Chapter 24 - The Wave Nature of Light
Summary

• Four Consequences of the Wave nature of Light:
  • Diffraction
  • Dispersion
  • Interference
  • Polarization

• Huygens’ principle: every point on a wavefront is a source of spherical wavelets

• Young’s double-slit experiment.

• Rainbows, Anti-Reflection Coatings
If Light is an electromagnetic wave, let's start by looking at how waves behave.

- Where the long ocean waves enter the opening of the cove, they spread out in rings, as if from a point.
- This phenomenon is Diffraction.
- Exactly the same thing happens to sound, and EM waves (light, radio, X-rays etc).
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

\[ n_1 \sin \theta_1 = n_2 \sin \theta_2 \]

\[ n = \frac{c}{v} \]

\[ \lambda n = \frac{\lambda}{n} \]
Huygens’ Principle and the Law of Refraction

Highway mirages are due to a gradually changing index of refraction in heated air.
The most bizarre thing you have likely encountered in Physics so far!

– Young’s Double-Slit Experiment
24.3 Interference – Young’s Double-Slit Experiment

If light is a wave, there should be an interference pattern.
The two waves shown are:

1) out of phase by 180°
2) out of phase by 90°
3) out of phase by 45°
4) out of phase by 360°
5) in phase
The two waves shown are

1) out of phase by 180°
2) out of phase by 90°
3) out of phase by 45°
4) out of phase by 360°
5) in phase

Follow-up: What would the waves look like for no. 4 to be correct?
Long straight ocean waves diffracting and creating interference patterns as they divide and recombine around an island-strewn coastline.
In this example, a laser shone through a piece of paper with two small holes in it. Instead of 2 spots, you see a central bright spot flanked by many alternating minima and maxima. Even more bizarrely, the effect persists when light is sent through the slit ONE PHOTON AT A TIME. Diffraction and interference have now been demonstrated with beams of electrons, atoms, and even molecules!

Try at home—it's easy!

Thomas Young used sunlight and black paper.
24.3 Constructive & Destructive Interference

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).
Condition for Bright and Dark Fringes

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

\[ d \sin \theta = m \lambda, \quad m = 0, 1, 2, \cdots. \]  
\[
(24-2a) 
\]

\[ d \sin \theta = (m + \frac{1}{2}) \lambda, \quad m = 0, 1, 2, \cdots. \]  
\[
(24-2b) 
\]

[constructive interference (bright)]

[destructive interference (dark)]
Interference Pattern

Between each maxima and the minima, the interference varies smoothly.

Constructive interference

\[ m = 3 \quad 2 \quad 1 \quad 0 \quad 1 \quad 2 \quad 3 \]

Destructive interference

\[ m = 2 \quad 1 \quad 0 \quad 0 \quad 1 \quad 2 \quad 3 \]
Diffraction Pattern for White Light

The position of the maxima (except the central one) depends on wavelength.

The first- and higher-order fringes contain a spectrum of colors.

This is the principle used in a Spectrograph.
24.4 The Visible Spectrum and Dispersion

- Wavelengths of visible light: 400 nm to 750 nm
- Shorter wavelengths are ultraviolet; longer are infrared
Dispersion by a Prism

Wavelength dependence of refractive index is why a prism will split visible light into a rainbow of colors.

\[ \lambda_n = \frac{\lambda}{n} \]

- Light rays bend towards the normal when entering a higher index material.
- Rays bend away from the normal when exiting
- Shorter wavelengths (Blue) are bent more than long ones (Red)
- White light separates into its components
- The angled faces of a Prism amplify the effect

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The Visible Spectrum and Dispersion

- The index of refraction of a material varies with the wavelength of the light.
- This leads to Dispersion - separation of light by frequency or color
- Useful for things like prisms, spectrographs or diamond rings
- Terrible for things like Lenses, telescopes, microscopes, spectacles
Dispersion in Nature: Rainbows

Actual rainbows are created by dispersion and internal reflection in tiny drops of water.

The Rainbow Angle is ~ 42 degrees
Light will also diffract around a single slit or obstacle.

Solid disk

Shadow

Bright spot
Diffraction by a Single Slit, Aperture or Disk

- 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.
- The minima of the single-slit diffraction pattern occur when

\[ D \sin \theta = m\lambda, \quad m = 1, 2, 3, \ldots \]
24.6 Diffraction Gratings

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. (greater spectral resolution)
- A normal CD or DVD is an excellent diffraction grating
- Gratings are more efficient than prisms and have largely replaced them
- The Bright Iridescent Colors of Birds’ Feathers are due to Diffraction-Grating effects
Diffraction Grating

• The maxima of the diffraction pattern are defined by

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

• Where \( d \) is the line spacing, and \( m \) is called the “order”

• The higher the order, the greater the dispersion, but the spectra get much fainter at the same time.
24.8 Interference by Thin Films: from Soap Bubbles to Anti-Reflection Coatings

• 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.

• The color seen depends on the thickness of the Film, and its refractive index.

• Thin Coatings on Camera Lenses (etc) are used to prevent reflections.

• But only for limited range of wavelength and incidence angle.
Anti-Reflective Coatings

• When a light wave is reflected from a surface (A), it changes in phase by a 1/2 cycle.
• Usually some of the light is transmitted and some reflected
• A thin layer (film) of a material with intermediate refractive index is deposited on the surface
• Some light is reflected at this second boundary B.
• If the thickness of the film is just right, the reflected wave from B will arrive at the surface 1/2 cycle out of phase with the original reflection.
• The waves cancel out!
• A certain AR layer only works for a narrow wavelength range, (because it depends on the index)
Summary of Chapter 24

• In the double-slit experiment

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

  destructive interference when
  \[ \sin \theta = (m + \frac{1}{2}) \frac{\lambda}{d} \]

• 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 as for a pair of slits.
- Light bends around obstacles and openings in its path, yielding diffraction patterns
- Light passing through a narrow slit (Diffraction at 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, leading to iridescence and Anti-reflection coatings
- Light whose electric fields are all in the same plane is called plane polarized
24.10 Polarization

• Light is polarized when its electric fields oscillate in a single plane.
• Consequence of the direction of oscillation of electrons in atoms
• Light gets polarized when it reflects off surfaces, or is scattered by gases (e.g. the atmosphere)
• Any electromagnetic wave can be polarized.
• Another important example is radio waves.
Polarizing Filters (polaroid)

- Polarized light will not be transmitted through a polarized film whose axis is perpendicular to the polarization direction.
- Polarizing filters are used in Photography, Sunglasses, Science Labs etc.
- Usually created by stressing plastics while they are still partially melted, creating a preferred direction of vibration for the molecules.
Crossed Polarizers

If initially unpolarized light passes through crossed polarizers, no light will get through the second one.

This can be very useful, as certain special materials can rotate the plane of polarization.
Polarization

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:

\[ I = I_0 \cos^2 \theta \]
Polarization upon Reflection

- 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%.
- Reflected Light is Horizontally Polarized

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

(24-6a)

For light in air, reflecting off water, Brewster’s angle is 53 degrees
Use of Polarizer to remove Reflections and Glare in Photography (and Everyday life)

Without polarizer:
(or adjusted horizontally)
Reflections in surface of water

With Polarizer:
(adjusted vertically)
Reflections suppressed.
The leaves at the bottom of the pond are now visible
Polarization of rainbows

- Rainbows involve reflection and refraction both inside and at the boundaries of the raindrops.
- The rainbow is 100% linearly polarized.
- The polarization axis is radial to the bow.
- Just rotate your head while wearing polarized sunglasses.
Why is the Sky Blue? and is it also Polarized?

• The clear sky is blue due to Scattering by air molecules.

• Scattering is a directional process.

• Examine the sky with polarized sunglasses!

• At 90 from the Sun, the polarization is upto 80%. -so it will look dark!
The blue sky is polarized
• Polarization of the sky reaches its maximum strength at 90 degrees from the sun
• Go see if you can observe the overall pattern for yourself
• It's very hard to photograph!