Lecture PowerPoints

Chapter 24

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Chapter 24
The Wave Nature of Light
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Huygens’ principle: Every point on a wave front acts as a point source; the wavefront as it develops is tangent to their envelope.
Huygens’ principle is consistent with diffraction:
24-2 Huygens’ Principle and the Law of Refraction
Huygens’ principle can also explain the law of refraction.

As the wavelets propagate from each point, they propagate more slowly in the medium of higher index of refraction.

This leads to a bend in the wavefront and therefore in the ray.
24-2 Huygens’ Principle and the Law of Refraction

The frequency of the light does not change, but the wavelength does as it travels into a new medium.

\[
\frac{\lambda_2}{\lambda_1} = \frac{v_2}{v_1} t = \frac{v_2}{v_1} = \frac{n_1}{n_2}
\]

\[
\lambda_n = \frac{\lambda}{n}
\]  (24-1)
Highway mirages are due to a gradually changing index of refraction in heated air.
If light is a wave, interference effects will be seen, where one part of wavefront can interact with another part.

One way to study this is to do a double-slit experiment:
If light is a wave, there should be an interference pattern.
The interference occurs because each point on the screen is not the same distance from both slits. Depending on the path length difference, the wave can interfere constructively (bright spot) or destructively (dark spot).
24-3 Interference—Young’s Double-Slit Experiment

We can use geometry to find the conditions for constructive and destructive interference:

\[ d \sin \theta = m\lambda, \quad m = 0, 1, 2, \ldots \quad \text{constructive interference (bright)} \quad (24-2a) \]

\[ d \sin \theta = \left( m + \frac{1}{2} \right)\lambda, \quad m = 0, 1, 2, \ldots \quad \text{destructive interference (dark)} \quad (24-2b) \]
24-3 Interference—Young’s Double-Slit Experiment

Between the maxima and the minima, the amplitude varies smoothly. The first minimum corresponds to $m=0$.
Problem 1

• Monochromatic light falling on two slits 0.018 mm apart produces the fifth-order bright fringe at an 8.6° angle. What is the wavelength of the light used?

• Solution: For constructive interference, the path difference is a multiple of the wavelength. In this case m=5, θ=8.6°.

\[
d \sin \theta = m \lambda, \quad m = 0, 1, 2, \ldots
\]

\[
\lambda = \frac{d \sin \theta}{m} = \frac{1.8 \times 10^{-5} m \cdot \sin(8.6^\circ)}{5} = 5.4 \times 10^{-7} m
\]
Problem 2

- Light of wavelength $5.0 \times 10^{-7}$ m passes through two parallel slits and falls on a screen 5 m away. Adjacent bright bands of the interference pattern are 2 cm apart. a) Find the distance between slits. b) The same two slits are next illuminated by light of a different wavelength and the fifth order minimum for this light occurs at the same point on the screen as the fourth-order minimum for the previous light. What is the wavelength of the second source of light?

- Solution:

$$d \sin \theta = m\lambda \Rightarrow d \frac{x}{l} = m\lambda \Rightarrow x = \frac{lm\lambda}{d};$$

$$\Delta x = x_2 - x_1 = \frac{l\lambda}{d} \Delta m; \quad \Delta m = 1 \text{(adjacent bands)}$$

$$d = \frac{l\lambda}{\Delta x} = \frac{5m \cdot 5 \times 10^{-7} m}{2 \times 10^{-2} m} = 1.25 \times 10^{-4} m$$
Problem 2 (cont.)

Part b) The fourth-order minimum corresponds to \( m = 3 \), and the fifth-order minimum corresponds to \( m = 4 \).

\[
d \sin \theta = \left( m + \frac{1}{2} \right) \lambda \implies
\]

For the first source: \( d \sin \theta = \left( m_1 + \frac{1}{2} \right) \lambda_1 \)

For the second source: \( d \sin \theta = \left( m_2 + \frac{1}{2} \right) \lambda_2 \)

\[
\left( m_1 + \frac{1}{2} \right) \lambda_1 = \left( m_2 + \frac{1}{2} \right) \lambda_2 \implies \lambda_2 = \frac{m_1 + \frac{1}{2}}{m_2 + \frac{1}{2}} \lambda_1 = \frac{3.5}{4.5} \times 5 \times 10^{-7} m = 3.9 \times 10^{-7} m
\]
Problem 3

- Light of wavelength 650 nm passes through two narrow slits 0.66 mm apart. The screen is 2.4 m away. A second source of unknown wavelength produces its second-order fringe 1.23 mm closer to the central maximum than the 650-nm light. What is the wavelength of the unknown light?
24-3 Interference—Young’s Double-Slit Experiment

Since the position of the maxima (except the central one) depends on wavelength, the first- and higher-order fringes contain a spectrum of colors.

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Two properties of light: intensity (brightness) and color. The intensity is the energy carried out by the EM wave of a particular wavelength per unit area per unit time. The color is related to the frequency $f$ of wavelength $\lambda$. Wavelengths of visible light: 400 nm to 750 nm

Shorter wavelengths are ultraviolet; longer are infrared
The index of refraction of a material varies somewhat with the wavelength of the light.
24-4 The Visible Spectrum and Dispersion

This variation in refractive index is why a prism will split visible light into a rainbow of colors. White light is the mixture of all visible wavelengths, and when incident on a prism, the different wavelengths are bent to varying degrees. Because the index of refraction is greater for the shorter wavelengths, violet is bent the most, and red the least. This spreading of white light into the full spectrum is called dispersion.
Atmospheric rainbows are created by dispersion in tiny drops of water.
24-5 Diffraction by a Single Slit or Disk

Light will also diffract around a single slit or obstacle.

(b): Each ray passing through the lower part of the slit will destructively interfere with a ray from the upper part.

(c) Rays from the bottom third part will cancel in pairs with those in the middle third, because they will be $\lambda/2$ out of phase.
The resulting pattern of light and dark stripes is called a diffraction pattern.

This pattern arises because different points along a slit create wavelets that interfere with each other just as a double slit would.
24-5 Diffraction by a Single Slit or Disk

The minima of the single-slit diffraction pattern occur when

\[ D \sin \theta = m\lambda, \quad m = \pm 1, \pm 2, \pm 3, \ldots, \quad (24-3b) \]

Example: Light of wavelength 750 nm passes through a slit 1.0 \times 10^{-3} mm wide. How wide is the central maximum in (a) degrees, (b) cm on a screen 20 cm away?

\[ \sin \theta = \frac{\lambda}{D} = 0.75 \Rightarrow \theta_{1/2} = 49^\circ \Rightarrow \theta = 98^\circ \]

\[ x = ?, \quad \tan \theta = \frac{x}{l} \Rightarrow x = l \tan \theta; \]

\[ 2x = 46 \text{ cm} \]
A diffraction grating consists of a large number of equally spaced narrow slits or lines. A transmission grating has slits, while a reflection grating has lines that reflect light.

The more lines or slits there are, the narrower the peaks.
The maxima of the diffraction pattern are defined by

\[
\sin \theta = \frac{m \lambda}{d}, \quad m = 0, 1, 2, \ldots
\]  

(24-4)
A spectrometer makes accurate measurements of wavelengths using a diffraction grating or prism.
24-7 The Spectrometer and Spectroscopy

The wavelength can be determined to high accuracy by measuring the angle at which the light is diffracted.

\[ \lambda = \frac{d}{m} \sin \theta \]

Atoms and molecules can be identified when they are in a thin gas through their characteristic emission lines.
Another way path lengths can differ, and waves interfere, is if the travel through different media.

If there is a very thin film of material—a few wavelengths thick—light will reflect from both the bottom and the top of the layer, causing interference.

This can be seen in soap bubbles and oil slicks, for example.
24-8 Interference in Thin Films

The wavelength of the light will be different in the oil and the air, and the reflections at points A and B may or may not involve reflection.
24-8 Interference in Thin Films

A similar effect takes place when a shallowly curved piece of glass is placed on a flat one. When viewed from above, concentric circles appear that are called Newton’s rings.
One can also create a thin film of air by creating a wedge-shaped gap between two pieces of glass.
Problem Solving: Interference

1. Interference occurs when two or more waves arrive simultaneously at the same point in space.

2. Constructive interference occurs when the waves are in phase.

3. Destructive interference occurs when the waves are out of phase.

4. An extra half-wavelength shift occurs when light reflects from a medium with higher refractive index.
The Michelson interferometer is centered around a beam splitter, which transmits about half the light hitting it and reflects the rest. It can be a very sensitive measure of length.
Light is polarized when its electric fields oscillate in a single plane, rather than in any direction perpendicular to the direction of propagation.

Linear polarization: oscillations are in a plane.
Polarized light will not be transmitted through a polarized film whose axis is perpendicular to the polarization direction.
When light passes through a polarizer, only the component parallel to the polarization axis is transmitted. If the incoming light is plane-polarized, the outgoing intensity is:

\[ I = I_0 \cos^2 \theta \quad (24-5) \]
24-10 Polarization

This means that if initially unpolarized light passes through crossed polarizers, no light will get through the second one.
24-10 Polarization

Light is also partially polarized after reflecting from a nonmetallic surface. At a special angle, called the polarizing angle or Brewster’s angle, the polarization is 100%.

\[ \tan \theta_p = \frac{n_2}{n_1} \]  

(24-6a)
Liquid crystals are unpolarized in the absence of an external voltage, and will easily transmit light. When an external voltage is applied, the crystals become polarized and no longer transmit; they appear dark.
Summary of Chapter 24

- The wave theory of light is strengthened by the interference and diffraction of light.
- Huygens’ principle: every point on a wavefront is a source of spherical wavelets.
- Wavelength of light in a medium with index of refraction $n$:
  \[ \lambda_n = \frac{\lambda}{n} \]
- Young’s double-slit experiment demonstrated interference.
Summary of Chapter 24

• In the double-slit experiment, constructive interference occurs when
  \[ d \sin \theta = m\lambda, \quad m = 0, 1, 2, \cdots. \]

• and destructive interference when
  \[ d \sin \theta = (m + \frac{1}{2})\lambda, \quad m = 0, 1, 2, \cdots. \]

• Two sources of light are coherent if they have the same frequency and maintain the same phase relationship
Summary of Chapter 24

• Visible spectrum of light ranges from 400 nm to 750 nm (approximately)

• Index of refraction varies with wavelength, leading to dispersion

• Diffraction grating has many small slits or lines, and the same condition for constructive interference

• Wavelength can be measured precisely with a spectroscope
Summary of Chapter 24

• Light bends around obstacles and openings in its path, yielding diffraction patterns

• Light passing through a narrow slit will produce a central bright maximum of width

\[
\sin \theta = \frac{\lambda}{D}.
\]

• Interference can occur between reflections from the front and back surfaces of a thin film

• Light whose electric fields are all in the same plane is called plane polarized
Summary of Chapter 24

• The intensity of plane polarized light is reduced after it passes through another polarizer:

\[ I = I_0 \cos^2 \theta \]

• Light can also be polarized by reflection; it is completely polarized when the reflection angle is the polarization angle:

\[ \tan \theta_p = n. \]
Example 1

• A diffraction grating has 5150 lines per centimeter ruled on it. What is the angular separation between the first- and the third-order bright spots on the same side of the central maximum when the grating is illuminated by a beam of light with wavelength 633 nm?

• **Answer:** 58.9°

• Solution: Diffraction has the same condition for the constructive interference. We know \( m_1 = 1 \), \( m_2 = 3 \) and \( \lambda = 633 \) nm.

\[
d \sin \theta = m \lambda, \quad m = 0, 1, 2, \cdots.
\]

We can find \( d \): \( d = 0.01 \text{ m/5150} = 1.9 \times 10^{-6} \). Now we can find angles:

\[
sin \theta_1 = \frac{m_1 \lambda}{d} = \frac{633 \cdot 10^{-9} m}{1.942 \cdot 10^{-6} m} = 325.95 \cdot 10^{-3} \quad \Rightarrow \quad \theta_1 = 19.02°
\]

\[
sin \theta_2 = \frac{m_2 \lambda}{d} = \frac{3 \cdot 633 \cdot 10^{-9} m}{1.942 \cdot 10^{-6} m} = 977.86 \cdot 10^{-3} \quad \Rightarrow \quad \theta_2 = 77.92°
\]

\[
\Delta \theta = \theta_2 - \theta_1 = 58.9°
\]
Example 2

- A piece of glass has a thin film of gasoline floating on it. A beam of light is shining perpendicular on the film. If the wavelength of light incident on the film is 560 nm and the indices of refraction of gasoline and glass are 1.40 and 1.50, respectively, what is the minimum nonzero thickness of the film to see a bright reflection?

- **Answer:** 200 nm

- Solution: A beam of light reflected by a material with index of refraction greater than that of the material in which it is traveling, changes phase by $180^\circ$ or $\lambda/2$. We have the phase shift twice (air-gasoline and gasoline-glass) – the total shift is $\lambda$. We need a constructive interference at the surface of the film to see a bright spot.

\[2t = m\lambda; \ m = 1; \ \lambda \text{ is the wavelength in the gasoline, } \lambda = 560\text{nm}/1.4 = 400\text{ nm}\]

\[t = 400\text{ nm}/2 = 200\text{ nm}.\]
Example 3

- Three perfectly polarizing sheets are placed 2 cm apart and in parallel planes. The transmission axis of the second sheet is 30° relative to the first one. The transmission axis of the second one is 90° relative to the first one. Unpolarized light is incident on the first sheet. What percent of the light is transmitted out through the third polarizer?

**Answer:** 9.4%

- Solution: If the original intensity is $I_0$, then the first polarizer will reduce the intensity to $I_1 = I_0/2$. The next one will reduce the intensity

$$I_2 = I_1 \cos^2(30°); \quad I_3 = I_2 \cos^2(60°) \quad \Rightarrow$$

$$I_f = \frac{1}{2} I_0 \cos^2(30°) \cos^2(60°) \Rightarrow$$

$$\frac{I_f}{I_0} = \frac{1}{2} \cos^2(30°) \cos^2(60°) = 0.094$$
Example 4

• A series of polarizers are each rotated 10° from previous polarizer. Unpolarized light is incident on this series of polarizers. How many polarizers does the light have to go through before it is 1/5 of its original intensity? Answer: 31 polarizers

• Solution: If the original intensity is $I_0$, then the first polarizer will reduce the intensity to $I_1 = I_0/2$. Each subsequent polarizer oriented at an angle $\theta$ to the preceding one will reduce the intensity as given by the equation: $I_t = I_t \cos^2 \theta$. We have $n$ polarizers, so the final intensity will be:

$$I_{\text{final}} = \frac{1}{2} I_0 \left(\cos^2 \theta\right)^{n-1} \quad \Rightarrow \quad \frac{1}{5} I_0 = \frac{1}{2} I_0 \left(\cos^2 \theta\right)^{n-1} \quad \Rightarrow$$

$$\left(\cos^2 \theta\right)^{n-1} = \frac{2}{5} \Rightarrow (n - 1) \ln(\cos^2 \theta) = \ln(0.4) \quad \Rightarrow$$

$$n = 1 + \frac{\ln(0.4)}{\ln(\cos^2 10^\circ)} = 31$$