenon in which bending of light around the sharp edge of an obstacle & its spreading into geometrical shadow of an obstacle is called diffraction of light. There are two main classes of diffraction, which are known as Fraunhofer diffraction and Fresnel diffraction.
- **Geometrical and Optical Path:** Optical path is the trajectory that a light ray follows as it propagates through an optical medium. The geometrical optical-path length or simply geometrical path length is the length of a segment in a given Optical path, i.e., the Euclidean distance integrated along a ray between any two points.

PLANE DIFFRACTION GRATING

An arrangement consists of large number of close, parallel, straight and equidistant slits of width ‘a’ separated by opaque portion with neighboring slit of distance ‘b’ is called **Diffraction action Grating”**.

Gratings are constructed by ruling equidistant parallel lines on a transparent material like Glass. The ruled lines are opaque to the light while space between line are transparent to the light which acts as slit, is also called as “**Grating**”.

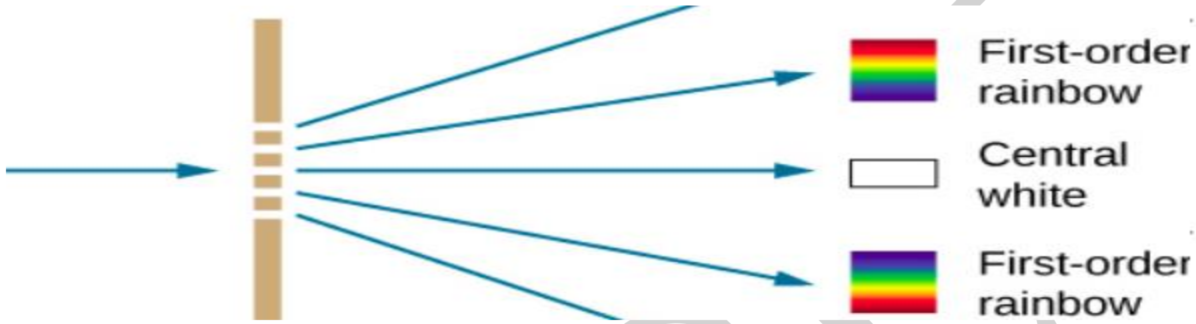


In above figure,

a= slit width and b= opaque portion between two slits

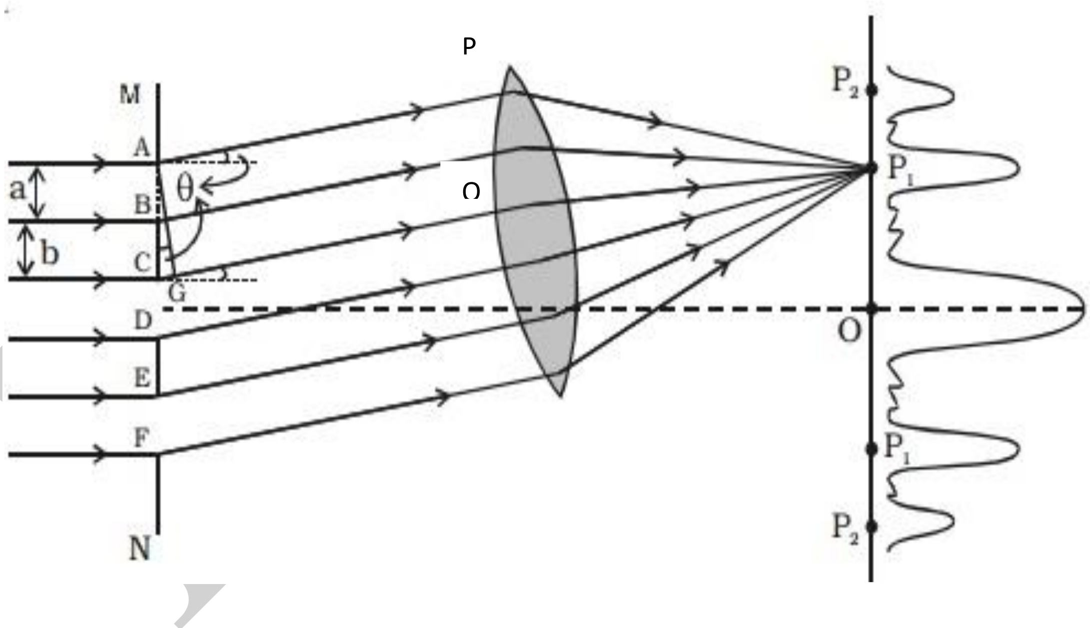
The distance between two neighboring slits is called as “ Grating Element”.

If, (a+b)=grating element and N= number of lines in diffraction grating then



Relation between (a+b) and N is, **(a+b) =1/ N.**

THEORY OF PLANE DIFFRACTION GRATING/ GRATING EQUATION



If the Slit width is comparable to the wavelength (λ) then light diffracted from each slit. According to Huygens wave theory of light each slit acts as a secondary source of light. The secondary waves emitted upward & downward directions at various angles. The conversing lens is used to collect all diffracted rays &

brought them to focus on Screen XY as shown in above figure, the intensity at point 'P' depends on Path difference between secondary waves.

Here we have to find out optical Path Difference between rays AP & CQ at angle 'θ'. Draw Perpendicular AM on ray CQ then,

In Δ ACG, $\mathrm{Sin}\,\theta = \frac{CQ}{AC}$ $\therefore\ CQ = AC\,\mathrm{Sin}\,\theta$ $i.e.\ CQ = (a+b)\,\mathrm{Sin}\,\theta\ [\because AC = a+b]$ …………(1)

If Path difference is integral multiple of wavelength then point P' will have maximum intensity

i.e. $n\lambda = (a+b)\ Sin\theta$ ………..(2)

If, incident light consists of more than one wavelength then beam will diffract at various angles. i.e. If λ & $\lambda+d\lambda$ are two nearby wavelengths present in incident light then light can diffract at angle θ & $\theta+d\theta$.

$\therefore$ For 1st order maximum, equation (2) can be written as

$$n\,(\lambda+d\lambda) = (a+b)\ \mathrm{Sin}\,(\theta+d\theta) \quad \text{…………….(3)}$$

But we know that, N= Total Number of lines on Grating = $\frac{1}{(a+b)}\,cm$

$\therefore$Equation (2) & (3) becomes,

$$N\,\lambda = \mathrm{Sin}\,\theta / N, \quad \text{i.e.} \quad nN\lambda = \mathrm{Sin}\theta \quad \text{…………….(4)}$$

$$\& \quad nN\,((\lambda+d\lambda) = \mathrm{Sin}(\theta+d\theta) \quad \text{…………….(5)}$$

Equation (4) and (5) gives Grating equations & it is called as **"Grating Law".**

RESOLVING POWER

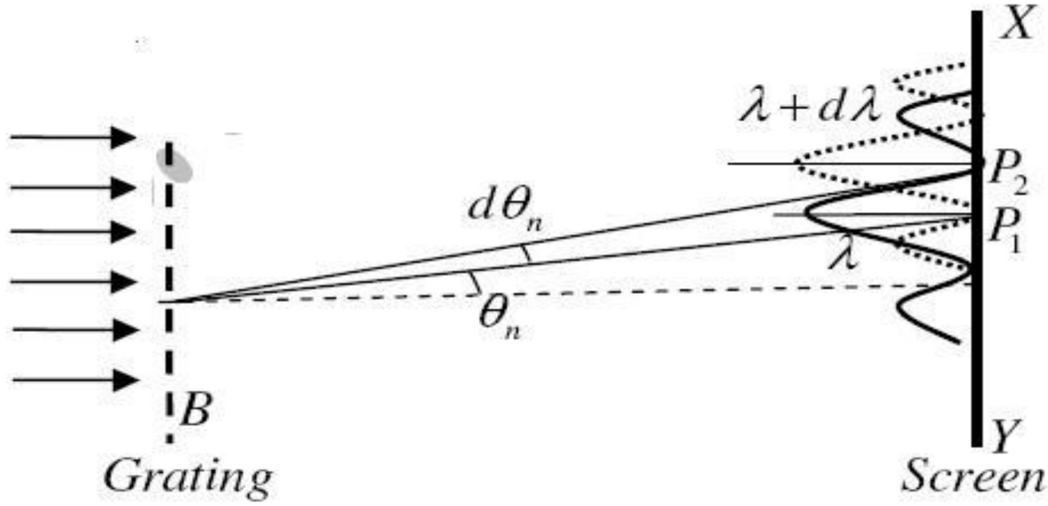
The ability of optical instrument to resolve images of two nearby objects is called its resolving Power.

OR

The ratio of wavelength of one spectral line (λ) to the wavelength difference (dλ) between neighboring spectral line.

$$\text{i.e. R.P.} = \frac{\lambda}{d\lambda}$$

RESOLVING POWER OF PLANE DIFFRACTION GRATING



Resolving Power is defined as "ratio of wavelength of spectral line to the smallest wavelength difference between neighbouring spectral line". AB is the grating surface on which light is to be incident & XY is the field of view of screen/telescope. Consider P_1 is the mth principle maximum of wavelength λ & P_2 is mth principle maximum of wavelength $\lambda+d\lambda$ with diffraction angle θ_m & $\theta+d\theta_m$ respectively.

According to Rayleigh's criterion, these lines are appeared to resolve if principle maximum of P_2 falls on 1st minimum of P_1.

The mth principle maximum of P_1,

for single wavelength (λ) $(a+b)\sin(\theta_m) = m(\lambda)$ ……….(1)

for multiple of wavelength ($\lambda+d\lambda$) $(a+b)\sin(\theta_m+d\theta_m) = m(\lambda+d\lambda)$ ……….(2)

The two lines are said to be just resolved if $\theta_m+d\theta_m$ corresponds to 1st minimum of 1st diffraction pattern which can be done by adding path difference of λ/N.

Therefore, equation (1) becomes,

$$(a+b)\,\mathrm{Sin}(\theta_m + d\theta_m) = m\lambda + \lambda/N \quad \text{………….(3)}$$

From equation (2) and (3), we get,

$$m(\lambda + d\lambda) = m\lambda + \lambda/N$$

$$\therefore\ m\lambda + md\lambda = m\lambda + \lambda/N$$

$$\frac{\lambda}{d\lambda} = mN \qquad \text{............(4)}$$

$$R.P. = mN$$

equation (4) shows R.P. of grating which proportional to m & N.

NEWTON'S RING

When a plano-convex lens with its convex surface is placed on a plane glass plate, an air film is formed between lower surface of lens and upper surface of plate. Thickness of the film gradually increases from the point of contact. If monochromatic light is allowed to fall normally on film, a system of alternate bright and dark concentric rings with central dark spot. Called as **"Newton's Rings"**

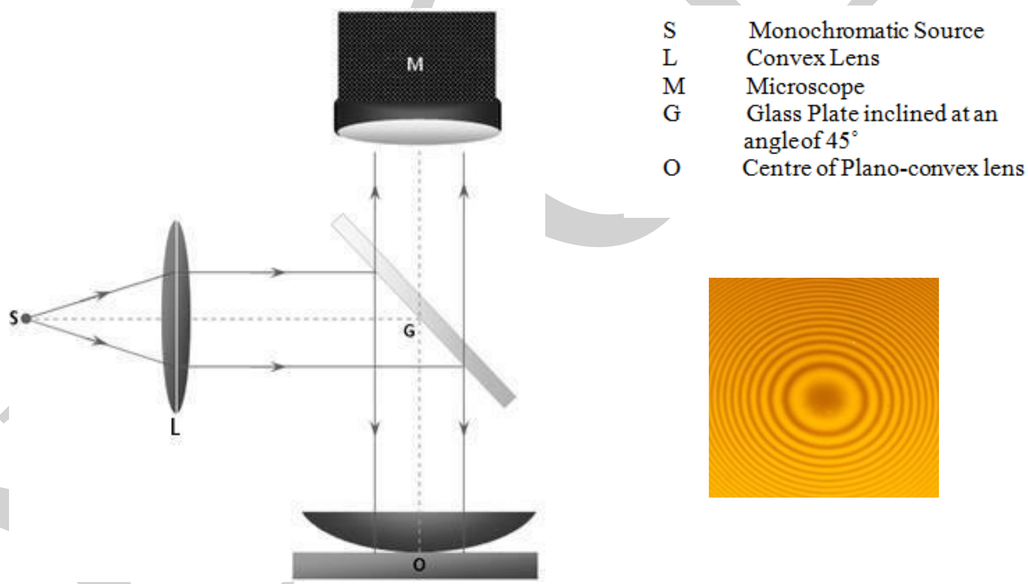


Figure-Experimental arrangement of the Newton's Ring apparatus

A parallel beam of monochromatic light is reflected towards the lens *L*. Consider a beam of monochromatic light strikes normally on the upper surface of the air film. The beam gets partly reflected and partly refracted. The refracted beam in the air film is also reflected partly at the lower surface of the film. The two reflected rays, i.e. produced at the upper and lower surface of the film, are coherent and interfere constructively or destructively. When the light reflected upwards is observed through microscope *M* which is focused on the glass plate, a pattern of dark and bright concentric rings are observed from the point of contact *O*. These concentric rings are known as ***Newton's Rings***.

- **Condition for Central dark, Maximum Intensity and Minimum Intensity using newton's ring**

1) Condition for central dark spot

In reflected light, the path difference between the two successive reflected rays are

$$D = 2\mu t \cos r + l / 2 \qquad (1)$$

For air film, refractive index (μ) to be 1, and at normal incidence, $i = r = 0$, hence eqn. (1) reduces to,

$$D = 2t \pm l / 2 \qquad (2)$$

At the point of contact of the lens and the glass plate (O), the thickness of the film is effectively zero i.e. $t = 0$

$$D = \pm l / 2 \qquad (3)$$

This is the condition for minimum intensity. Hence, the center of Newton rings generally appears dark.

2) Condition of maximum Intensity (Bright fringe)

$$\Delta = n\lambda$$

$$\therefore 2t + \lambda / 2 = n\lambda$$

$$\therefore 2 \mu t = (2n-1) \lambda / 2 \quad \textbf{(Maxima)}$$

3) Condition for minimum Intensity (Dark fringe)

$$\Delta = (2n+1)) \lambda / 2$$

$$\therefore 2t + \lambda / 2 = (2n+1) \lambda / 2$$

$$\therefore 2 \mu t = n \lambda \quad \textbf{(Minima)}$$

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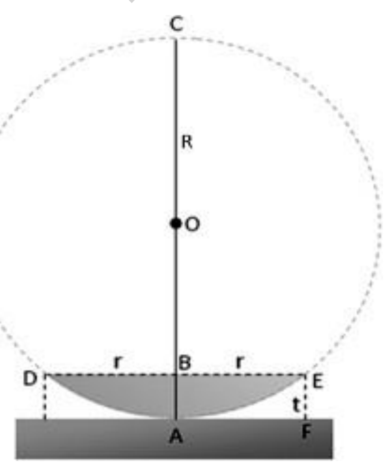
❖ **Diameter of Bright Rings:**



According to the geometrical theorem (i.e. property of the circle), the product of intercepts of the intersecting chord is equal to the product of sections of the diameter.

$$DB \times BE = AB \times BC \tag{4}$$

$$r \times r = t(2R - t) \tag{5}$$

$$r^2 = 2Rt - t^2 \tag{6}$$

Since t is very small hence t^2 will also be negligible, thus,

$$r^2 = 2Rt \tag{7}$$

$$t = \frac{r^2}{2R} \tag{8}$$

- ***Condition for a bright ring (constructive interference in thin film)***

$$2\mu t = (2n-1)\frac{\lambda}{2} \qquad \text{where } n = 1, 2, 3 \ldots.. \tag{9}$$

Putting eq. (8) in eq. (9) we get

$$2\mu\left(\frac{r^2}{2R}\right) = (2n-1)\frac{\lambda}{2} \tag{10}$$

Radius of the n^{th} bright ring becomes

$$r_n^2 = (2n-1)\frac{\lambda R}{2\mu} \tag{11}$$

Thus diameter of the n^{th} bright ring is

$$\left(\frac{D_n}{2}\right)^2 = (2n-1)\frac{\lambda R}{2\mu} \tag{12}$$

$$D_n^2 = 2(2n-1)\frac{\lambda R}{\mu} \tag{13}$$

$$D_n = \sqrt{2(2n-1)\frac{\lambda R}{\mu}} \tag{14}$$

If the medium considered is air, then $\mu = 1$ and eq. (14) simplifies to

$$D_n = \sqrt{2(2n-1)\lambda R} \tag{15}$$

$$D_n \propto \sqrt{(2n-1)} \qquad \text{where } n = 1, 2, 3 \ldots.. \tag{16}$$

Thus, diameter of the bright rings is proportional to the square root of odd natural numbers.

- ***Condition for a dark ring (destructive interference in thin film)***

$$2\mu t = n\lambda \qquad \text{where } n = 0, 1, 2, 3\ldots.. \tag{17}$$

Putting eq. (8) in eq. (17) we get

$$2\mu \frac{r^2}{2R} = n\lambda \tag{18}$$

Radius of the n^{th} dark ring becomes

$$r_n^2 = \frac{n\lambda R}{\mu} \tag{19}$$

Thus, diameter of the n^{th} dark ring is

$$\left(\frac{D_n}{2}\right)^2 = \frac{n\lambda R}{\mu} \tag{20}$$

$$D_n^2 = \frac{4n\lambda R}{\mu} \tag{21}$$

$$D_n = \sqrt{\frac{4n\lambda R}{\mu}} \qquad \text{where } n = 0, 1, 2, 3\ldots.. \tag{22}$$

If the medium considered is air then, $\mu = 1$ and eq. (22) simplifies to

$$D_n = \sqrt{4n\lambda R} \tag{23}$$

$$D_n \propto \sqrt{4n\lambda R} \qquad \text{where } n = 0, 1, 2, 3\ldots.. \tag{24}$$

Thus *diameter of the dark rings is proportional to the square root of the natural numbers*.

APPLICATIONS OF NEWTON'S RING

- **Determination of Wavelength of Monochromatic Light (λ)**

The diameter of the n^{th} dark ring is given by:

$$D_n^2 = 4n\lambda R \tag{25}$$

Similarly, the diameter of the $(n + p)^{th}$ dark ring is given by:

$$D_n^2 = 4(n + p)\lambda R \tag{26}$$

Subtracting eq. (25) from eq. (26), we get

$$\lambda = \frac{D_{n+p}^2 - D_n^2}{4pR} \qquad (27)$$

where, p is an integer.

- **Determination of Refractive Index of the Liquid (μ)**

The diameter of the nth dark ring in air film is given by

$$\left(D_n^2\right)_{air} = 4n\lambda R \qquad (28)$$

Similarly, the diameter of nth dark ring in liquid film is given by

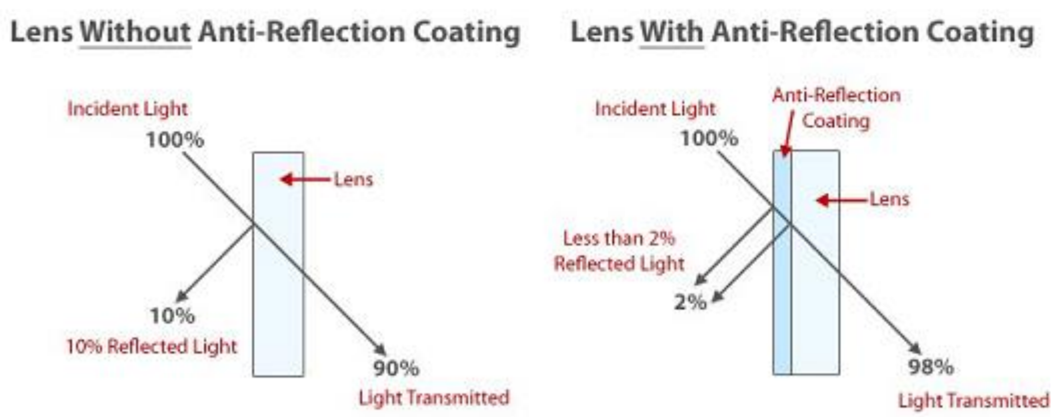
$$\left(D_n^2\right)_{liquid} = \frac{4n\lambda R}{\mu} \qquad (29)$$

Therefore, the Refractive Index of the Liquid is obtained as

$$\mu = \frac{\left(D_n^2\right)_{air}}{\left(D_n^2\right)_{liquid}} \qquad (30)$$

APPLICATION OF INTERFERENCE IN ANTI REFLECTIVE COATING

Antireflection coatings minimize the reflection of one or many wavelengths and are typically used on the surface of lenses so that less light is lost.



Anti-reflective coatings are used in a wide variety of applications where light passes through an optical surface, and low loss or low reflection is desired. Followings are some examples where the anti-reflecting coatings done.

- anti-glare coatings on corrective lenses (such as spectacles)
- Camera lens elements: Anti-reflective coatings are often used in camera lenses, to giving lens elements distinctive colours.
- antireflective coatings on solar cells
- Photolithography**:** Antireflective coatings (ARC) are often used in micro-electronic photolithography to help reduce image distortions associated with reflections off the surface of the substrate.
- Laptop Screen
- LCD and LED Screens
- Glasses of cars
- Spectacles, etc

* **Links for self-study**

1) https://sites.google.com/site/puenggphysics/home/Unit-II/thin-film-interference

2)http://hyperphysics.phy-astr.gsu.edu/hbase/phyopt/grating.html