2.11. Wave optics: Interference & polarization

TEASER?

- ANSWER FRAGMENT

Slide 1: Wave Optics: Interference & Polarization

- having examined geometric optics and the ray model of light, we now explore phenomena that reveal light's wave nature
- while the ray model is useful for macroscopic interactions, wave effects become significant at smaller scales
- we will focus on interference and polarization
    - the superposition of light waves leads to interference patterns

        - the transverse nature of light results in polarization

Slide 2: Huygens' Principle

Limits of the Ray Model

- the ray model encounters its limits when dealing with light interacting with objects comparable in size to its wavelength
- consider sunlight entering a dark room through a small pinhole
        - ray model prediction: a sharp, well-defined bright spot (projection of the hole)
        - observation: a more complex pattern (central bright spot with concentric rings or fringes)
- this contradicts the ray model and indicates light's wave nature
- the spreading of light and the formation of intricate patterns are due to interference and diffraction

Huygens' Principle: A Wave Framework

- christian Huygens (1629-1695) proposed a principle to analyze wave propagation
- imagine every point of a wavefront as a source of secondary spherical wavelets
- these wavelets propagate outwards in all directions at the speed of the wave
- the new wavefront at a later time is the tangent surface to all of these secondary wavelets

Understanding Wavefronts and Wavelets

- **wavefront**: a surface connecting points of a wave that are in phase
    - example: ripples on a pond
    - for light: connects points with oscillating electric and magnetic fields in the same way
- think of a wavefront as a line (in 2D) or a surface (in 3D) of many tiny sources
- each tiny source emits a **wavelet**, spreading out like tiny ripples

Superposition and Wavefront Propagation

- **superposition of wavelets generates the new wavefront**
    - individual wavelets interfere with each other
    - their combined effect determines the shape and position of the wavefront at the next instant (tangent to all wavelets)
- **direction of the wave's travel is perpendicular to the wavefront**

Slide 3: Revisiting Refraction from a Wave Perspective

Refraction and Wave Speed

- light travels from medium 1 to medium 2
- mediums are isotropic (same wave speed v in all directions) but have different refractive indices n_1 and n_2
- distance traveled by a wave in time t: $r = vt$
- speed of light in a vacuum: c
- speed of light in a medium with refractive index n: $v = \frac{c}{n}$

- therefore, in our two mediums: $v_1 = \frac{c}{n_1}$ and $v_2 = \frac{c}{n_2}$
- consequently, distance traveled in the same time t will be different: $r_1 = v_1 t \neq r_2 = v_2 t$

Deriving Snell's Law

- for non-zero angle of incidence ($\theta_1 \neq 0$), refraction occurs (change in propagation direction)
- consider a wavefront approaching the interface at angle θ_1
- point A is where one part of the wavefront first hits medium 2
- point B is where another part reaches the interface after time t
- during time t, the part at A travels $v_2 t$, while the part at B travels $v_1 t$
- AB is the length of the wavefront segment about to cross the interface

Geometric Derivation

- from the geometry:
    - $\sin\theta_1 = \frac{v_1 t}{AB}$

    - $\sin\theta_2 = \frac{v_2 t}{AB}$
- dividing the first by the second:

$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{v_1 t/AB}{v_2 t/AB} = \frac{v_1}{v_2}$$

- substituting $v_1 = \frac{c}{n_1}$ and $v_2 = \frac{c}{n_2}$:

$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{c/n_1}{c/n_2} = \frac{n_2}{n_1}$$

- rearranging gives Snell's Law:

$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

Frequency and Wavelength Changes

- **frequency of the wave does not change** during refraction (determined by the source)
- **wavelength λ does change** because speed v changes ($v = \lambda f \leftrightarrow \lambda = \frac{v}{f}$)
- ratio of wavelengths in the two mediums:

$$\frac{\lambda_1}{\lambda_2} = \frac{v_1/f}{v_2/f} = \frac{v_1}{v_2}$$

- since $\frac{v_1}{v_2} = \frac{n_2}{n_1}$, we have:

$$\frac{\lambda_1}{\lambda_2} = \frac{n_2}{n_1}$$

- wavelength is shorter in a medium with a higher refractive index

Wavelength in a Medium

- if λ is the wavelength in a vacuum ($n = 1, v = c$), then the wavelength λ_n in a medium with refractive index n is:

$$\lambda_n = \frac{\lambda}{n}$$

Slide 4: Polarization

Transverse Nature of Light

- electromagnetic (EM) waves are transversal waves and can be polarized
- **plane-polarized waves** (linearly polarized): oscillate in a single plane
- imagine a rope swung horizontally through a vertical slit: only horizontal oscillations pass
- unpolarized light: electric field oscillates randomly in all directions perpendicular to

propagation

Polarization by Absorption (Polaroids)

- polaroid sheets contain long molecules aligned parallel to each other (act like parallel slits)
- component of electric field parallel to molecules causes electron movement and energy transfer (absorbed)
- light oscillating perpendicular to molecules is transmitted
- **transmission axis** (polarization axis): direction of the transmitted electric field (perpendicular to molecules)
- a polaroid acts as a **polarizer**, creating plane-polarized light from unpolarized light

Malus's Law

- intensity of polarized light transmitted through a polaroid:

$$I = I_0 \cos^2 \theta$$

  - I_0: incident intensity

    - θ: angle between incident polarization and transmission axis
- for unpolarized light, the transmitted intensity is halved:

$$I = \frac{1}{2} I_0$$

Polaroids as Analyzers

- polaroids can determine if light is polarized and its plane of polarization (intensity changes upon rotation)
- **crossed polaroids** (transmission axes perpendicular) block all light
- **three polaroids**: even if the first and third are crossed, placing the second at 45 degrees allows some light to pass

Polarization by Reflection

- unpolarized light can be polarized upon reflection from a nonmetallic surface at non-perpendicular angles
- reflected light is preferentially polarized parallel to the reflecting surface

- light is preferentially transmitted and refracted with a polarization plane perpendicular to the surface
- **polaroid sunglasses** (vertical transmission axes) reduce glare from horizontal surfaces (blocking horizontally polarized reflected light)

Brewster's Angle

- degree of polarization in reflected beam varies with the angle of incidence
- 100% polarization at the **polarizing angle** or **Brewster's angle** (θ_p)
- Brewster's Law:

$$\tan\theta_p = \frac{n_2}{n_1}$$

  - n_1: refractive index of incident medium
  - n_2: refractive index of reflecting medium
- if incident from air ($n_1 = 1$):

$$\tan\theta_p = n_2$$

- at Brewster's angle, reflected and refracted rays are perpendicular ($\theta_p + \theta_r = 90^\circ$)

Slide 5: Scattering in the Atmosphere

Why the Sky is Blue

- blue sky, red sunsets, and polarized skylight are due to light scattering by atmospheric molecules (nitrogen, oxygen)
- sunlight causes molecules' electrons to oscillate, re-emitting light in all directions
- scattered light intensity is strongest perpendicular to oscillation and zero along it
- observer at 90 degrees to sunlight sees plane-polarized light
- amount of scattering is inversely proportional to the fourth power of wavelength ($1/\lambda^4$)
- shorter wavelengths (blue, violet) scatter much more effectively than longer wavelengths (red, orange)
- blue light is preferentially scattered in all directions, making the sky appear blue

Red Sunsets

- at sunset, sunlight travels through a much longer path in the atmosphere
- most blue light is scattered away during this extended passage
- light reaching our eyes directly from the setting sun (or reflected off clouds) is depleted in blue and appears reddish

Scattering by Clouds

- scattering depends on particle size relative to wavelength
- air molecules (much smaller than wavelength): strong wavelength dependence ($1/\lambda^4$)
- clouds (water droplets or ice crystals, larger than wavelength): scatter all colors nearly uniformly, appearing white

Slide 6: Brightness

Quantifying Light

- **physical intensity**: power per unit area [W/m^2]
- **radiant flux**: total power output [W]

- **perceived brightness**: considers visible spectrum and eye's sensitivity (peak at 550 nm)
- **luminous flux** (F_l): visual sensation, measured in lumens [lm] (1 lm = 1/683 W of 555 nm light)
- **luminous intensity** (I_l): luminous flux per unit solid angle (steradian), unit candela [cd] (1 cd = 1 lm/sr)
- **illuminance** (E_l): luminous flux incident on a surface per unit area, unit lumens per square meter [lm/m^2]

Slide 7: Interference: Newton's Rings & Thin Films

Monochromatic Light

- **monochromatic light**: single wavelength or narrow range of wavelengths (e.g., lasers, specific filters)

Newton's Rings with Monochromatic Light

- plano-convex lens with large radius of curvature on a flat glass surface creates a thin, wedge-shaped air gap
- illuminated from above with monochromatic light, observer sees concentric bright and dark circular rings (**Newton's rings**)
- appear where air gap thickness is a few multiples of the light's wavelength
- **interference pattern** due to light reflected from two surfaces:
    - bottom surface of the lens (glass-air interface)
    - top surface of the flat glass plate (air-glass interface)

Path Difference and Interference

- consider a light ray incident on the setup
- part reflected from the bottom of the lens
- part refracted into the air gap, reflected from the flat plate, and then to the observer
- the second part travels an extra distance of approximately twice the air gap thickness ($2t$)
- this extra distance is the **path difference**

Phase Shift upon Reflection

- at the point of contact (zero air gap), a dark spot is observed (destructive interference)
- reason: **180° phase shift ($\lambda/2$ path difference)** when light reflects from a medium of lower refractive index to one of higher refractive index (air to glass at the top of the flat plate)
- reflection from glass-air interface (bottom of the lens) has no such phase shift
- at the center, phase difference is $\lambda/2$ due to reflection, leading to destructive interference

Conditions for Rings

- as distance from the center increases, air gap thickness (t) increases
- path difference ($2t$) combined with $\lambda/2$ phase shift determines interference:
    - **dark rings (destructive interference)**: total path difference is half-integer multiple of wavelength

$$2t + \frac{\lambda}{2} = m\lambda \implies 2t = (m - \frac{1}{2})\lambda,$$

    - $m = 0$ corresponds to the dark center
  - **bright rings (constructive interference)**: total path difference is integer multiple of wavelength

$$2t + \frac{\lambda}{2} = (m + \frac{1}{2})\lambda \implies 2t = m\lambda,$$

    - $m = 1$ is the first bright ring

Newton's Rings with White Light

- using white light (spectrum of wavelengths) results in colored concentric rings
- constructive interference occurs for different wavelengths at different air gap thicknesses
- rings closest to the center are vibrant (rainbow sequence)
- further from the center, rings overlap more, color contrast decreases, eventually becoming nearly white or blurry

Interference in Thin Films

- interference also occurs in other thin films (soap bubbles, oil films on water, coatings)
- colors are due to interference of light reflected from the two interfaces
- for near-normal incidence, path difference is approximately $2nt$ (n: refractive index of film, t : thickness)
- phase shifts depend on refractive indices at each interface
- if reflection at both interfaces is lower to higher (or vice versa), phase shifts cancel

Non-Reflective Coatings

- application of thin-film interference
- thin layers on optical components (lenses) with carefully chosen refractive index and thickness (often $\lambda/4$ for minimized reflection, around 550 nm)
- destructive interference between light reflected from air-coating and coating-glass interfaces
- reduces reflected light intensity, increases transmission, improves optical instrument

performance

Slide 8: Interference: Young's Double-Slit Experiment

Thomas Young's Experiment

- thomas Young (1773-1829) provided strong evidence for the wave nature of light
- illuminated a screen with two closely spaced, narrow slits S_1 and S_2 (separation d)
- if d is on the order of the wavelength, interference occurs
- **diffraction** also occurs (next chapter), conceptually similar to interference at this level

Double-Slit with Monochromatic Light

- two slits act as **coherent sources** (same wavelength, constant phase relationship)
- waves diffract and overlap behind the screen
- consider a point on a viewing screen (distance L) at an angle θ
- **path difference** (Δ) between waves from S_1 and S_2 is approximately $\Delta = d \sin \theta$ (for

$L \gg d$)

Constructive Interference (Bright Fringes)

- occurs when path difference is an integer multiple of the wavelength (λ):

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

  - m is the order of the bright fringe
- **central bright fringe** ($m = 0$) at $\theta = 0$ (zero path difference, waves in phase)
- first-order bright fringes ($m = 1$) at angles where path difference is one wavelength
- distance between bright fringes is approximately constant for small angles ($\sin\theta \approx \theta$)

Destructive Interference (Dark Fringes)

- occurs when path difference is a half-integer multiple of the wavelength:

$$d \sin\theta = (m + \frac{1}{2})\lambda, \quad m = 0, 1, 2, \ldots$$

- waves from the two slits arrive exactly out of phase, amplitudes cancel

- viewing screen shows alternating bright and dark parallel fringes

Double-Slit with White Light

- white light (continuous spectrum of wavelengths) results in a more complex interference pattern
- condition for constructive interference ($d \sin \theta = m\lambda$) depends on λ
- for a given order m (except $m = 0$), different wavelengths interfere constructively at different angles θ

Colored Fringes

- **central fringe** ($m = 0$) remains white (zero path difference for all wavelengths)
- **first-order fringes** ($m = 1$): violet light (shorter λ) has smaller θ than red light (longer λ)
    - results in a spectrum of colors (violet closest to center, red furthest)
- higher-order fringes also show spectra but are broader and overlap more (colors less distinct)

- observation of colored fringes supported the idea that different colors correspond to different wavelengths
- enabled Young to measure wavelengths of visible light

Slide 1

Ovgu_fnw_logo & wave optics: interference & polarization

- introduction to the wave nature of light beyond the ray model
- focus on interference phenomena and polarization effects
- relevance for experimental physics in engineering studies

Slide 2

wave optics overview

- light behaves as a wave at scales comparable to its wavelength
- interference arises from the superposition of waves

- polarization reflects the transverse oscillation of electromagnetic fields
- key experiments and phenomena: diffraction, refraction, Newton's rings, Young's double-slit

---

Slide 3

huygens' principle

- every point on a wavefront acts as a source of secondary spherical wavelets
- new wavefront is the envelope (tangent surface) of all these wavelets
- explains diffraction and the spreading of light beyond simple straight-line propagation
- analogy: ripples from a stone in a pond, where all points on the crest contribute to the next ripple

Details on wavefronts

- a wavefront connects points that are in phase (e.g. crest of ripples)

- secondary wavelets interfere, forming the new wavefront shape
- direction of wave propagation is perpendicular to the wavefront

---

Slide 4

revisiting refraction from a wave perspective

- light travels with speed $v = c/n$, where c is the speed in vacuum and n is the refractive index
- distance travelled in time t is given by $r = vt$

Wave model at an interface

- two media: medium 1 with n_1 and medium 2 with n_2
- speeds are $v_1 = c/n_1$ and $v_2 = c/n_2$
- when a wavefront strikes an interface, different parts cross at different times
- geometry leads to bending of the wavefront and a change in propagation direction

Derivation of Snell's law

- consider a wavefront hitting the interface at an angle θ_1
- point A enters medium 2 first; after time t, point B is still in medium 1
- distances: in medium 2, light travels $v_2 t$; in medium 1, light travels $v_1 t$
- using the geometry of the wavefront segment, we obtain:

$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

- note: frequency remains constant while wavelength changes ($\lambda = v/f$)

Slide 5

polarization

- electromagnetic waves are transverse; the electric field oscillates perpendicular to propagation
- unpolarized light has random oscillations in all directions perpendicular to the propagation

- plane-polarized light oscillates in a single, fixed plane

Polarization by absorption (polaroids)

- polaroid sheets contain long molecules aligned in parallel
- molecules absorb the component of the electric field oscillating parallel to them
- transmitted light oscillates perpendicular to the molecule alignment
- Malus's law governs the transmitted intensity:

$$I = I_0 \cos^2 \theta$$

- two crossed polaroids (axes at 90°) block all light; a third at 45° can reintroduce some transmission

Polarization by reflection

- reflection at a nonmetallic surface polarizes light parallel to the surface
- maximum polarization occurs at Brewster's angle, where:

$$\tan \theta_p = \frac{n_2}{n_1}$$

- at Brewster's angle, the reflected and refracted rays are perpendicular

---

Slide 6

scattering in the atmosphere

- scattering by atmospheric molecules causes the blue sky and red sunsets
- electric fields of light induce oscillations in molecules, which re-emit light in all directions
- intensity of scattered light $\propto \frac{1}{\lambda^4}$, favoring shorter (blue) wavelengths

Detailed effects

- at a 90° viewing angle, scattered light appears plane-polarized
- during sunset, light traverses a longer atmospheric path, scattering out most blue light
- clouds, composed of larger water droplets or ice crystals, scatter all wavelengths nearly

equally, resulting in white appearance

Slide 7

brightness

- physical intensity is measured in watts per square meter [W/m^2]
- luminous flux F_l, in lumens [lm], accounts for the human eye's sensitivity (peaking at 550 nm)
- luminous intensity I_l is the luminous flux per unit solid angle, measured in candela [cd]
- illuminance E_l measures luminous flux per unit area (lm/m^2)
- these measures distinguish physical energy from human-perceived brightness

---

Slide 8

interference: newton’s rings & thin films

- setup: a plano-convex lens placed on a flat glass surface forms a thin, wedge-shaped air gap
- monochromatic light creates a pattern of concentric rings due to interference between reflections

Newton's rings details

- light reflects from two surfaces:
    - bottom of the lens (glass-air interface)
    - top of the glass plate (air-glass interface)
- the extra path difference is approximately $2t$, where t is the air gap thickness
- a phase shift of $\lambda/2$ occurs when light reflects from a medium of higher refractive index

Conditions for interference

- dark rings (destructive interference):

$$2t + \frac{\lambda}{2} = m\lambda \quad \Rightarrow \quad 2t = \left(m - \frac{1}{2}\right)\lambda$$

- bright rings (constructive interference):

$$2t + \frac{\lambda}{2} = \left(m + \frac{1}{2}\right)\lambda \quad \Rightarrow \quad 2t = m\lambda$$

- using white light produces colored rings as different wavelengths satisfy the condition at different air gap thicknesses

Interference in thin films

- similar interference occurs in soap bubbles, oil films, and non-reflective coatings
- for near-normal incidence, the path difference is about $2nt$, with n the refractive index of the film
- design of non-reflective coatings uses a quarter-wavelength thickness to cause destructive interference of reflected light

---

Slide 9

interference: young's double-slit experiment

- two closely spaced slits S_1 and S_2 act as coherent light sources
- light waves diffract at the slits and overlap to produce an interference pattern on a screen

Monochromatic light setup

- for a viewing screen at distance L, the path difference at an angle θ is:

$$\Delta = d \sin \theta$$

- bright fringes (constructive interference) occur when:

$$d \sin \theta = m\lambda \quad (m = 0, 1, 2, \ldots)$$

- dark fringes (destructive interference) occur when:

$$d \sin \theta = \left(m + \frac{1}{2}\right) \lambda \quad (m = 0, 1, 2, \ldots)$$

- the central bright fringe ($m = 0$) appears white as all wavelengths constructively interfere

Young's experiment with white light

- white light contains a spectrum of wavelengths
- the central fringe remains white while higher-order fringes separate into different colors

- observation of colored fringes supports that different colors correspond to different wavelengths
- enables experimental determination of wavelengths in the visible spectrum