PH 301

ENGINEERING OPTICS

Lectures_1-3

Syllabus

Lens systems: Basics & concepts of lens design, some lens systems.
Optical components: Reflective, refractive & diffractive systems; Mirrors, prisms, gratings, filters, polarizing components.
Interferometric systems: Two beam, multiple beam, shearing, scatter fringe & polarization interferometers.
Vision Optics: Eye & vision, colorimetry basics.
Optical sources: Incandescent, fluorescent, discharge lamps, Light emitting diode.
Optical detectors: Photographic emulsion, thermal detectors, photodiodes, photomultiplier tubes, detector arrays, Charge-coupled device, CMOS.
Optical Systems: Telescopes, microscopes (bright field, dark field, confocal, phase contrast, digital holographic), projection systems, interferometers, spectrometers.
Display devices: Cathode ray tube, Liquid crystal display, Liquid crystals on silicon, Digital light processing, Digital micro-mirror device, Gas plasma, LED display, Organic LED.
Consumer devices: Optical disc drives: CD, DVD; laser printer, photocopier, cameras, image intensifiers.

Texts

1. R. S. Longhurst, *Geometrical & Physical Optics*, 3rd ed., Orient Longman, 1988.
2. R. E. Fischer, B. Tadic-Galeb, & P. R. Yoder, *Optical System Design*, 2nd ed., SPIE, 2008
3. W. J. Smith, *Modern Optical Engineering*, 3rd ed., McGraw Hill, 2000.
4. K. Iizuka, *Engineering Optics*, Springer, 2008.
5. B. H. Walker, *Optical Engineering Fundamentals*, SPIE Press, 1995.

Engineering Optics

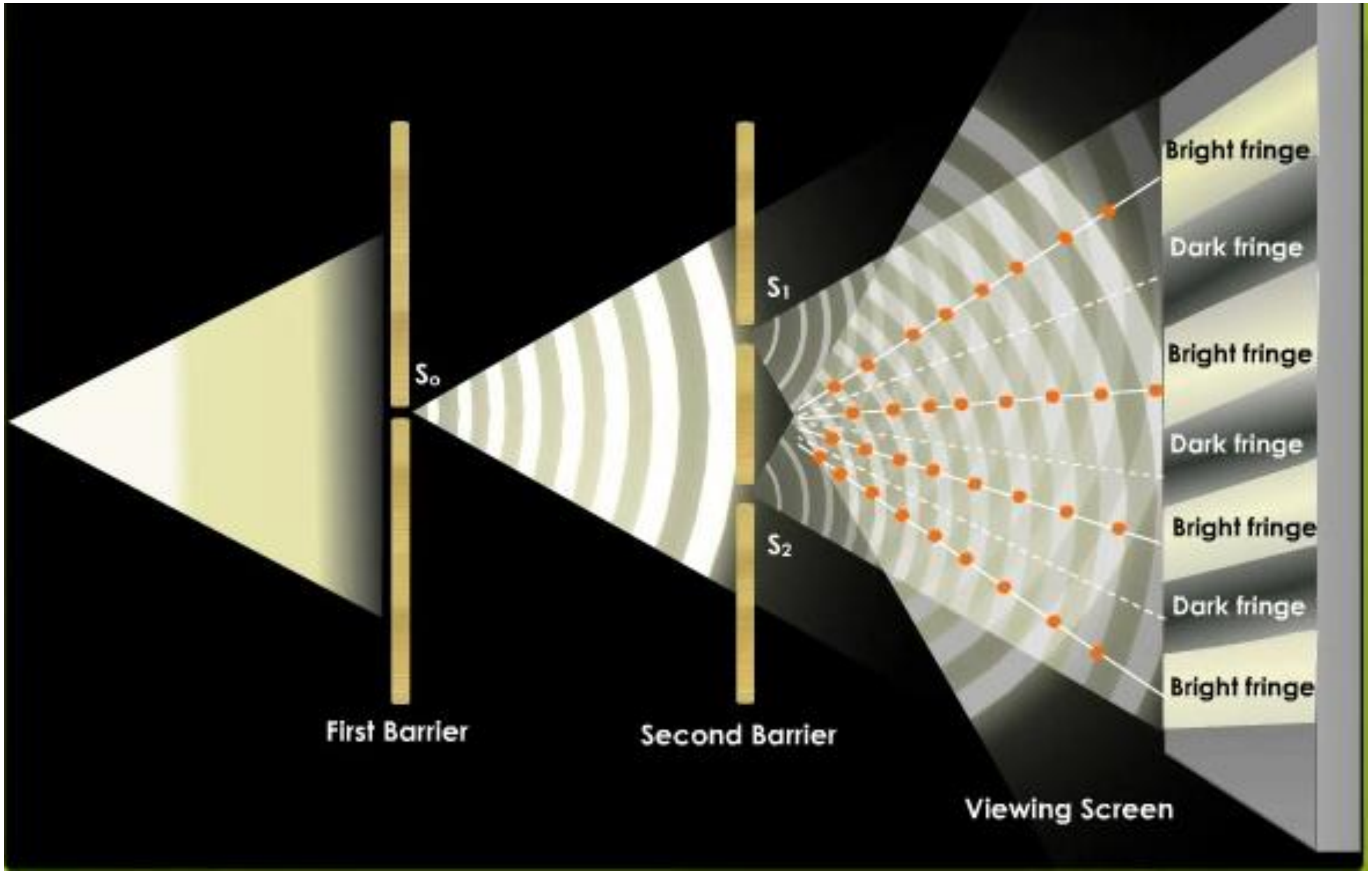
Engineering Optics deals with the engineering aspects of optics, & its main emphasis is on applying the knowledge of optics to the solution of engineering problems.

Optical phenomena

- Interference
- Diffraction
- Polarization

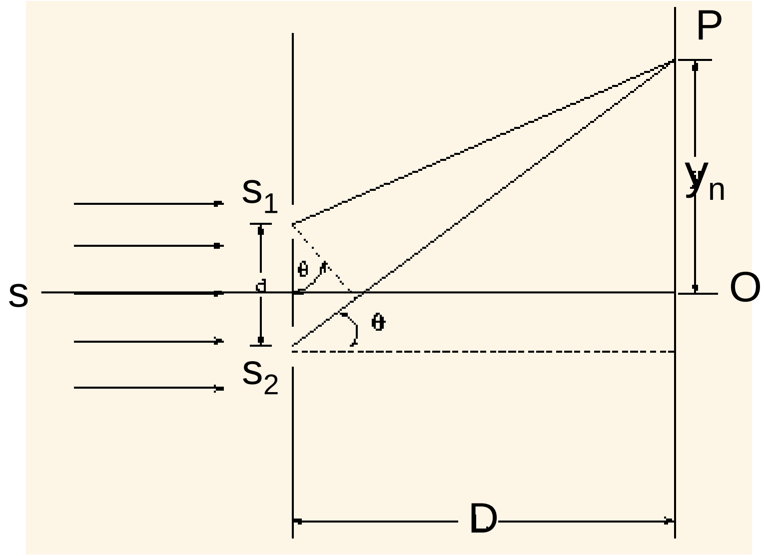
Young's Experiment

(1801)



Young's Experiment

Two light rays pass through two slits, separated by a distance *d* & strike a screen a distance *D*, from slits. Interference pattern consists of a series of dark & bright lines perpendicular to plane of Figure.



$$S_1S_2 = d, \qquad OP = y_n$$

For an arbitrary point *P* to correspond to a maximum

$$S_2P - S_1P = n\lambda; \qquad n = 0,1,2,\ldots$$

$$(S_2P)^2 - (S_1P)^2 = [D^2 + (y_n + d/2)^2] - [D^2 + (y_n - d/2)^2]$$

$$= 2y_n d$$

$$S_2P - S_1P = \frac{2y_n d}{S_2P + S_1P}$$

If y_n, d << D then negligible error will be introduced if $S_2P + S_1P \sim 2D$.

Ex. d = 0.02 cm; D = 50 cm; OP = 0.5 cm

$S_2P + S_1P$ = 100.005 cm

Error = 0.005 % Negligible

$$S_2P - S_1P = \frac{2y_n d}{2D} = \frac{y_n d}{D}$$

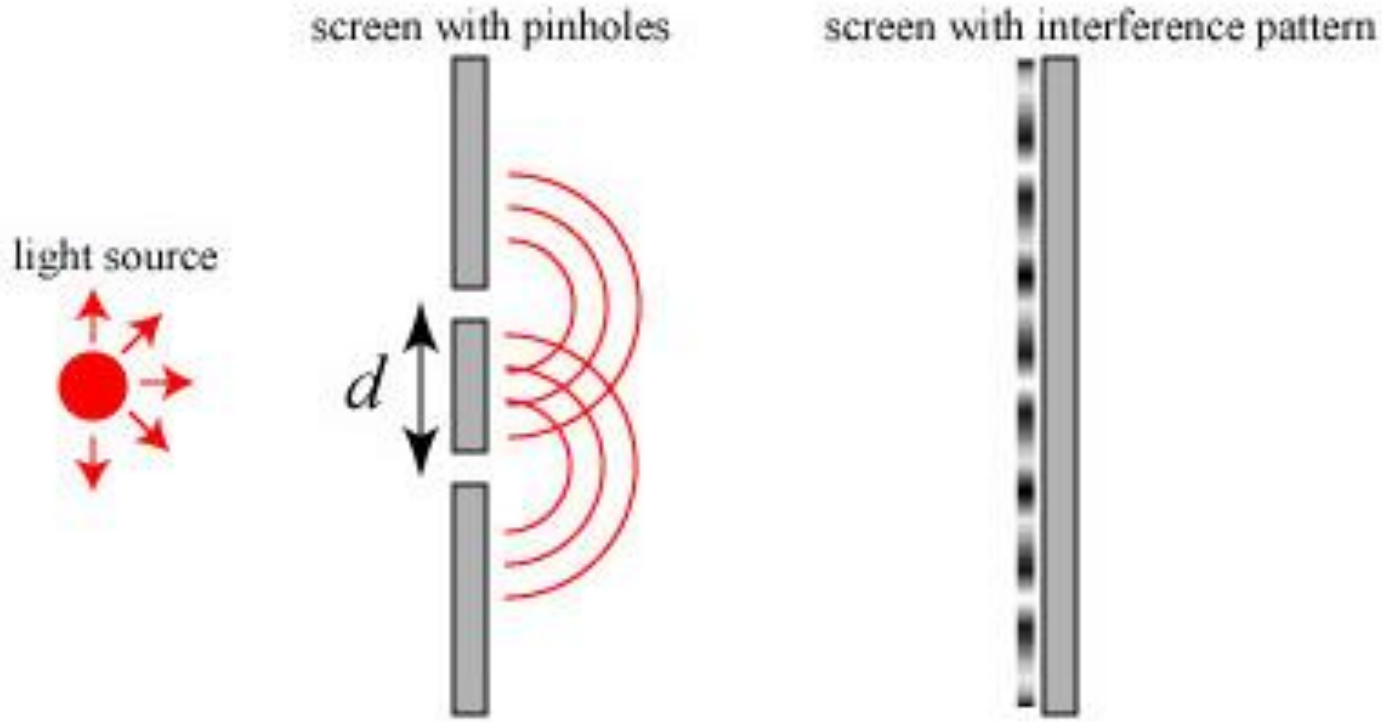
$$y_n = \frac{n\lambda D}{d}$$

Thus dark & bright fringes are equally spaced & distance between two consecutive dark (or bright) fringes is

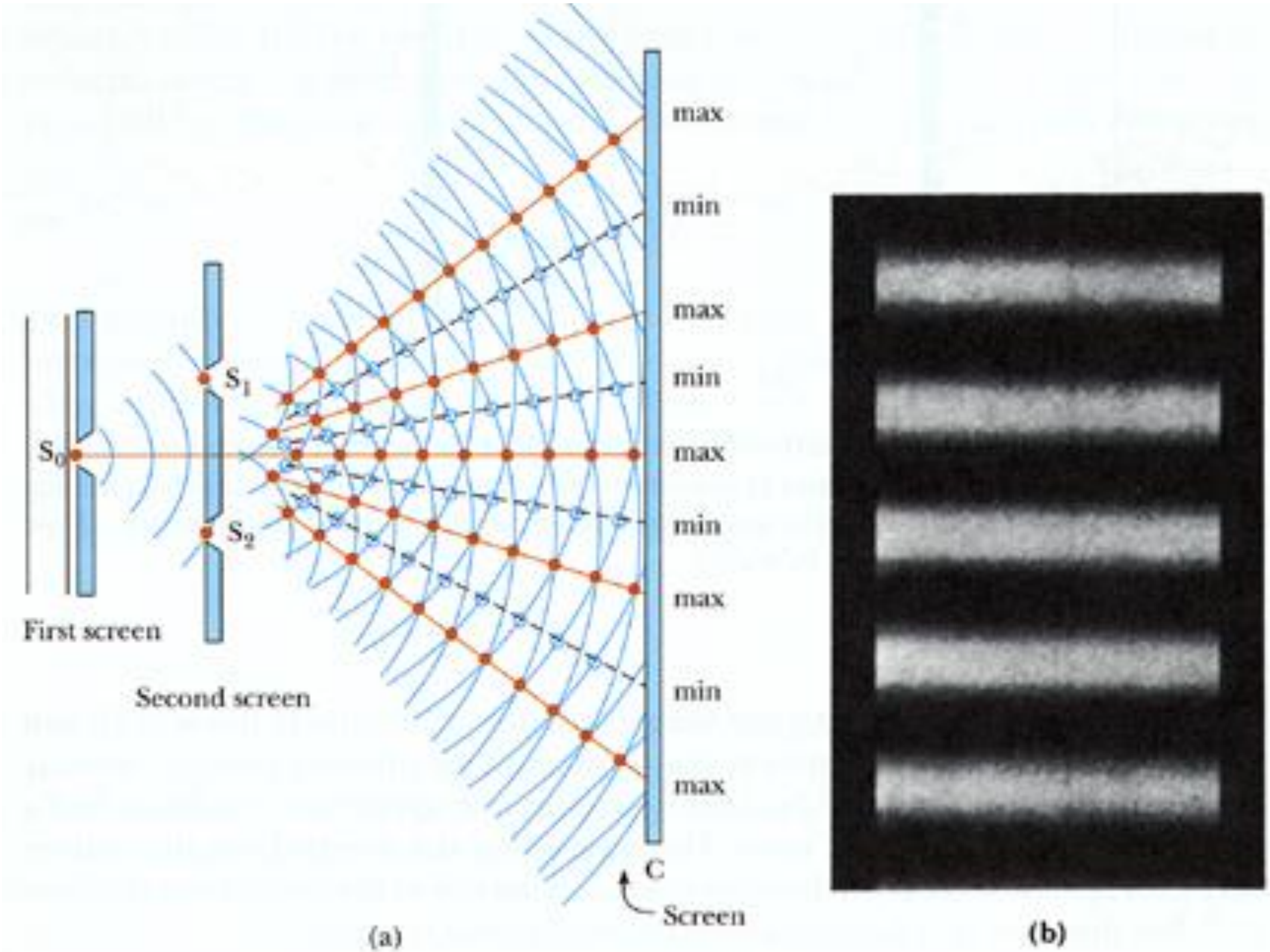
$$\beta = y_{n+1} - y_n = \frac{(n+1)\lambda D}{d} - \frac{n\lambda D}{d}$$

$$\beta = \frac{\lambda D}{d}$$

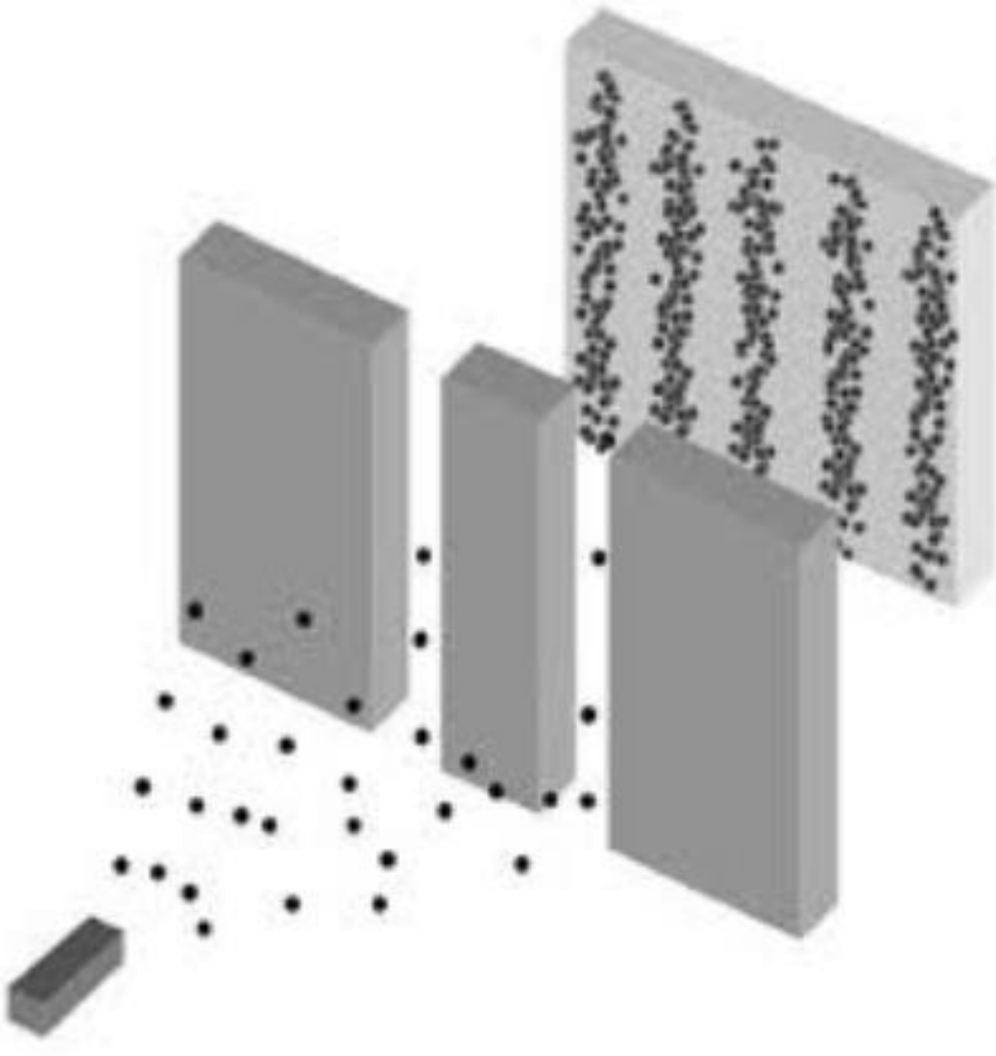
Expression for fringe width


screen with pinholes
screen with interference pattern
light source
d

Young's Double Slit Experiment



Young's Double Slit Experiment



Displacement of fringes

2.30 DISPLACEMENT OF FRINGES

If a thin glass or mica strip or any other transparent plate of uniform thickness is introduced in the path of one of the two interfering beams from two coherent sources, then central bright fringe will be displaced. This displacement from C to C_0 will be towards the side of lamina. This is due to the fact that beam is retarded due to lesser velocity of light in a denser medium such as glass or mica.

In order to calculate the displacement, we shall find the path difference between two beams, from coherent sources S_1 and S_2, at any point P on the screen. P is at a distance y from central point C. Let t be the thickness of sheet or strip and μ the refractive index of its material.

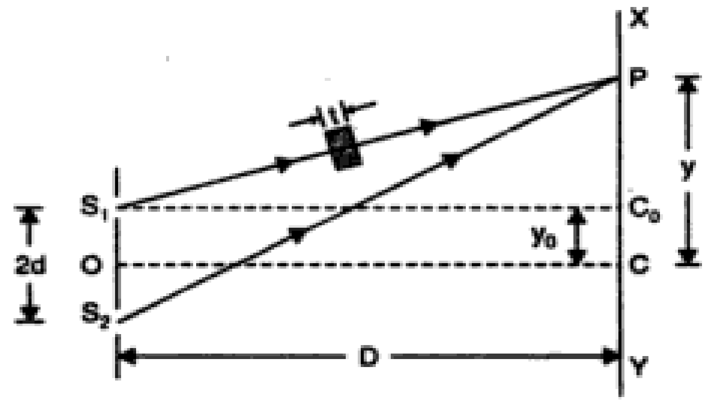


Fig. 2.27. Displacement of fringes.

Time T taken by the beam to reach from S_1 to P is given by

$$T = \frac{S_1P - t}{c} + \frac{t}{v}$$

where c is the velocity of light in air and v is the velocity of light in the medium of the plate.

or

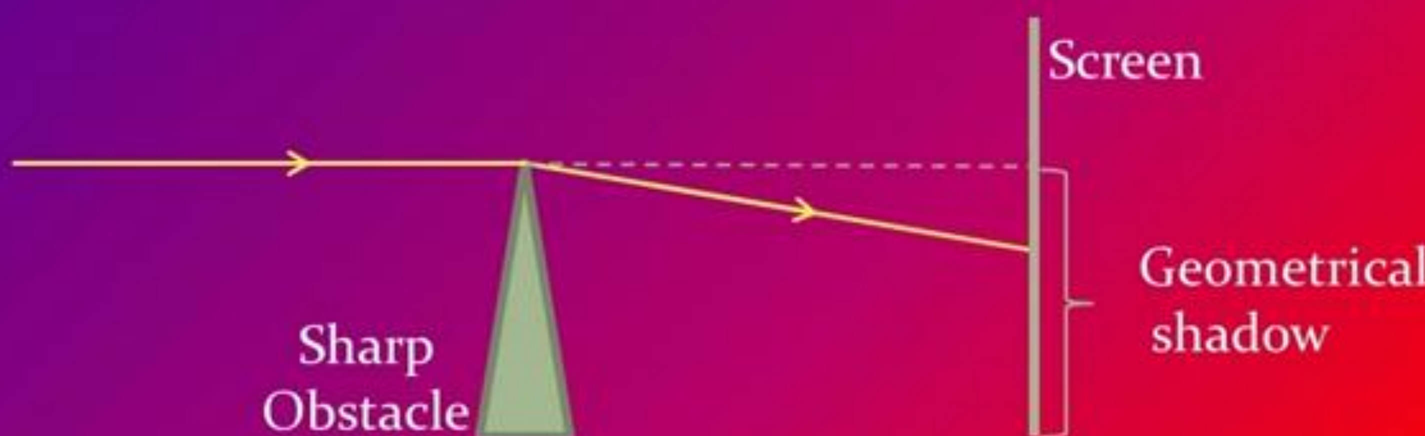
$$T = \frac{S_1P - t}{c} + \frac{\mu t}{c} \qquad \left(\because \quad \mu = \frac{c}{v}\right)$$

$$= \frac{S_1P - t + \mu t}{c} = \frac{S_1P + (\mu - 1)t}{c}$$

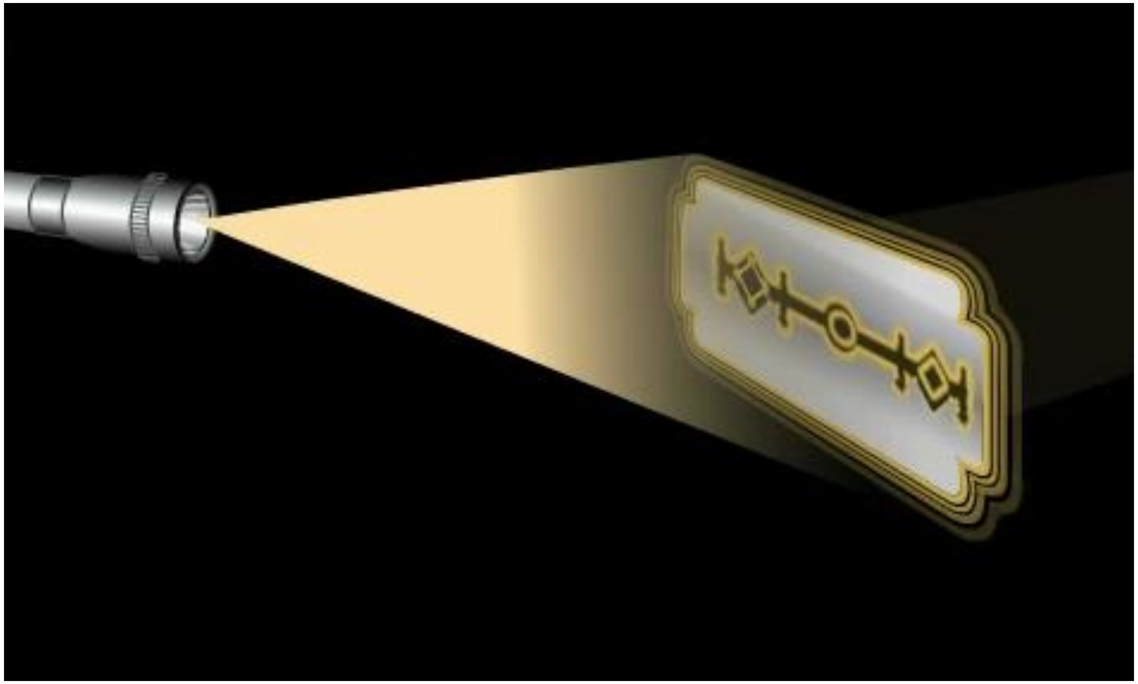
Diffraction

Tracks of a *CD* act as a diffraction grating, producing a separation of colors of white light. Nominal track separation on a *CD* is 1.6 *μm*, corresponding to about 625 tracks per mm. For λ = 600 *nm*, this would give a first order diffraction maximum at about 22º.

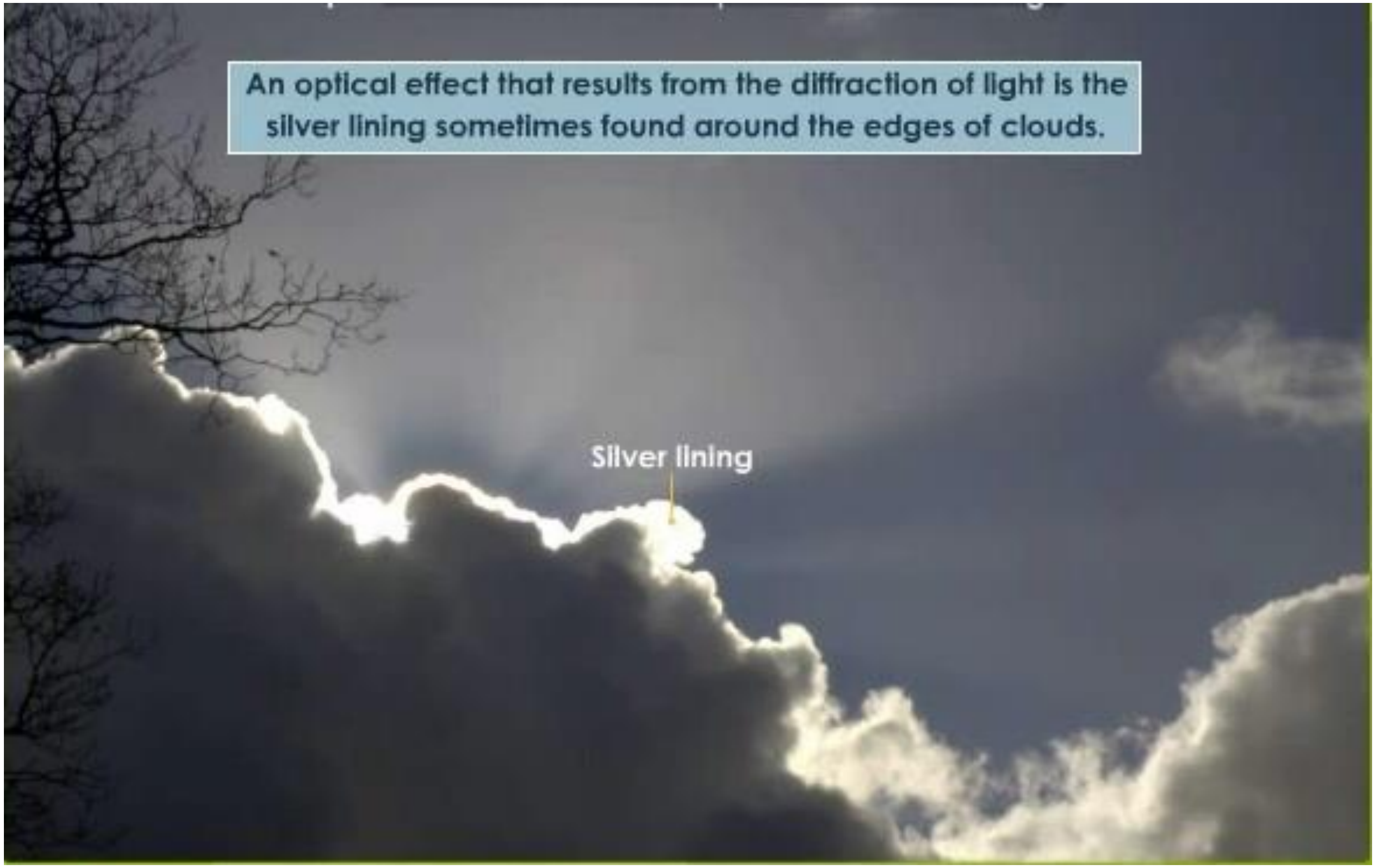
Bending of light across the edges of an obstacle is called as diffraction.

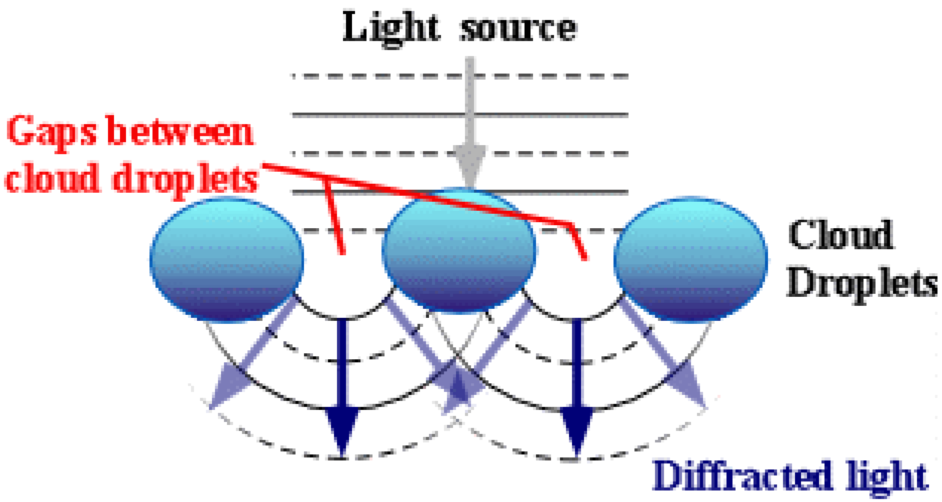


Diffraction



Diffraction




Light source
Gaps between
cloud droplets
Cloud
Droplets
Diffracted light

Diffraction

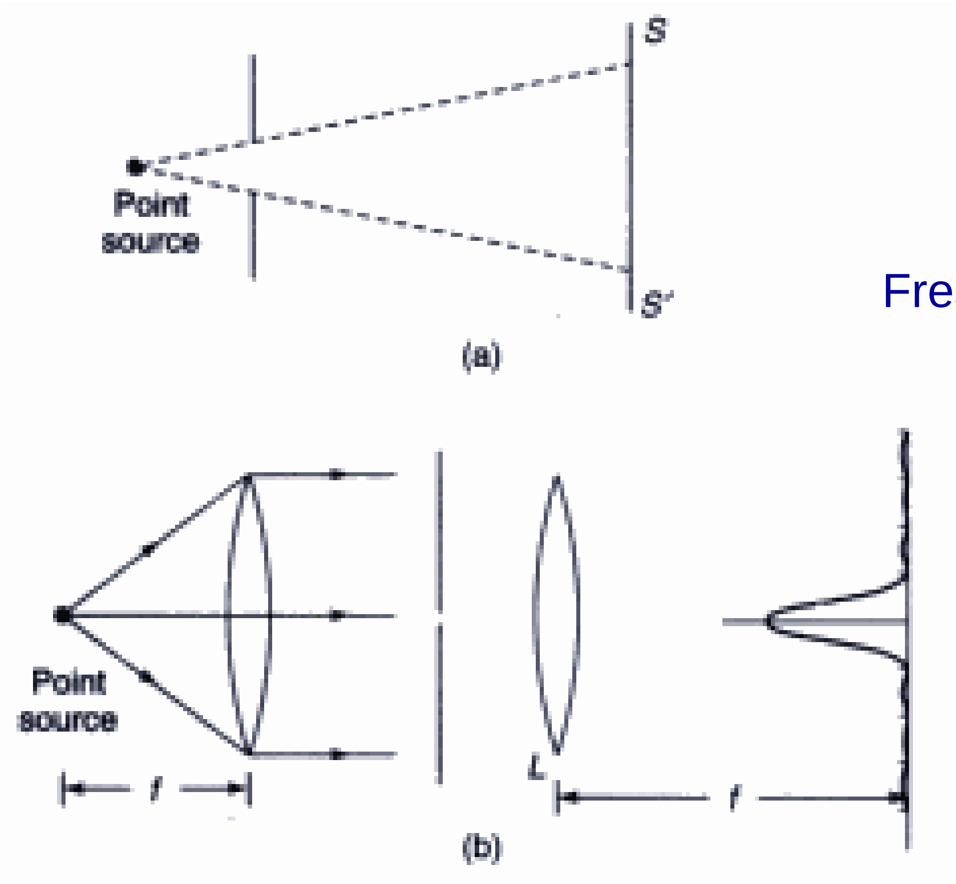
Interference corresponds to situation when we consider superposition of waves coming out from a number of point sources &

Diffraction corresponds to situation when we consider waves coming out from an area source like a circular or rectangular aperture or even a large no. of rectangular apertures (like diffraction grating).

Diffraction phenomena are usually divided into two categories:

Fresnel diffraction: Source of light & screen are at a finite distance from diffracting aperture.

Fraunhofer diffraction: Source & screen are at infinite distances from aperture. This is easily achieved by placing source on the focal plane of a convex lens & placing screen on the focal plane of another convex lens.

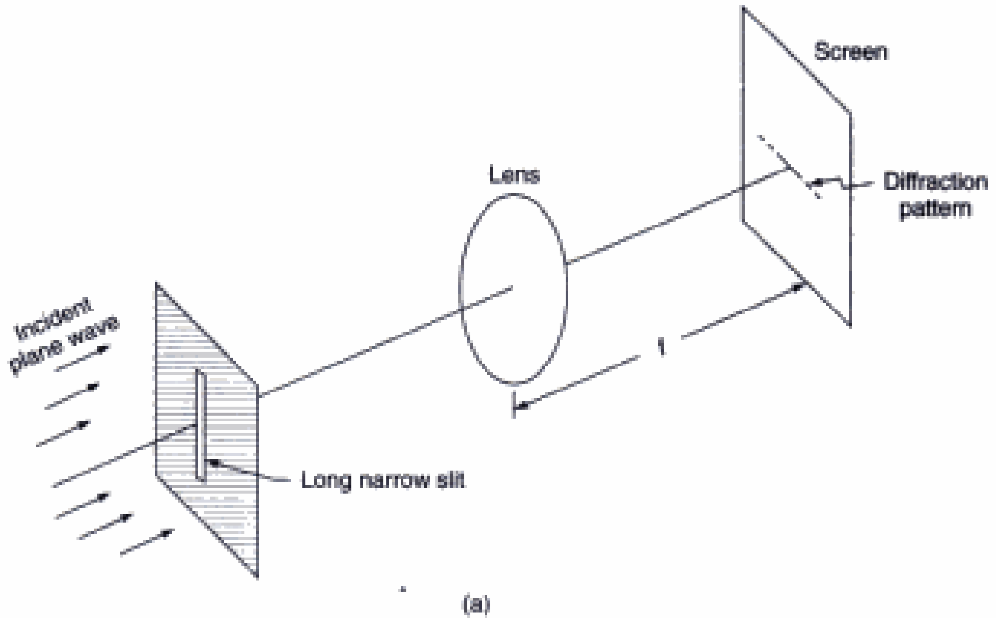


Fresnel diffraction

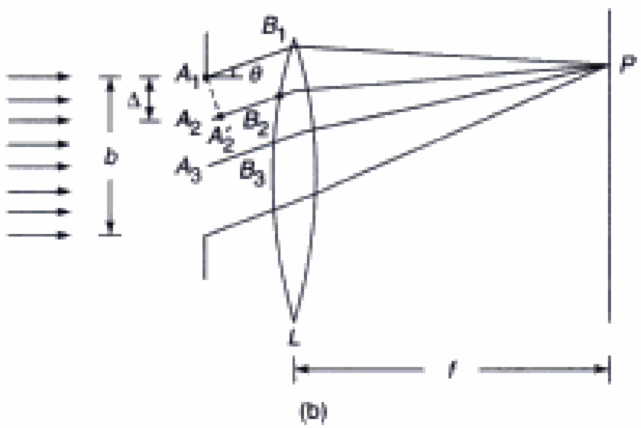
Fraunhofer diffraction

Single-slit diffraction pattern

A slit is a rectangular aperture of length large compared to its breadth.



Diffraction of a plane wave incident normally on a long narrow slit of width *b*. Spreading occurs along width of the slit.



In order to calculate diffraction pattern, slit is assumed to consist of a large no. of equally spaced points.

Assume, slit consists of a large no. of equally spaced point sources & that each point on slit is a source of Huygens' secondary wavelets which interfere with wavelets emanating from other points.

Let point sources be at A_1, A_2, A_3, ….. And let distance between two consecutive points be Δ. Thus, if no. of point sources be n, then

$$b = (n-1)\Delta$$

At P, amplitudes of disturbances reaching from A_1, A_2, A_3, ….. will be very nearly same because point P is at a distance which is very large in comparison to b.

However, because of even slightly different path lengths to P, field produced by A_1 will differ in phase from field produced by A_2. If diffracted rays make an angle θ with normal to the slit then path difference would be

$$A_2A_2' = \Delta \sin\theta \qquad \phi = \frac{2\pi}{\lambda}\Delta \sin\theta$$

If field at *P* due to disturbances emanating from A_1 is *acosωt* then field due to disturbances emanating from A_2 would be *acos*(*ωt*-*Φ*).

Resultant field

$$E = a[\cos\omega t + \cos(\omega t - \phi) + \ldots\ldots\ldots\ldots + \cos(\omega t - (n-1)\phi)]$$

$$\cos\omega t + \cos(\omega t - \phi) + \ldots\ldots\ldots\ldots + \cos(\omega t - (n-1)\phi)$$

$$= \frac{\sin n\phi/2}{\sin\phi/2}\cos[\omega t - \frac{1}{2}(n-1)\phi]$$

$$E = E_0 \cos[\omega t - \frac{1}{2}(n-1)\phi]$$

$$E_0 = a\frac{\sin n\phi/2}{\sin\phi/2}$$

$$\textit{In the} \lim \textit{it} \quad n\to\infty, \quad \Delta\to 0, \quad \textit{such that} \quad n\Delta\to b$$

$$\Rightarrow \frac{n\phi}{2} = \frac{\pi}{\lambda} n\Delta\sin\theta = \frac{\pi}{\lambda} b\sin\theta$$

$$E_0 = \frac{a\sin(n\phi/2)}{\phi/2} = \frac{na\sin\left(\frac{\pi b\sin\theta}{\lambda}\right)}{\pi b(\sin\theta)/\lambda} = A\frac{\sin\beta}{\beta}$$

$$A = na; \quad \beta = \frac{\pi b\sin\theta}{\lambda}$$

$$E = A\frac{\sin\beta}{\beta}\cos(\omega t - \beta)$$

$$\textit{Corresponding} \text{ int } \textit{ensity}$$

$$I = I_0\frac{\sin^2\beta}{\beta^2} \qquad I_0 \textit{ represents} \text{ int } \textit{ensity at } \theta = 0$$

Positions of Maxima & Minima

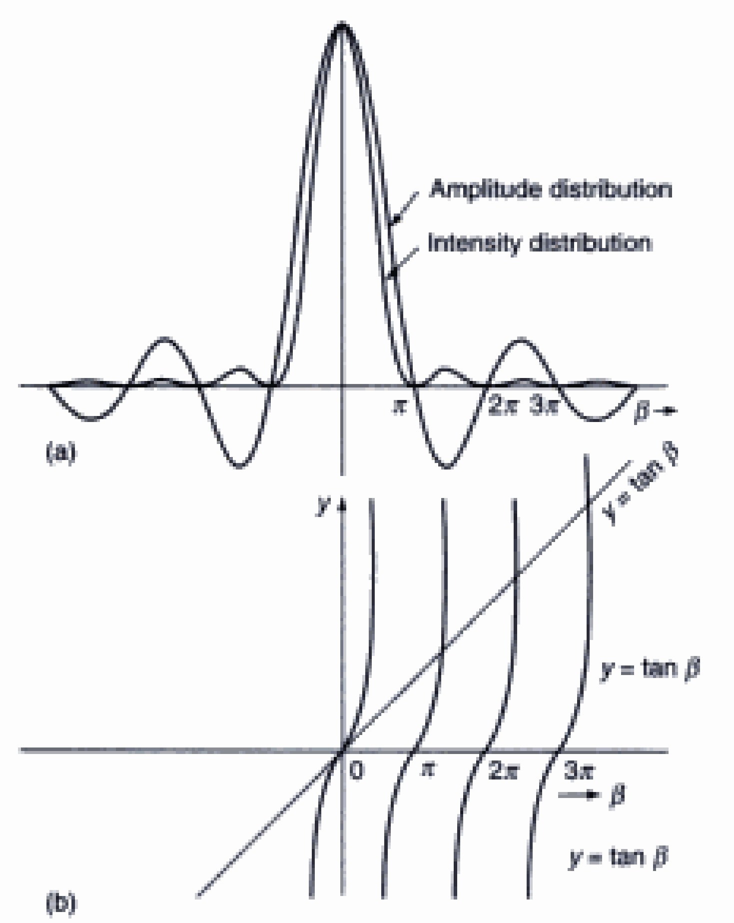
$$I = 0, \quad when \quad \beta = m\pi, \quad m \neq 0$$

$$When \quad \beta = 0, \quad \frac{\sin\beta}{\beta} = 1 \qquad \Rightarrow I = I_0$$

$$\Rightarrow b\sin\theta = m\lambda; \qquad m = \pm 1, \pm 2, \pm 3, \ldots\ldots (Minima)$$

$$I_{\min}\ \theta = \pm\sin^{-1}(\lambda / b)$$

$$II_{\min}\ \theta = \pm\sin^{-1}(2\lambda / b)$$



Intensity distribution corresponding to single slit diffraction pattern.

Graphical method for determining roots of Eq.

tanβ = β.

To determine positions of maxima, we differentiate intensity distribution with respect to β & set it equal to zero.

$$I = I_0 \frac{\sin^2 \beta}{\beta^2}$$

$$\frac{dI}{d\beta} = I_0 \left[\frac{2\sin\beta\cos\beta}{\beta^2} - \frac{2\sin^2\beta}{\beta^3} \right] = 0$$

$$\Rightarrow \sin\beta[\beta - \tan\beta] = 0$$

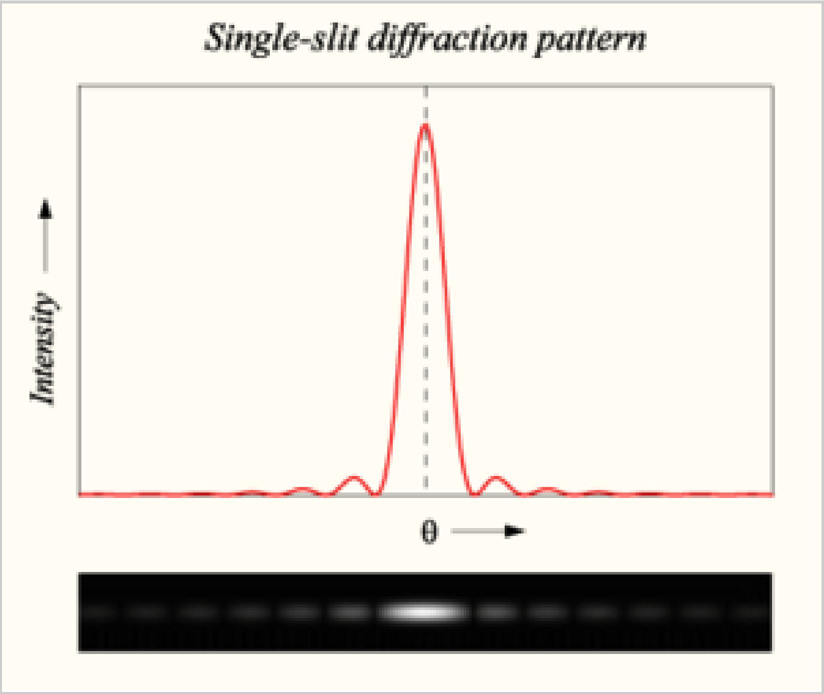
Condition $\sin\beta = 0$, or $\beta = m\pi$ ($m \neq 0$) correspond to minima. Conditions for maxima are roots of following Eqn.

$\tan\beta = \beta$ **(Maxima)**

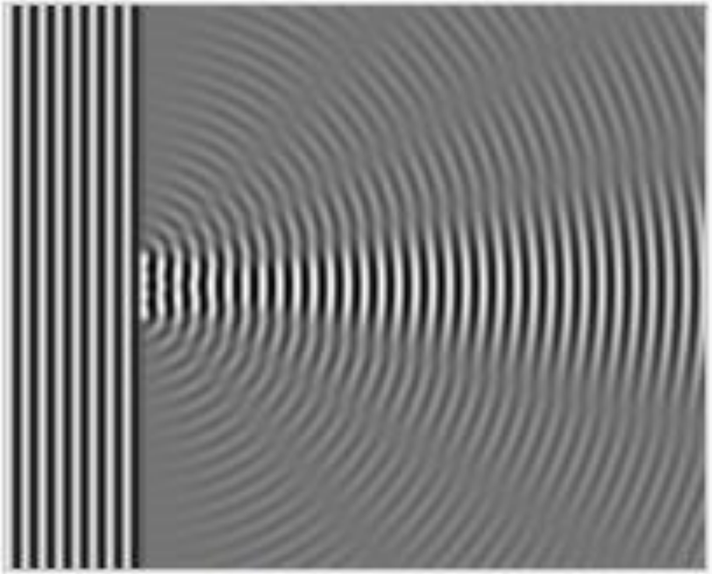
Root $\beta = 0$ corresponds to central maximum & other roots can be found by determining points of intersections of curves ***$y = \beta$*** & ***$y = \tan\beta$***. Intersections occur at $\beta = 1.43\pi$, $\beta = 2.46\pi$, etc. & are known as first maximum, second maximum, etc. Since

$$\left[\frac{\sin(1.43\pi)}{1.43\pi} \right]^2$$

is about 0.0496, intensity of 1st maximum is about 4.96% of central maximum. Similarly, intensities of 2nd & 3rd maxima are about 1.68% & 0.83% of central maximum respectively.



Graph and image of single-slit diffraction



Single-slit diffraction pattern

Two-slit Fraunhofer diffraction pattern

Fraunhofer diffraction pattern produced by two parallel slits (each of width *b*) separated by a distance *d*. **Resultant intensity is a product of single-slit diffraction pattern & interference pattern produced by two point sources separated by a distance *d*.**

Assume that slits consist of a large no. of equally spaced point sources & that each point on slit is a source of Huygens' secondary wavelets. Let point sources be at A_1, A_2, A_3, ….. (1st slit) & at B_1, B_2, B_3, ……(2nd slit). Assume distance between two consecutive points in either of slits is Δ.

If diffracted rays make an angle θ with normal to plane of slits, then path difference between disturbances reaching P from two consecutive points in a slit will be $\boldsymbol{\Delta \sin\theta}$.

Field produced by first slit at *P*

$$E_1 = A\frac{\sin\beta}{\beta}\cos(\omega t - \beta)$$

Similarly, second slit will produce a field at *P*

$$E_2 = A\frac{\sin\beta}{\beta}\cos(\omega t - \beta - \phi_1) \qquad \phi_1 = \frac{2\pi}{\lambda}d\sin\theta$$

Resultant field

$$E = E_1 + E_2 = A\frac{\sin\beta}{\beta}[\cos(\omega t - \beta) + \cos(\omega t - \beta - \phi_1)]$$

This represents interference of two waves, each of amplitude $A(\sin\beta)/\beta$ & differing in phase by Φ_1.

$$E = A\frac{\sin\beta}{\beta}\cos\gamma\cos(\omega t - \frac{1}{2}\beta - \frac{1}{2}\phi_1)$$

$$\gamma = \frac{\phi_1}{2} = \frac{\pi}{\lambda}d\sin\theta$$

$$\Rightarrow I = 4I_0\frac{\sin^2\beta}{\beta^2}\cos^2\gamma$$

$I_0(\sin^2\beta)/\beta^2$ represents intensity distribution produced by one of the slits.

Intensity distribution is a product of two terms;

1st term ($\sin^2\beta)/\beta^2$ represents diffraction pattern produced by a single slit of width b &

2nd term ($\cos^2 \gamma$) represents interference pattern produced by two point sources separated by a distance d.

If slit widths are very small (so that there is almost no variation of $\sin^2\beta/\beta^2$ term with θ) then one simply obtains Young's interference pattern.

Positions of Maxima & Minima

Intensity is zero whenever **$\beta = \pi, 2\pi, 3\pi, \ldots\ldots..$** or

when **$\gamma = \pi/2, 3\pi/2, 5\pi/2, \ldots\ldots$**

Corresponding angles of diffraction are

$$b \sin\theta = m\lambda; \qquad (m = 1,2,3\ldots.)$$

$$d \sin\theta = (n + \frac{1}{2})\lambda; \qquad (n = 1,2,3\ldots.)$$

Interference maxima occur when **$\gamma = 0, \pi, 2\pi, \ldots..$** or

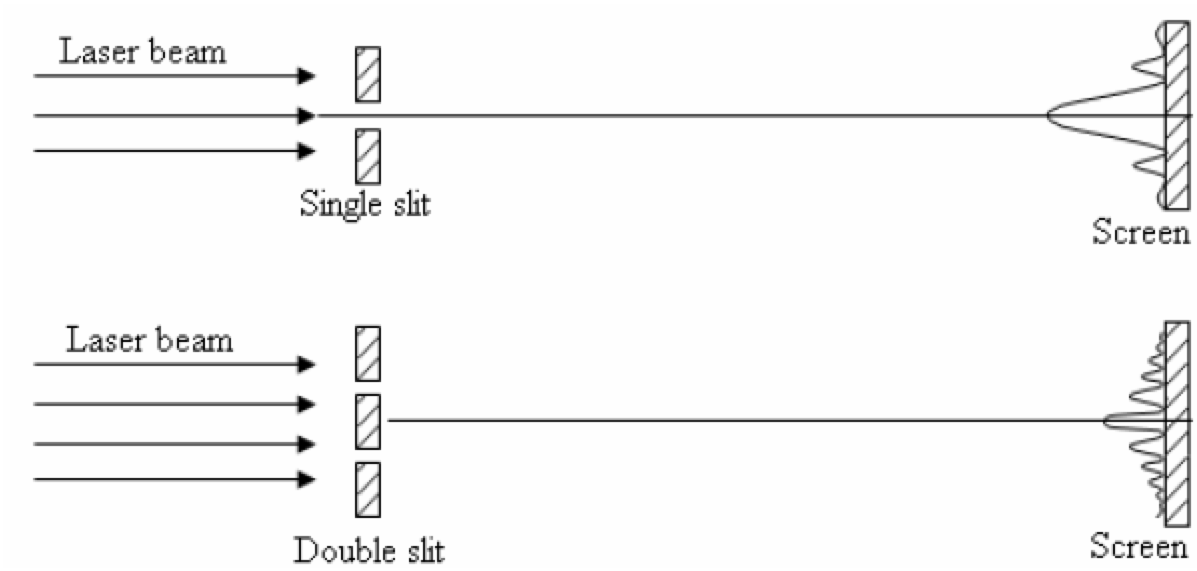
when **$d\sin\theta = 0, \lambda, 2\lambda, 3\lambda, \ldots.$**

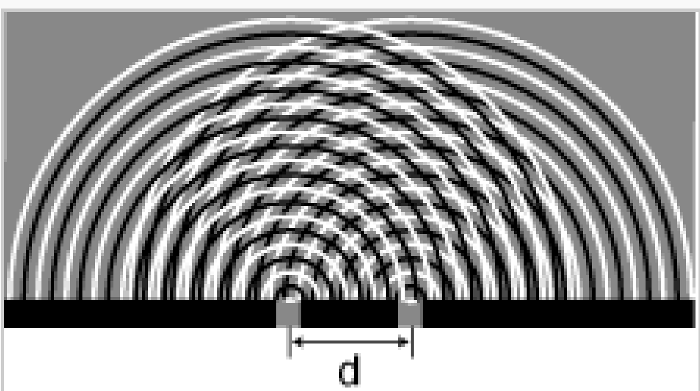
Actual positions of maxima will approximately occur at above angles provided variation of diffraction term is not too rapid. A maximum may not occur at all if θ corresponds to a diffraction minimum, i.e., if

$$b\sin\theta = \lambda, 2\lambda, 3\lambda, \ldots.$$

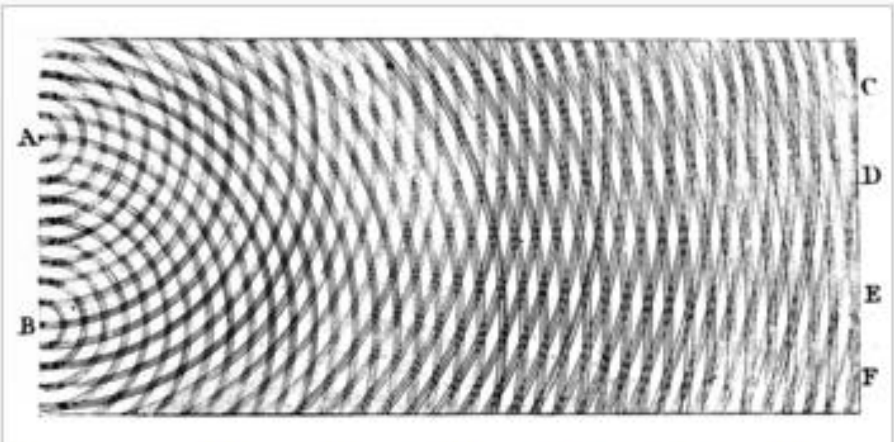
These are usually referred to as **missing orders**, which occur where conditions for a maximum of interference & for a minimum of diffraction are both fulfilled for same value of θ.

Diffraction



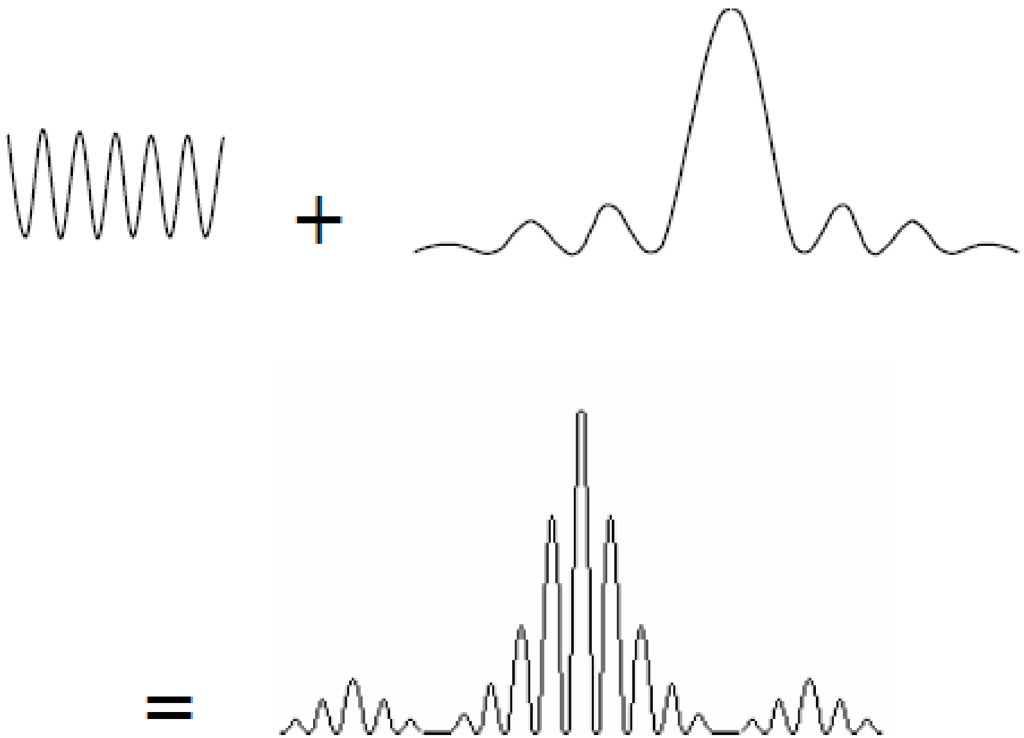


Double-slit diffraction and interference pattern



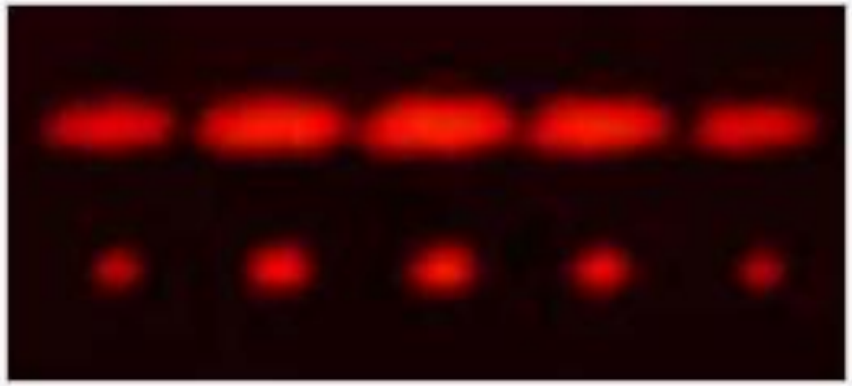
Thomas Young's sketch of two-slit diffraction, which he presented to the Royal Society in 1803

If one or other of two slits is covered, we obtain exactly same single-slit pattern in same position, while if both slits are uncovered, pattern, instead of being a single-slit one with twice intensity, breaks up into narrow maxima & minima called **interference fringes**. Intensity at maximum of these fringes is 4 times intensity of either single-slit pattern at that point, while it is zero at minima.

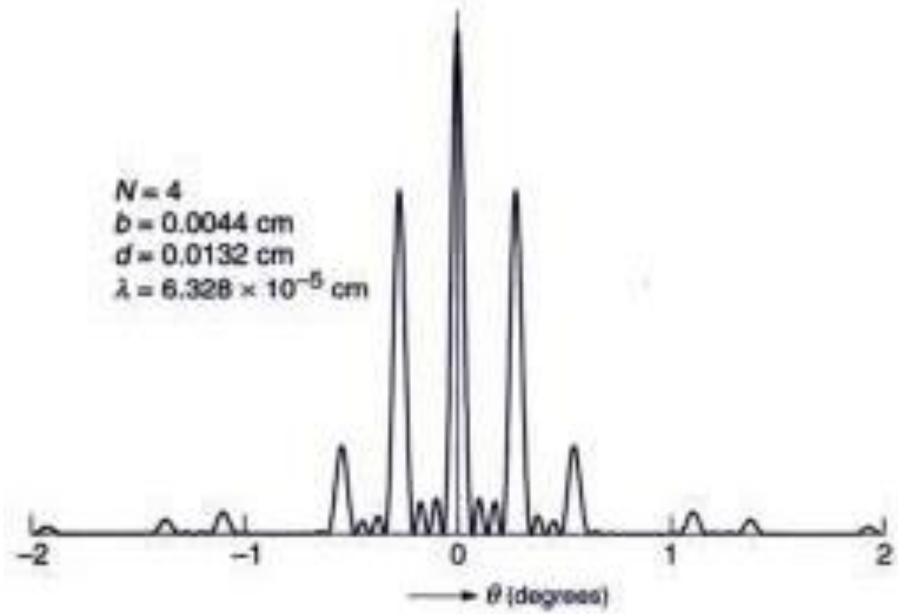


Double-slit pattern: **combination of interference & diffraction**.

Interference of beams from two slits produces narrow maxima & minima, & diffraction modulates intensities of these interference fringes.

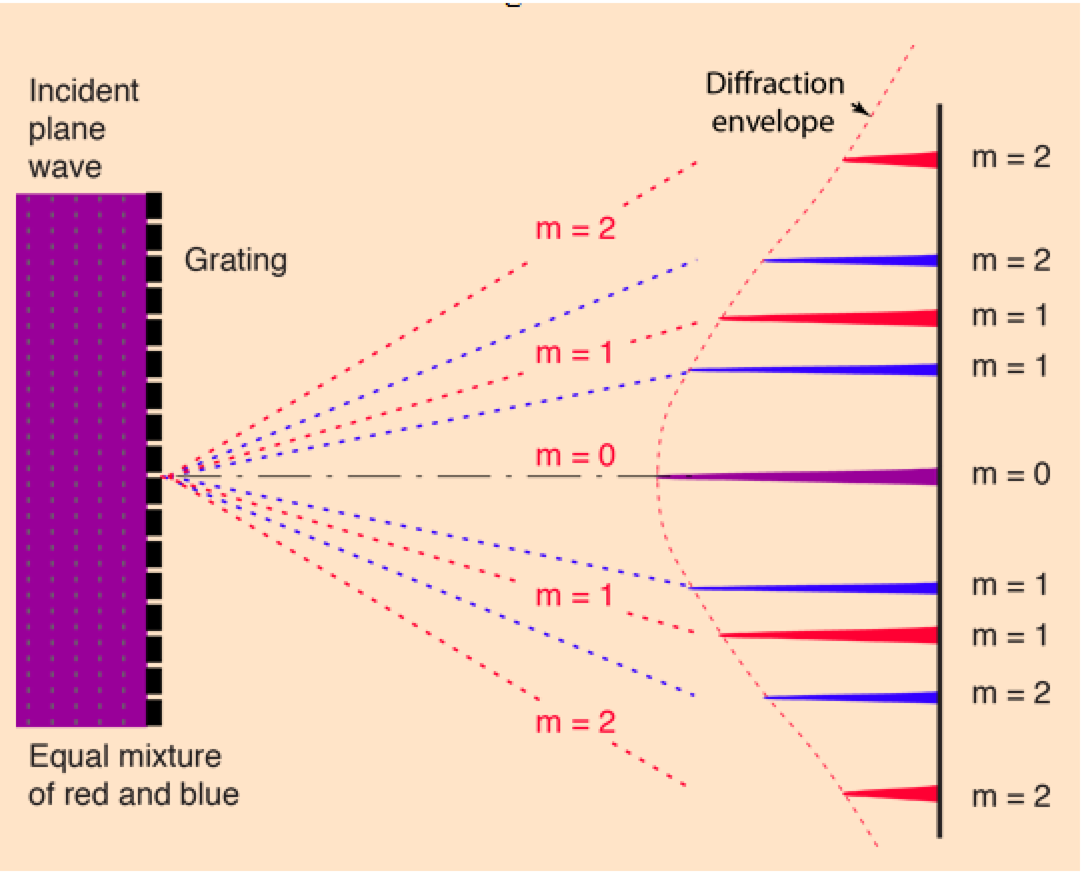


2-slit (top) and 5-slit diffraction of red laser light



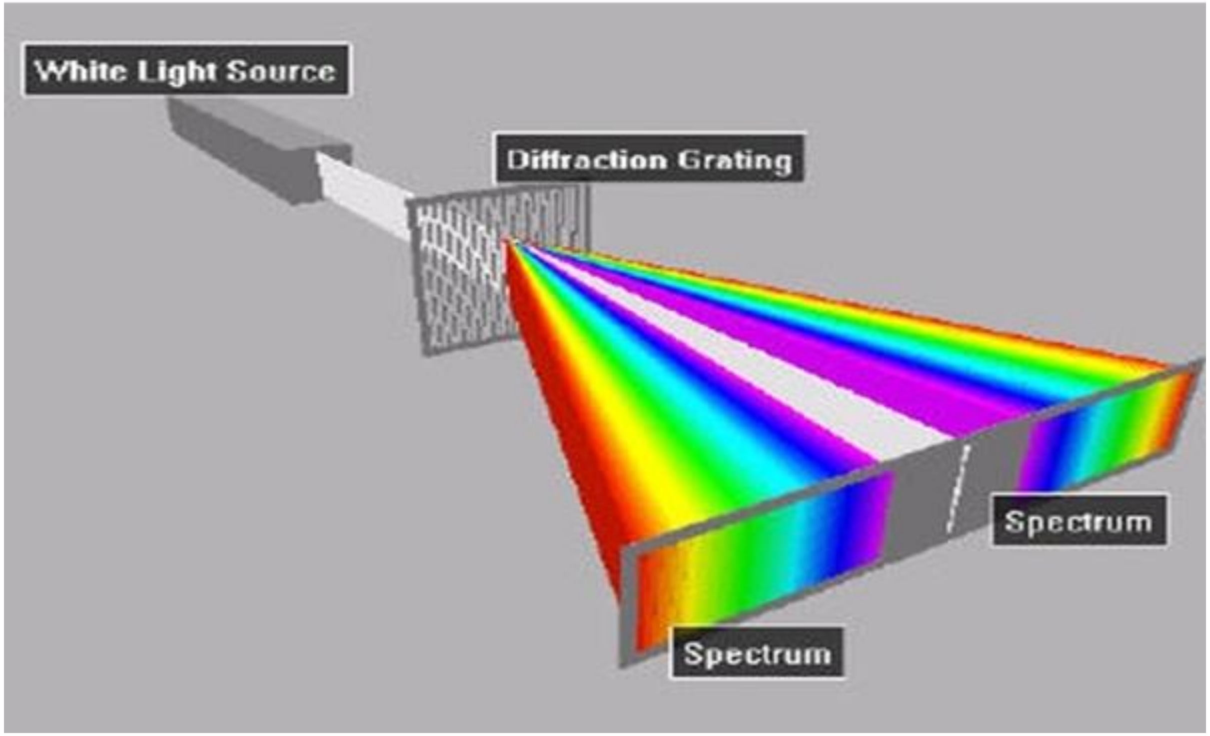
Intensity distribution corresponding to 4 slit Fraunhofer diffraction pattern

Diffraction grating



A diffraction grating is a tool of choice for separating colors in incident light.

Diffraction Grating

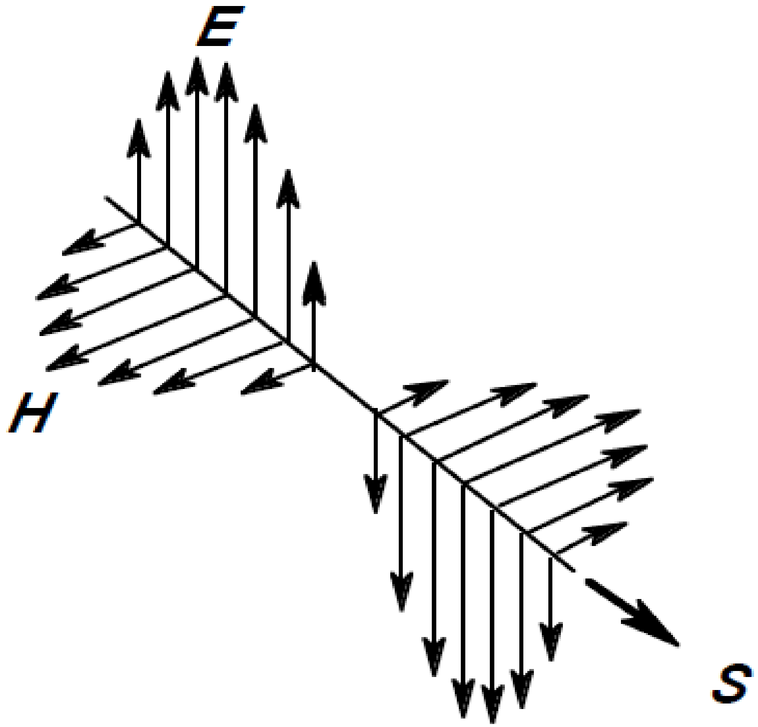


No one has ever been able to define the difference between interference & diffraction satisfactorily. It is just a question of usage, & there is no specific, important physical difference between them. The best we can do is, roughly speaking, is to say that when there are only a few sources, say two, interfering, then the result is usually called interference, but if there is a large no. of them, it seems that the word diffraction is more often used.

Richard Feynman

Electromagnetic Waves

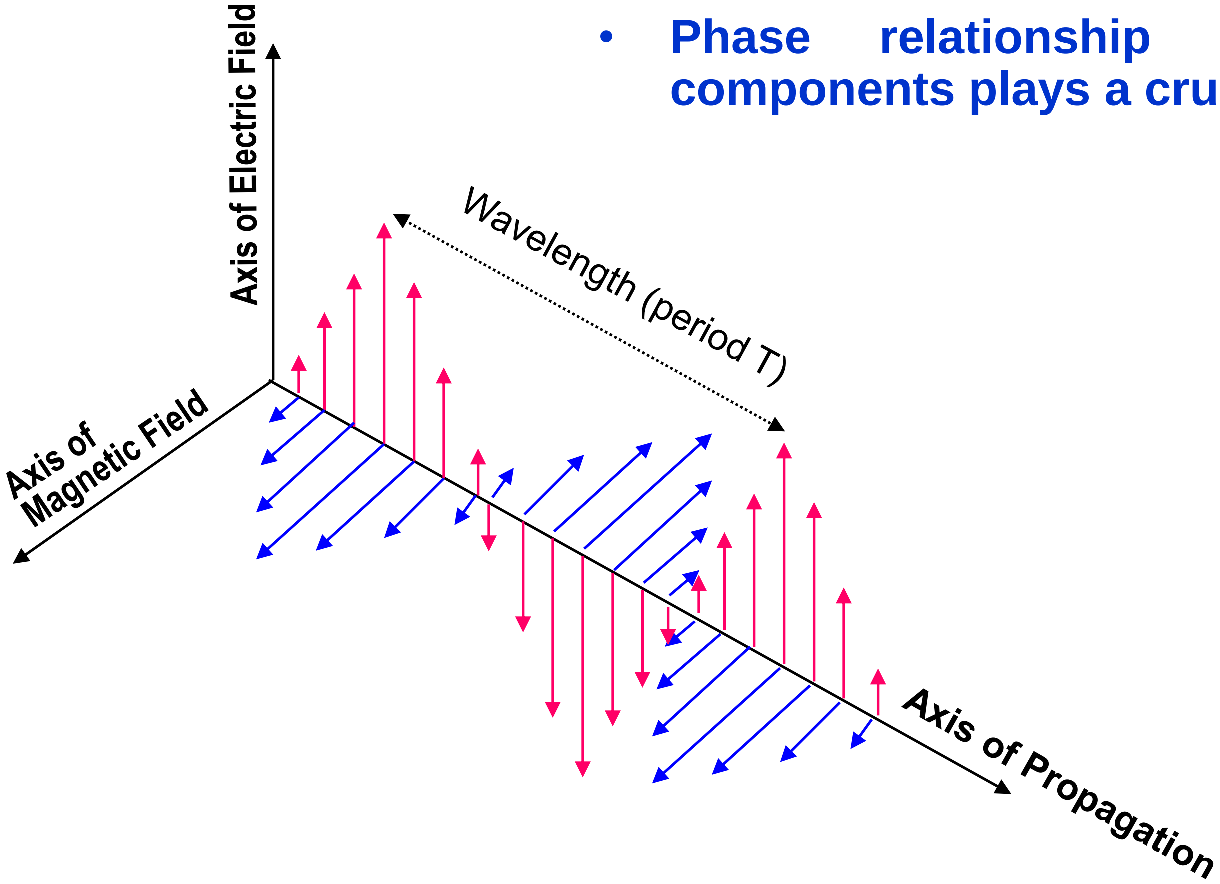
Light is an *em* wave & is produced whenever a charged particle is accelerated. In 3-D appearance of an *em* wave (if we could see it) would be two perpendicular waves, one of electric field ***E*** & one of magnetic field ***H***, in phase rippling along in a straight line.

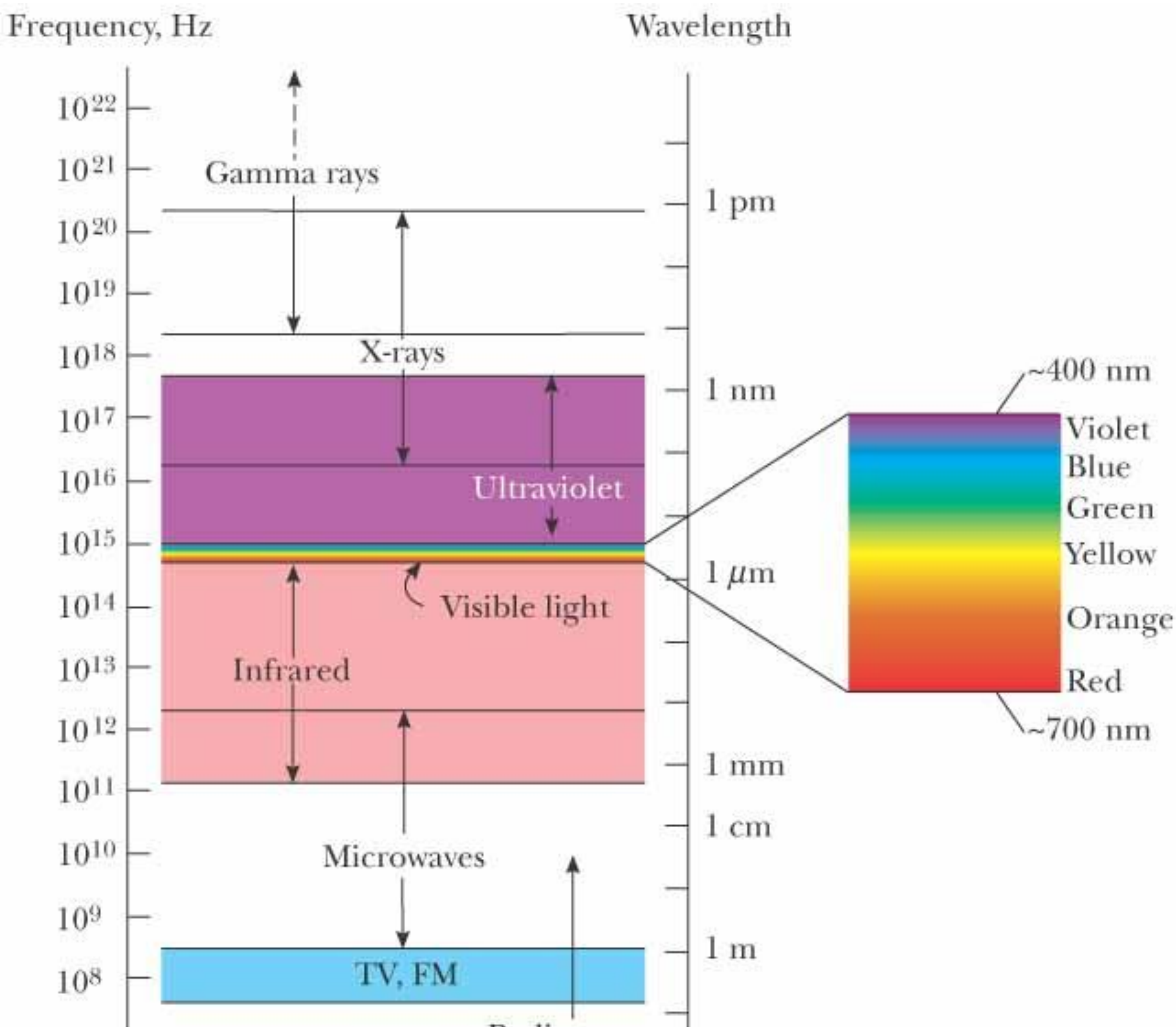


Vector *S* is pointing vector. Its magnitude is amount of energy carried by wave & its direction is direction of propagation of wave.

Directionality of Component

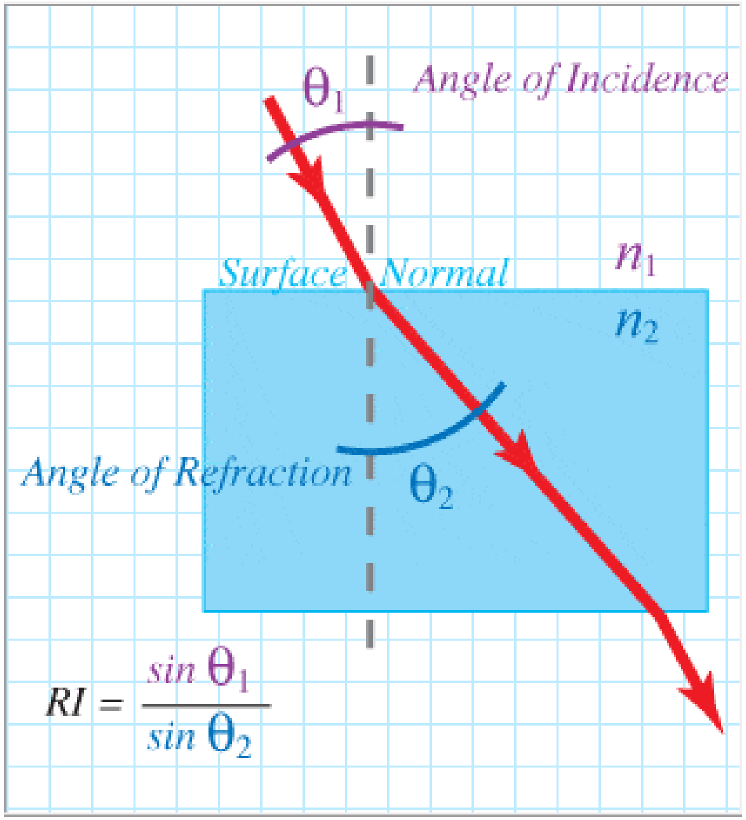
- Electric & magnetic fields are vectors - i.e. they have both magnitude & direction
- Inverse of period (wavelength) is frequency (Hz)
- Phase relationship between E & B components plays a crucial role





Frequency, Hz
Wavelength
10^{22}
10^{21}
10^{20}
10^{19}
10^{18}
10^{17}
10^{16}
10^{15}
10^{14}
10^{13}
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
Gamma rays
X-rays
Ultraviolet
Visible light
Infrared
Microwaves
TV, FM
1 pm
1 nm
1 μm
1 mm
1 cm
1 m
~400 nm
Violet
Blue
Green
Yellow
Orange
Red
~700 nm

Refractive Index



Light travels through different substances at different speeds. Generally speaking, **the denser the substance, the slower light moves**. When light enters a substance at an angle, this change in velocity causes ray to be deflected, or bent.

This bending is called **Refraction**. Amount that substance bends light is its Refraction (or Refractive) Index (RI). It's determined by using **Snell's law.**

RI for a given substance at a given temp & pressure is a constant.

RIs are used in real world to determine everything from **percentage of water in a sample of honey** to **composition & purity of gemstones**.