AP Physics-B **Physical Optics**

Introduction: We have seen that the reflection and refraction of light can be understood in terms of both rays and wave fronts of light. Light rays are quite compatible with the idea that light consists of a beam of particles. We will consider more evidence for a particle view of light later, now we will devote this unit to an investigation of some of the wave properties of light. The most pronounced of these wave properties are the related phenomena of diffraction and interference.

Any bending of light by means other than reflection and refraction is called diffraction. Recall your ripple tank experiments and the diffraction of straight water waves through a small opening or around an obstacle. The amount of diffraction depended upon the wavelength of the wave compared to the size of the opening and the size of the obstruction. The larger the wavelength compared to the opening or obstruction the greater the diffraction. Visible light has wavelengths in the range of 390 nm to 760 nm. This is so small that is difficult to notice diffraction of light in our everyday activities.

The superposition of a pair of identical waves in phase with each other produces a wave of the same frequency but with twice the amplitude. If the pair of waves are exactly one-half wavelength out of phase, their superposition results in complete cancellation. If they are out of phase by any other amounts, partial cancellation occurs. Starting with Sir Isaac Newton, scientists believed that the wave nature of light could be shown conclusively if such an interference pattern could be observed for light rays. In 1801 the wave nature of light was convincingly demonstrated when the British physicist and physician Thomas Young performed his now famous interference experiment. Young found that light directed through two closely spaced pinholes recombined to produce an alternating pattern of light and dark, similar to the pattern of wave activity and no wave activity you observed in the ripple tank experiments earlier this year.

Performance Objectives: Upon completion of the readings and activities of this unit and when asked to respond either orally or on a written test, you will:

- Explain the two-slit experiment and the constructive and destructive interference of light.
- Explain the geometry of the two-slit arrangement, use the derived equations to solve problems. Calculate the wavelength of light.
- Explain the advantage of using a diffraction grating by comparing it to a double slit; use the derived equations to calculate the wavelength of light.
- Explain the interference pattern obtained from thin films such as soap bubbles, oil slicks, and the air wedge. Use the air wedge to measure very small diameters. Solve problems using these concepts.
- Explain how thin film interference can be used to enhance reflection or refraction in optical systems.
- Explain how light can be used to reduce diffraction for a narrow lens.
- Describe some effects and uses of polarized light
- Explain how the polarization of light is used to determine the wave nature of light.
- Explain the geometry of the single-slit diffraction technique; use the derived equations to calculate the wavelengths of light waves.

Textbook Reference: Physics (Wilson, Buffa, Lou): Chapter 24

"Light is the propagated or diffused not only directly, by refraction and by reflection, but also in still a fourth way - by diffraction." ~*Francesco Grimaldi (1611-1663)*

Interference: In order to observe sustained interference in light, the following conditions must be met:

1) The sources must be coherent, that is, they must maintain a constant phase with respect to each other.
2) The sources must be monochromatic, that is, of a single wavelength.
3) The superposition principle must apply.

Young's Double-Slit Experiment:

Light from a single monochromatic source is incident upon a card which has two narrow, parallel slits. These two slits serve as a pair of coherent light sources because a single source produces the original light beam. The light from the two slits produces a visible pattern on a screen; this interference pattern consists of a series of bright and dark parallel bands called fringes. Where m = 0, 1, 2,…, λ is the wavelength, d is the distance between slits, x is the perpendicular distance from the central maximum to the fringe, L is the length from the slits to the fringe and θ is the angular displacement from the center of the central maximum to the fringe.

For Nodes: (dark fringes)

$$\frac{(m-\frac{1}{2})\lambda}{d} = \frac{x}{L} = \sin\Theta$$

For Antinodes: (light fringes)

$$\frac{m\lambda}{d} = \frac{x}{L} = \sin\Theta$$

Color	**λ (nm)**
violet	390 – 450
blue	450 – 490
green	490 – 560
yellow	560 – 590
orange	590 – 630
red	630 – 760

1. Violet light falls on two small slits 1.9×10^{-4} cm apart. A first order bright fringe appears 13.2 cm from the central bright spot on a screen opposite the slits. The distance from the center of the slits to the first-order violet line is 60.0 cm. What is the wavelength of the violet light? *4.2×10^{-5} cm*

2. Yellow light of wavelength 6.0×10^{-5}cm is used instead of the violet light in Problem 1. The distance from the center of the slits to the first-order line for the yellow light is measured and found to be 58 cm. How far from the central maximum on the screen is the first order yellow line? *18.3 cm*

3. Two slits 4.8×10^{-6} m apart, illuminated by parallel rays, form the fifth order bright band at an angle of 30° from the center line. What is the wavelength of the light used? *480 nm*

4. Light of wavelength 4.0×10^{-7} m falls on a pair of slits, and the third order bright band falls at an angle of 30° from the main beam. How far apart are the slits? *2.4×10^{-6} m*

5. Two slits are illuminated by light that consists of two wavelengths. One wavelength is known to be 600 nm. On a screen the fourth dark fringe of the pattern for the known wavelength coincides with the fifth light fringe for the other wavelength. What is the unknown wavelength? *420 nm*

6. Two slits are spaced 0.30 mm apart and are placed 50.0 cm from the screen. What is the distance between the second and the third dark fringes of the interference pattern when the slits are illuminated with light of 600.0 nm wavelength? *1.0 mm*

Interference Patterns From More Than Two Slits - Diffraction Gratings:

When the number of slits is increased the number of secondary maxima increase. The number of secondary maxima is always equal to N-2, where N is the number of slits. However as the number of secondary maxima increases, the intensity of these maxima decreases. The primary maxima on the other hand increase in intensity and become narrower. Where N is very large the primary maxima are very distinct and the secondary maxima are not noticeable. Diffraction gratings are made by scratching very fine lines with a diamond point on glass. The clear spaces between the lines serve as slits. It is possible to make gratings with 5,000 to 10,000 lines per centimeter.

Diffraction gratings are used to create interference patterns to analyze light sources; the distance between slits is 1/N. The two slit formulae can be used for diffraction gratings.

There are two types of diffraction gratings: Transmission and Reflection.

7. The first order line of 550 nm light falling on a diffraction grating is observed at a 12° angle. How far apart are the slits? How many lines per centimeter are on the grating? *2.6×10^{-6} m*

8. At what angle will 710 nm light produce a third-order maximum when falling on a grating whose slits are 1.0×10^{-3} cm apart? *12°*

9. How many lines per centimeter does a grating have if the third-order occurs at a 20° angle for 650 nm light? *1754 lines/cm*

10. A grating has 5000 lines/cm. How many spectral orders can be seen when it is illuminated by white light? Assume the white light contains wavelength from 380 to 760 nm. *Two complete and part of another.*

11. A grating of 4000 slits/cm is used to form a spectrum of a source that emits two wavelengths, a violet line of wavelength, 400 nm, and a red line of wavelength 750 nm. What is the angular separation between red and violet lines in the third order? *35°*

12. White light containing wavelengths from 400 to 700 nm falls on a grating with 8000 lines/cm. How wide is the first order spectrum on a screen 2.0 m away? *0.67 m*

Interference From Thin Films:

The colors that we see when sunlight falls on a soap bubble or an oil slick are caused by the interference of light waves reflected from the front and back surfaces of a thin transparent film. The film thickness is typically of the order of magnitude of the wavelength of the light involved. Thin-film technology, including the deposition of multilayered films, is highly developed and is widely used for the control of the reflection and/or transmission of light or radiant heat at surfaces.

Consider a film of uniform thickness t and index of refraction n, and assume that the light rays incident upon the film are nearly normal to the surface. To determine whether the two reflected rays (one from the top and one from the bottom of the film) interfere constructively or destructively, we must first note the following facts:

1.) A wave traveling in a medium of low refractive index undergoes a 180° phase change upon reflection from a medium of higher refractive index.
2.) Destructive interference occur when waves meet 180° out of phase and constructive interference occurs when waves meet in phase.
3.) The wavelength of light λ_n in a medium whose refraction index is n is given by $\boldsymbol{\lambda_n=\lambda/n}$, where λ is the wavelength of light in free space.

From our study of waves, we recall that any time that a wave reaches the boundary to a new medium – it is partially reflected from the surface and partially transmitted into the new medium. In the case of thin films, a portion of the light incident on a thin film (like a soap bubble) is reflected from the top surface and a portion of the light is transmitted through the film. This portion which is transmitted through the film undergoes the same procedure when it reaches the other surface of the film. The portion of light reflected from the back surface of the film may then interfere with the original reflected pulse from the front surface. Let's take a closer look at this interference.

For a film of thickness *t* (surrounded by air) and light of normal incidence: According to fact 1 above, the portion of the incident wave that is reflected from the top surface of the film (Ray 1) undergoes a 180˚ phase change with respect to the original incident wave (since the film is of higher index of refraction than the surrounding air). The portion of the incident wave that gets transmitted into the thin film will eventually be reflected from the back surface of the film. This reflected (Ray 2) portion of the wave however, does not undergo this same phase change that Ray 1 did - since the surrounding air is of lower index of refraction. Therefore Ray 1 is 180° out of phase with respect to Ray 2, which is equivalent to a path difference of λ_n / 2.

Now, consider that Ray 2 has to travel through twice the thickness of the film (2t) - as it gets transmitted through and reflected from the back surface - before the waves recombine. If 2t = λ_n / 2, then Rays 1 and 2 will be in-phase with each other when they recombine and therefore will constructively interfere with each other.

From this it follows that:

$$2t = (m + \tfrac{1}{2})\lambda_n \text{ where } (m = 0, 1, 2, \ldots) \text{ for Constructive Interference}$$

or

$$2nt = (m + \tfrac{1}{2})\lambda$$

If the extra distance (2t) traveled by Ray 2 is a whole number multiple of λ_n, then the two waves will be 180° out of phase when they recombine and destructive interference will be the result.

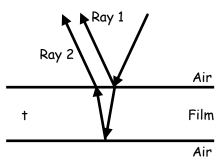
Therefore:

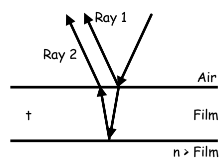
$$2t = m\lambda_n \text{ where } (m = 0, 1, 2, \ldots) \text{ for Destructive Interference}$$

or

$$2nt = m\lambda$$

Remember that these equations assume that the film is surrounded by a common medium. In general, these relationships are reversed if the third medium different (and more optically dense) than the first.





13. Light of wavelength 500.0 nm is incident perpendicularly on a soap film which is surrounded by air. The film is 1.0×10^{-4} cm thick and has an index of refraction of 1.375. Part of the light enters the film and is reflected back at the second face. a.) How many wavelengths are contained along the path of the light in the film? b.) What is the phase difference between these reflected rays as they leave the film and as they enter it? *5.5 180°*

14. A soap film of thickness 210 nm has an index of refraction of 1.89. What color does the film appear when viewed perpendicularly in white light? *Green*

15. A soap film (n = 1.34) appears blue (480 nm) at the film's top. What is the minimum thickness there? *90 nm*

16. A soap film 500.0 nm thick is illuminated with white light. The index of refraction of the film is 1.35. What colors are not seen in the soap film? *675 nm – red 450 nm – blue*

17. Silicon solar cells (n = 3.5) are coated with a transparent thin film of silicon monoxide (n = 1.45) in order to minimize reflective losses from the surface. Determine the minimum thickness of the film that will produce the least reflection at a wavelength of 550 nm, which is the center of the visible spectrum. *94.8 nm*

18. A "non-reflecting" coated lens has a thin film of magnesium fluoride (n = 1.38) that is deposited on the surface of the glass (n = 1.56). What should be the thickness of the film in order that the reflected ray will be exactly out of phase for green light (λ = 500.0 nm)?   *91 nm*

19. A thin film of MgF_2 (n = 1.38) which is 1.0×10^{-5} cm thick is used to coat a camera lens. Will any wavelength in the visible spectrum by intensified in the reflected light?   *No reflection maxima in visible range.*

20. A lens appears greenish yellow (λ = 570 nm) when white light reflects from it. What minimum thickness of coating (n = 1.38) do you think is used on such a glass lens and why?
207 nm – Constructive Interference at 570 nm.

21. A thin layer of oil (n = 1.25) is floating on water (n = 1.33). How thick is the oil in the region that reflects green light (λ = 525 nm)?   *210 nm*

22. A thin layer of liquid methylene iodide (n = 1.756) is sandwiched between two flat parallel plates of glass. What must be the thickness of the liquid layer if normally incident light with λ = 600 nm is to be strongly reflected?   *85.4 nm*   *256 nm*   *427 nm*

Diffraction and the Wave Theory of Light:

We loosely defined diffraction as the bending of light around obstacles in its path. However, when light is incident upon a single small slit – more than just bending occurs – and a diffraction pattern may still be observed. The light which passes through each portion of the slit acts as a source of waves according to Huygens' principle. Therefore, light from one portion of the slit can interfere with light from another portion and the resultant intensity on a viewing screen will depend on the distance from the center of the central maximum. The following formulas are similar to the ones used for double-slit interference patterns with one exception: 'w' is for the width of the slit.

Constructive Interference (m = 1, 2, 3,…)

$$\frac{(m-\frac{1}{2})\lambda}{w} = \frac{x}{L} = \sin\Theta$$

Destructive Interference (m = 1, 2, 3, …)

$$\frac{m\lambda}{w} = \frac{x}{L} = \sin\Theta$$

23. Monochromatic green light falls on a slit 0.01 cm wide and produces a first-order dark band 0.55 cm from the center of the central maximum on a screen 100 cm away. find the wavelength of the green light.   *550 nm*

24. Monochromatic light falls on a slit 2.2×10^{-3} mm wide. If the angle between the first dark fringes on either side of the central maximum is 30°, what is the wavelength of the light used?   *570 nm*

25. When 450 nm indigo light falls on a slit, the central diffraction maximum on a screen 2.0 m away is 6.0 cm wide. Calculate the slit width.   *3.0×10^{-5} m*

26. Green light (λ = 550 nm) is passed through a single slit and falls on a screen 160 cm away. What must be the width of the slit so that the distance from the center of the first-order dark band to the center of the central band will be o.40 cm?   *2.2×10^{-2} cm*