TA/TI survey
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Chapter 35
Diffraction and Polarization
Two sources of light are coherent if they have the same frequency and maintain the same phase relationship.
34-4 Intensity in the Double-Slit Interference Pattern

Intensity as a function of angle

\[ I_\theta \]

\[ \delta \]

\[ y \] (if \( y \ll \ell \))

- \( 5\pi \)
- \( 4\pi \)
- \( 3\pi \)
- \( 2\pi \)
- \( \pi \)
- \( 0 \)
- \( \pi \)
- \( 2\pi \)
- \( 3\pi \)
- \( 4\pi \)
- \( 5\pi \)

\[ -\frac{5\lambda l}{2d} \]
\[ -\frac{2\lambda l}{d} \]
\[ -\frac{3\lambda l}{2d} \]
\[ -\frac{\lambda l}{d} \]
\[ -\frac{\lambda l}{2d} \]
\[ 0 \]
\[ \frac{\lambda l}{2d} \]
\[ \frac{\lambda l}{d} \]
\[ \frac{3\lambda l}{2d} \]
\[ \frac{2\lambda l}{d} \]
\[ \frac{5\lambda l}{2d} \]
34-4 Intensity in the Double-Slit Interference Pattern

\[ I = I_{\text{max}} \cos^2\left(\frac{\pi d \sin \theta}{\lambda}\right) \]
Two sources of waves are perfectly coherent if they emit waves with the same frequency and maintain the same phase relationship at all times.

If the waves from the two sources have random phase with respect to each other over time the sources are incoherent.
Interference vs. Diffraction

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

– Richard P. Feynman

Interference and diffraction arise from the same phenomenon—the superposition of coherent waves of different phase.

The bending of waves behind obstacles into the shadow region is an effect of diffraction.
Diffraction Pattern

A computer simulation of a diffraction pattern of a single 4-wavelength-wide slit.
If light is a wave, it will diffract around a single slit or obstacle.
The resulting pattern of light and dark stripes is called a diffraction pattern. We are not always aware of diffraction because most sources of light in everyday life are not points.
Diffraction Pattern

A computer simulation of the intensity pattern formed wave incident on a sphere.
Computer simulation of the intensity pattern formed by a laser of $\lambda = 663$ nm incident on a square aperture of 20x20 µm, visible on a screen at 1 m from the aperture.
Diffraction Pattern

A computer generated image of an Airy disk: far-field diffraction of a plane wave incident on a circular aperture
Diffraction by a Single Slit

(a) $\theta = 0$
Bright
Diffraction by a Single Slit

\[ D \sin \theta = m\lambda, \quad m = \pm 1, \pm 2, \ldots \]

Minima

(b) \( \sin \theta = \frac{\lambda}{D} \)

Dark
Diffraction by a Single Slit

(c) \( \sin \theta = \frac{3 \lambda}{2D} \)

Bright
This pattern arises because different points along a slit create wavelets that interfere with each other just as a double slit would.

(a) $\theta = 0$
- Bright

(b) $\sin \theta = \frac{\lambda}{D}$
- Dark

(c) $\sin \theta = \frac{3\lambda}{2D}$
- Bright

(d) $\sin \theta = \frac{2\lambda}{D}$
- Dark
Diffraction by a Single Slit

Minima

\[ D \sin \theta = m\lambda, \quad m = \pm 1, \pm 2, \ldots \]
The minima of the single-slit diffraction pattern occur when

\[ D \sin \theta = m\lambda, \quad m = \pm 1, \pm 2, \pm 3, \ldots \]  

[minima]
Light passing through a single slit can be divided into a series of narrower strips; each contributes the same amplitude to the total intensity on the screen, but the phases differ due to the differing path lengths:

\[ \Delta \beta = k \Delta x = \frac{2\pi}{\lambda} \Delta y \sin \theta \]
35-2 Intensity in Single-Slit Diffraction Pattern

\[ \Delta \beta = \frac{2\pi}{\lambda} \Delta y \sin \theta \quad \beta = N \Delta \beta = \frac{2\pi}{\lambda} (N \Delta y) \sin \theta \]

\[ \beta = \frac{2\pi}{\lambda} D \sin \theta \]

(a) At center, \( \theta = 0 \).

(b) Between center and first minimum.

(c) First minimum, \( E_\theta = 0 \) (\( \beta = 2\pi = 360^\circ \)).

(d) Near secondary maximum.

\[ E_\theta < E_0 \]
35-2 Intensity in Single-Slit Diffraction Pattern

\[ \begin{align*}
N & \to \infty \\
\Delta y & \to dy
\end{align*} \quad \Rightarrow \quad E_\theta = 2r \sin \frac{\beta}{2}; \quad E_0 = r \beta
\]

\[ \begin{align*}
E_\theta &= E_0 \frac{\sin \beta/2}{\beta/2} \\
\beta &= \frac{2\pi}{\lambda} D \sin \theta
\end{align*} \]

\[ I_\theta = I_0 \left( \frac{\sin \beta/2}{\beta/2} \right)^2 \]

\( I_0 \) is the intensity at \( \theta = 0 \)
In Young’s double-slit experiment we assumed \textit{infinitesimally narrow} slits. This can never be the case for real slits and diffraction must be included.

\begin{align*}
E_\theta &= E_0 \frac{\sin \beta/2}{\beta/2} \\
\beta &= \frac{2\pi}{\lambda} D \sin \theta
\end{align*}

\begin{align*}
E_{\theta,0} &= 2E_0 \cos \frac{\delta}{2} \\
\delta &= \frac{2\pi}{\lambda} d \sin \theta
\end{align*}

\text{Diffraction factor} \quad \text{Interference factor}
35-3 Diffraction in the Double-Slit Experiment

(a) Diffraction factor, $(\sin^2 \beta/2)/(\beta/2)^2$ vs. $\theta$

(b) Interference factor, $\cos^2 \frac{\delta}{2}$ vs. $\theta$

(c) Intensity, $I_\theta$ vs. $\theta$
35-3 Diffraction in the Double-Slit Experiment

\[ d = 0.50 \text{ mm}; \quad D = 0.04 \text{ mm} \]

\[ d = 0.50 \text{ mm}; \quad D = 0.08 \text{ mm} \]

(c) Intensity, \( I_\theta \) vs. \( \theta \)
Resolution is the distance at which a lens can barely distinguish two separate objects.

Resolution is limited by aberrations and by diffraction.

Aberrations can be minimized, but diffraction is unavoidable; it is due to the size of the lens compared to the wavelength of the light.
The diffraction pattern from a circular aperture produces the **Airy disk** with the radius of the central disk subtending an angle

\[ \theta = 1.22 \frac{\lambda}{D} \]
When light is focused using a lens of focal length $f$ with a circular aperture of diameter $D$, the diameter of the focused spot is

$$2w = 2\theta f = 2 \left(1.22 \frac{\lambda}{D}\right) f$$
When light is focused using a lens of focal length $f$ with a circular aperture of diameter $D$, the diameter of the focused spot is

$$2w = 2 \theta f = 2 \left(1.22 \frac{\lambda}{D}\right) f$$
35-4 Limits of Resolution; Circular Apertures

A lens, because it has edges, acts like a round slit. The imagine of a point object consists of a circular central peak, called the *diffraction spot* or *Airy disk* and faint circular fringes.
The Rayleigh criterion states that two images are just resolvable when the center of one peak is over the first minimum of the other.

\[ \theta = 1.22 \frac{\lambda}{D} \]
Diffraction Limit; Resolution
Example 35-6: Eye resolution.

You are in an airplane at an altitude of 10,000 m. If you look down at the ground, estimate the minimum separation $s$ between objects that you could distinguish. Could you count cars in a parking lot? Consider only diffraction, and assume your pupil is about 3.0 mm in diameter and $\lambda = 550$ nm.