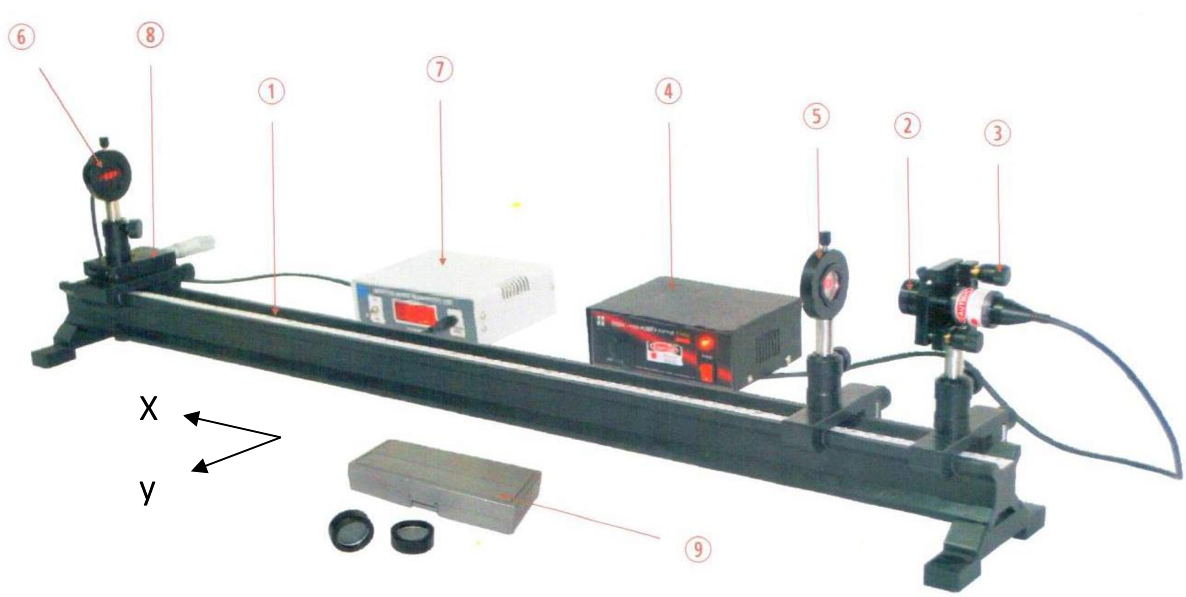
Diffraction of Light

Aim:

To observe the intensity patterns generated by the diffraction of a laser beam when passed through a single slit, a double slit and a pin-hole and to measure the sizes of these diffracting elements up to micro-meter (micron) scale accuracy. Due to time constraint, in the lab, you should **perform the experiments for the double slit and the pin-hole only**. Details are given later in the procedure section.

Apparatus:



1. Optical Rail
2. Diode Laser (wave length 650nm)
3. Kinematic Laser Mount
4. Power supply for laser
5. Cell mount with Diffraction cell
6. Pinhole detector
7. Output Measurement Unit
8. Linear translation stage
9. Slit Box

Figure 1. Experimental Set-up with part list **[Ref.1,2]**

Diffraction of Light

The device consists of a one meter long optical rail on which the light source (laser), the diffracting element (slit, hole or wire) and the photo detector which measures the intensity of the diffracted light, are mounted. Their locations along the rail (x) and perpendicular to the rail (y), in case of the detector, can be controlled with a precision of mm and micron, respectively.

Theoretical Background :

For many of the phenomena involving light, more generally electro magnetic waves, geometric optics is sufficient which relies on the observation that light travels in straight line. But when light rays are partially obstructed, for example, by an opaque screen with a circular aperture or a knife edge held on the path of light, the light rays tend to show some amount of bending around the obstacle which results in complex pattern of illuminated and dark spots on a screen located on further downstream. This is known as diffraction.

This bending of light can be explained by Huygen's principle (1678) which states that that every point on the wave front that arrives at the aperture acts as a source of spherical waves and these secondary waves interfere on the screen to generate the diffraction pattern (see Figure.2). This also requires that the width (d) of the aperture be only few times larger than the wave-length (λ) of the monochromatic light. If the distance between the diffracting obstacle and the screen (D) is large compared to the slit width (d) then the waves arrive at the screen as plane waves and creates Fraunhofer or far field diffraction pattern. When the distance is less one get the Fresnel or near field diffraction pattern. In this experiment we will be concerned with Fraunhofer patterns only.

1. Diffraction of light by single slit

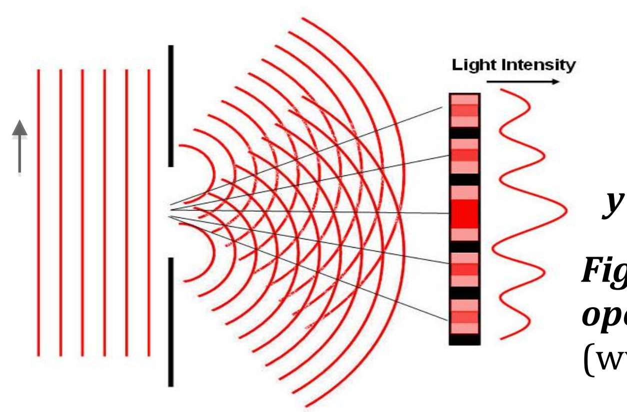


Figure 2. Each point on the slit opening generates spherical waves (www.cronodon.com)

Diffraction of Light

y

y3

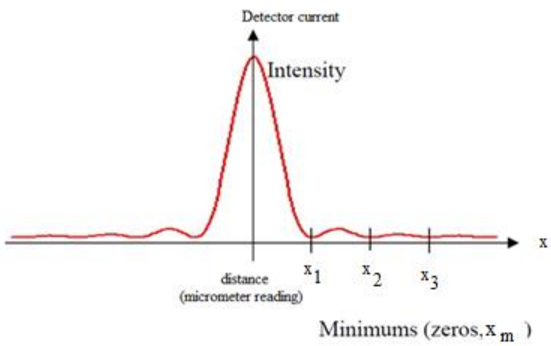


Figure 3. Intensity pattern on the screen

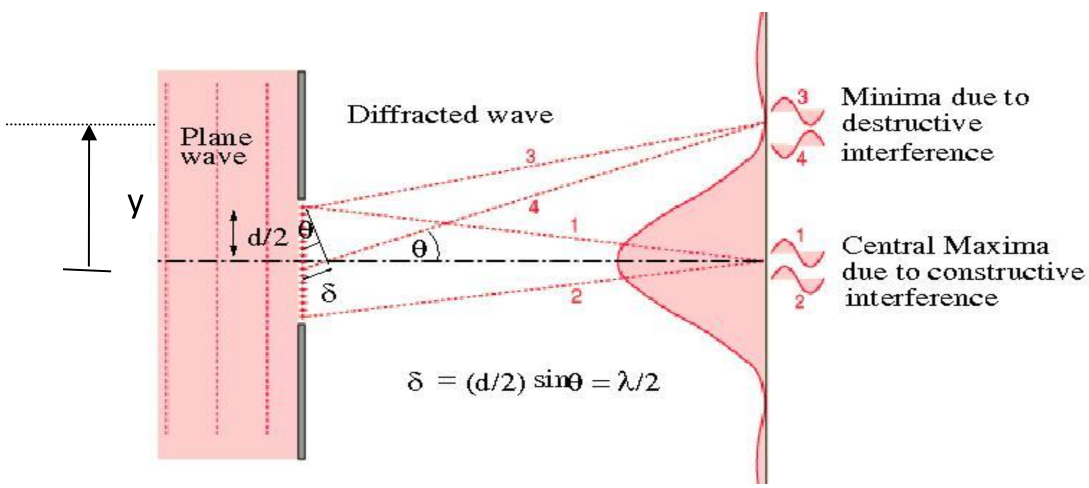


Figure 4. Location of the 1st minima corresponds to path difference
$\delta = \lambda / 2$.

Adapted from hyperphysics.phy-astr.gsu.edu

Using superposition principle one can derive that the intensity pattern on the screen should follow $I(\theta) = I_0 \left[\frac{\sin\beta}{\beta} \right]^2$, where $\beta = (\pi d / \lambda) \sin\theta$.

Diffraction of Light

From this expression it follows that the minima occur when $\beta_m = \pm m p$,$m = 1,2,..$ and correspondingly at angles $\theta_m = \pm\sin^{-1}(m\lambda / d)$. The central maxima occurs at $\theta = 0$ and the other maxima when $\beta_m = \pm(2\text{m}+1)\pi/2, m = 1,2,..$ occurs at $\theta_m = \pm\sin^{-1}[(2\text{m}+1)\lambda/2\text{d}]$. Note that m=0 is not a local maxima. Minimas and maximas are caused by destructive (for path difference of odd multiples of $\lambda/2$) and constructive interference (for path difference mλ) of the diffracted waves, respectively.

Thus from the positions of the **maxima,** we can find out the slit width using, **d = mλ/sin $\boldsymbol{\theta_m}$**, Experimentally, we measure θ_m by recording y_m , the y-positions of the minima, and then using the relation **tan $\boldsymbol{\theta_m = y_m/D}$.**

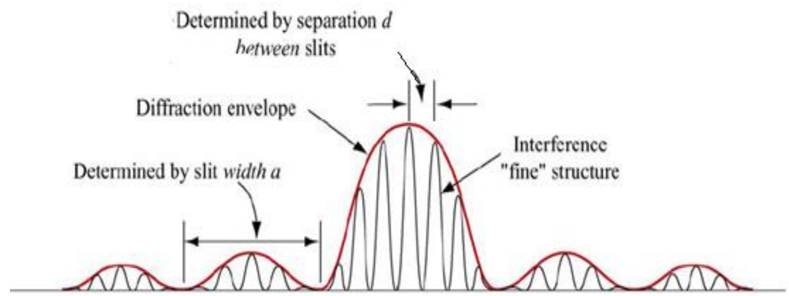
2. Diffraction of light by double slit

In the two slit interference, light from the laser hits two very narrow slits, which then act like in-phase point sources of light. When light waves are travelling from the slit to screen, both the waves are travelling different distance from two slits. As shown in Figure 5, light hitting point P from the bottom slit travels longer distance than the light from the top slit. This extra path introduces a phase shift between the two waves and leads to a position dependent interference pattern on the screen. Here the extra path is $\delta = d \sin\theta = \lambda$, which makes a phase shift $\varphi = 2\pi$.

Intensity pattern now follows $I(\theta) = I_0\cos^2\left[\frac{\pi d\sin\theta}{\lambda}\right]\left[\frac{\sin\beta}{\beta}\right]^2$, where $\beta = (\pi a/\lambda)\sin\theta$ and *a* is the width of each slit while *d* is their separation.

The phase shift that are even multiples π, gives constructive interference and odd multiples of π gives destructive interference. Therefore the conditions for maxima are $d \sin\theta = m\lambda$, and conditions for minima are $d \sin\theta = (m+(1/2))/\lambda$; where m = 0, ±1, ±2, ±3,…

Diffraction of Light



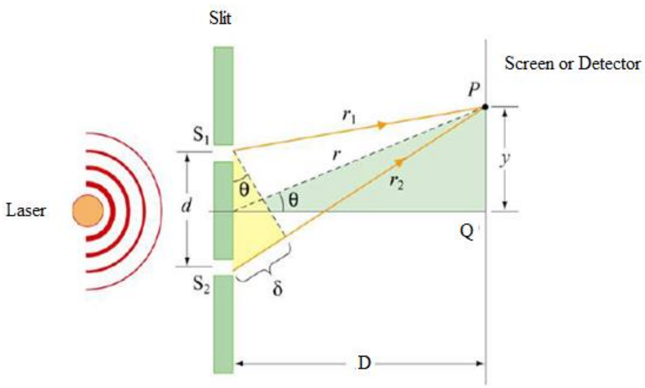


Figure 5. Location of the 1st maxima for shift $\delta = \lambda$

[Ref.3].   ***Figure 6. Diffraction pattern for double slit***

Here the diffraction envelope is set by the width of the slits a, while the individual wiggles are due to the interference between the light coming from the two different slits at separation d. Since here $d>a$, the locations of the minima are more closely packed here compared to the diffraction pattern of the earlier case, generated by a single slit of width a.

Thus from the positions of the **maxima** we can now find the slit separation, $\mathbf{d = m\lambda \; / \; \sin\theta_m}$

3. Diffraction of light by pinhole :

Diffraction of Light

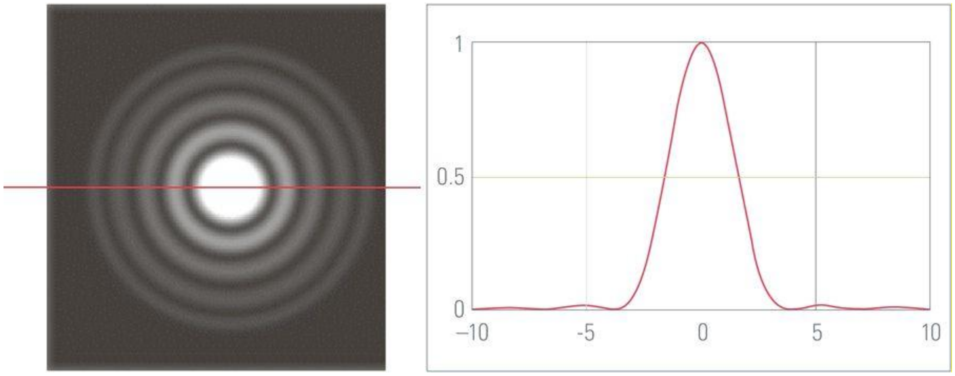
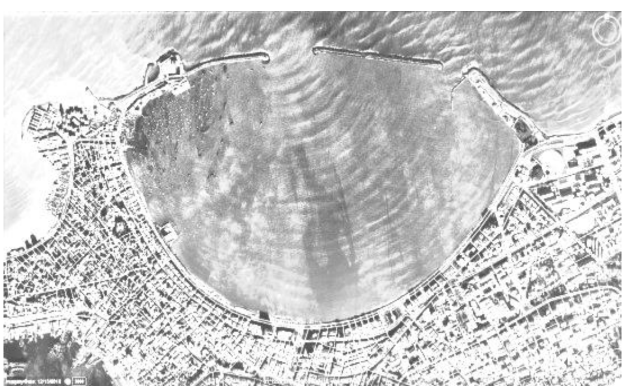


Figure 7. *Diffraction pattern for a pinhole and the corresponding intensity profile. The central bright disc is known as the Airy disc (en.wikipedia.com).*

Intensity pattern now follows $I(\theta) = I_0\left[\frac{2J_1(ka\sin\theta)}{ka\sin\theta}\right]^2$, where $k = 2\pi/\lambda$ and J_1 is the Bessel function of the first kind of order one. Bright rings appear around a central maxima, which is called the Airy disc (see Figure.7). Minima occurs at the zeros of J_1, at $ka\sin\theta = 3.83, 7.0156, 10.1735, \ldots\ldots$ We will focus on the 1st minima for which $\sin\theta = 1.22\lambda/2a$.

.



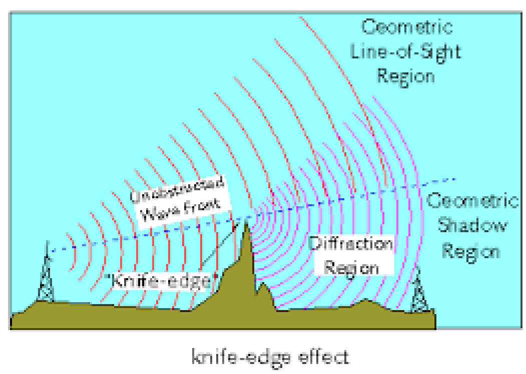


Fig.8. Left: *Diffraction of water waves at the opening of the port of Alexandria in Egypt (adapted from google earth).* ***Right:*** *Diffraction of radio waves from a tower (* www.atis.org)

Some interesting facts about diffraction

1. Babinet's principle: the diffraction pattern for a single slit of width d is same as that of a thin wire of width d. This can be explained by Babinet's principle: a slit and wire, when superposed, produce a completely opaque sheet which will produce a dark screen. This implies that the net electric

Diffraction of Light

field $\mathbf{E} = \mathbf{E}_{slit} + \mathbf{E}_{wire} = 0$ at the screen, which means $\mathbf{E}_{slit} = -\mathbf{E}_{wire}$, but since intensity $I \propto \vec{E}^2$ both slit and wire produce the same pattern, except at the centre.

2. In the near field Fresnel diffraction pattern, for a circular aperture, a central minima replaces the bright central Airy disc, characteristic of the far field pattern.

3. Diffraction limits the resolution of optical microscopes to 0.25 micron. The airy discs of two points closer than this will overlap and hence cannot be resolved.

Some applications

1. To determine the track width on a CD by reflecting laser light and measuring the diffraction pattern.
2. To measure the wavelength λ of the laser light using double slit width.
3. To measure thickness of fine fibers, eg, human hair.
4. To measure size of red blood cells.

1. Procedures for Single and double slit :

1. The laser, the pin-hole and the detector all are fixed on a rail and made co-linear, so that the laser beam in incident on the detector after passing through the slit.
2. Observe the diffraction pattern and adjust the distance between slit and detector *(D)* to get a sharp pattern. The detector shows maximum intensity (adjust for > 50 micro-Amp) when laser beam falls on the detector. This should correspond to detector position in the range 10-12mm on the circular scale. Also measure *D*.
3. 1st scan the diffraction pattern (of varying intensity) by turning the circular scale. When you actually take readings turn the circular scale in

one direction only and go from one end of the pattern to the other across the central maxima. Do not move back and forth which will generate backlash error.

Experimental set up and the measured quantities are same for both single and double slit cases, except that while we need to **locate the maxima in the double slit case** we need the minima in the single slit case.

Data and analysis for double slit : Record current (microA) versus detector position (millimeter). While recording positions show, **a) the main scale, b) the Vernier scale and c) the net readings. Plot current versus position,** showing current on the y-axis. From the graph identify total **five maxima** : the central one and two each, on both sides of the central maxima. Try to use **not more than 30 points** to cover all the 5 maxima. Compute the slit separation d using the distance between the central maxima and the side maxima. Compute **average d and its error** (standard deviation) and present it as $d \pm \Delta d$, keeping only **significant digits.** Since the angles θ_m are small gap between successive maxima are almost same. So you can, alternatively, use these gaps in the formula for m=1 to get corresponding θ_1 and then use average θ_1 and its error to compute $d \pm \Delta d$.

2. Procedure for pin-hole :

1. Set the position of the detector between 10-12mm mark so that you can detect intensity along both +y & -y covering the whole diameter of the ring.

2. Align all three: laser source, pinhole and detector on the rail (adjust along both x & y) such that the maximum intensity at the centre of the rings be high enough (> 50 microA). Larger the distance between the pinhole & the detector, bigger the rings and clearer are the spacings between the rings, but lesser is the intensity. So strike a balance. Suggested distance is 30-50cm. The intensity along the peripheri of the circular rings may not be uniform due to imperfections of the pin-hole; for better clarity you can rotate the hole so that the ring boundary is sharp along the horizontal direction along which you will detect the intensity.

Diffraction of Light

Data and analysis for pin-hole : Record the positions of the **central maxima and the 1st minima** on both sides of it. Do not use more than **10 points** to scan the intensity profile. The measurement intervals need not be equal; regions near the minima and maxima should be relatively better sampled. Using the distance between the central maxima and the 1st minima compute the diameter of the Airy disc and then compute the aperture diameter. **Intensity plot and error estimate are not needed**.

Safety instructions

1. Laser radiation predominantly causes injury via thermal effects; **avoid looking directly into the laser beam. The beam of laser source is so intense that it can cause damage to retina. Do not shine them on others or on yourself.**
2. Care should be taken while handling diffraction slits and the other components.
3. Do not touch the inner surface of diffraction cell.
4. Avoid backlash error while moving the micrometer scale on the detector.

Appendix:

Least count = (Smallest div on Main Scale) / (No. of div on circular scale)

= 0.05 cm /50 = 0.001 cm

Micrometer reading = Main scale reading + (number of div. on circular scale x L.C.)

References:

1. HOLMARC opto –Mechanics Pvt. Ltd Instruction manual for Detection based Diffraction Experiments Model: HO-EQ-D-02.
2. website for HOLMARC opto –Mechanics Pvt. Ltd http://www.holmarc.com/differ_detector.php , accessed on June 2015

3. Department of Physics, Massachusetts Institute of Technology," Expt. No. 9. Interference and diffraction". ocw.mit.edu/courses/physics/8-02-physics...spring.../experiment9.pdf, accessed on June 2015

4. Abbei Tippie, Tammy Lee "experiments with Diffraction", Rochester Education www.optics.rochester.edu/workgroups/.../EDay2008_Diffraction.pdf ,accessed on June 2015