WEL03 INTERFERENCE IN THIN FILMS

SPH4U

CH 10 (KEY IDEAS)

- describe polarized light in terms of its properties and behaviour and how it is applied in everyday applications
- explain single-slit diffraction and diffraction grating interference patterns, both qualitatively and quantitatively
- explain the operation of the spectroscope and the interferometer in terms of the wave properties of light
- describe how the wave properties of light are important in resolution of optical instruments and how these properties are applied in various applications of thin-film interference, for example: Newton’s rings, colours in thin films, coated surfaces, CDs, and DVDs
- explain the basic concepts holography
- describe electromagnetic waves in terms of their properties and where they belong in the electromagnetic spectrum

EQUATIONS

- Reflected Light off Thin Films
  - Constructive Interference

    $$t = \frac{\lambda}{4}, \frac{3\lambda}{4}, \frac{5\lambda}{4}, \ldots$$

    Destructive Interference

    $$t = 0, \frac{\lambda}{2}, \lambda, \frac{3\lambda}{2}, \ldots$$

- Transmitted Light through Thin Films
  - Constructive Interference

    $$t = 0, \frac{\lambda}{2}, \lambda, \frac{3\lambda}{2}, \ldots$$

    Destructive Interference

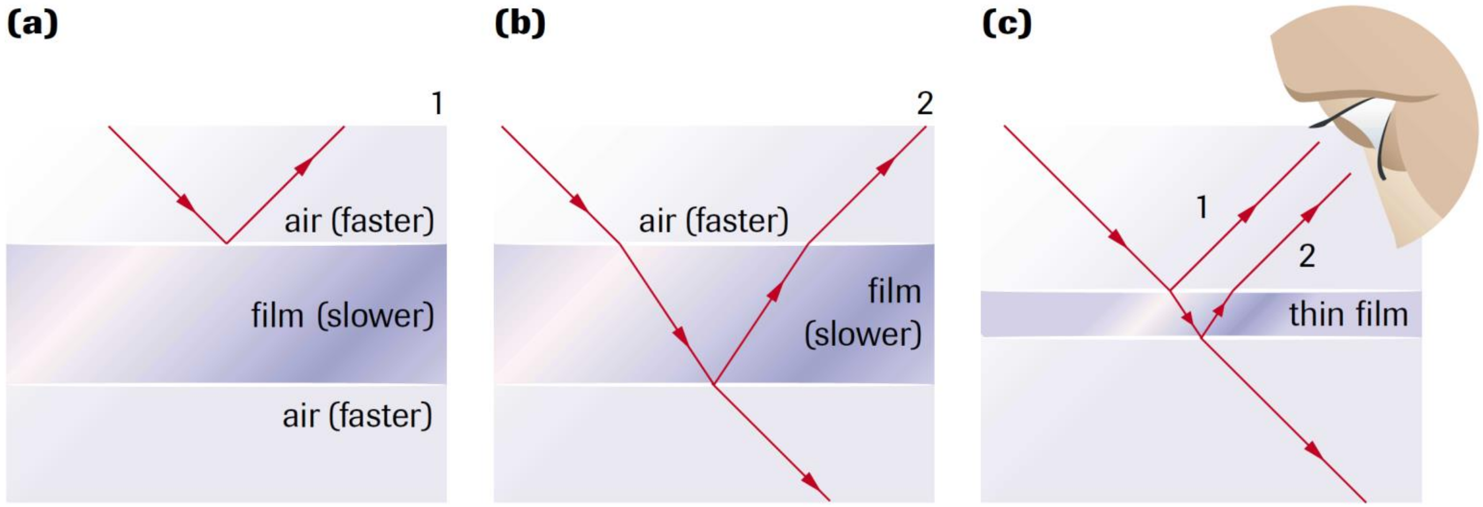
    $$t = \frac{\lambda}{4}, \frac{3\lambda}{4}, \frac{5\lambda}{4}, \ldots$$

- Air Wedges

$$\Delta x = L\left(\frac{\lambda}{2t}\right)$$

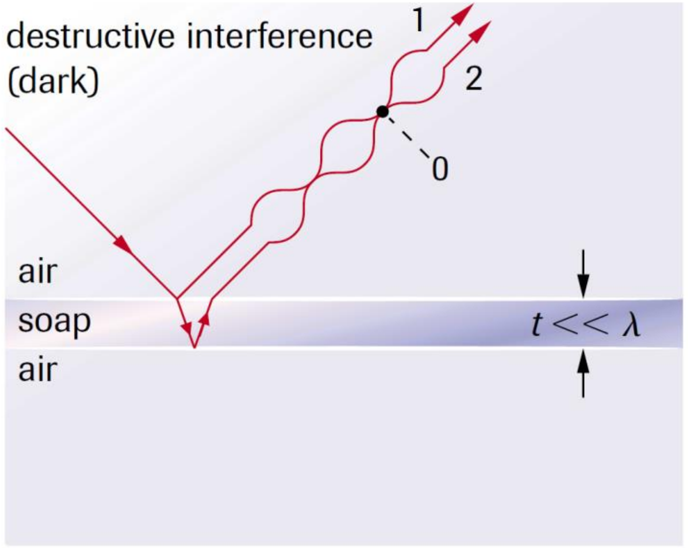
INTERFERENCE IN THIN FILMS

- Consider a soap bubble. If we look close enough the surface appears flat.
- Some light reflects off the surface of the bubble
- The remainder passes through, refracting in the slower medium.
- Some light reflects off the second boundary, passing out of the upper layer of the bubble.



INTERFERENCE IN THIN FILMS – REFLECTED LIGHT

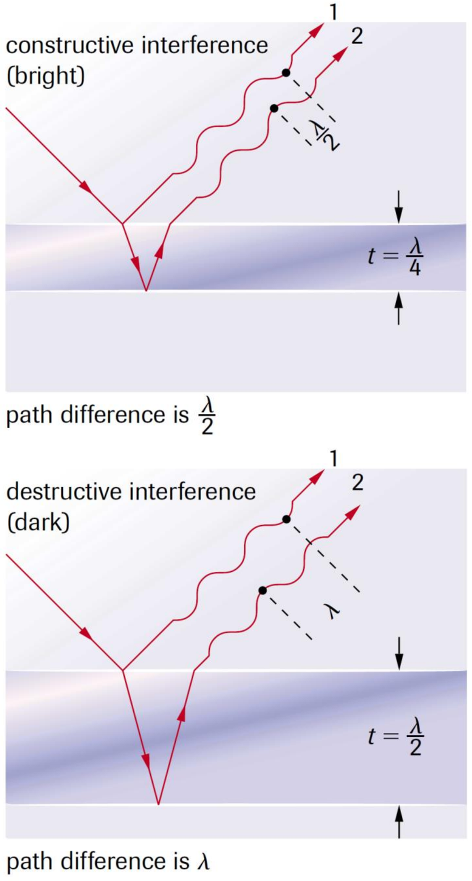
- Light travels more slowly through the soap layer than it does through air
- This behaves as fixed end for the waves reflecting off the surface, inverting the reflected waves
- The second boundary is a free end, as light travels faster in air, so the reflected waves do not invert
- With a very thin film the distance travelled within the film is negligible, resulting in destructive interference between the two sets of reflected rays
  - This is why the very top of a soap bubble will look dark (where it is thinnest)



path difference approaches zero

INTERFERENCE IN THIN FILMS – REFLECTED LIGHT CONT.

- When the film is a little thicker ($t = \frac{\lambda}{4}$) the two reflected rays show constructive interference
  - Light travels a distance of $2t = \frac{\lambda}{2}$ within the film, allowing the waves to be back in phase
  - This occurs when $t = \frac{\lambda}{4}, \frac{3\lambda}{4}, \frac{5\lambda}{4}, \ldots$
- When the film has a thickness of $t = \frac{\lambda}{2}$ there is destructive interference
  - Light travels a distance of $2t = \lambda$ within the film, so the waves are still out of phase by half a wavelength
  - This occurs when $t = 0, \frac{\lambda}{2}, \lambda, \frac{3\lambda}{2}, \ldots$
- NOTE: λ is the wavelength <u>within the film</u>; recall $\lambda_2 = \frac{\lambda_1 n_1}{n_2}$

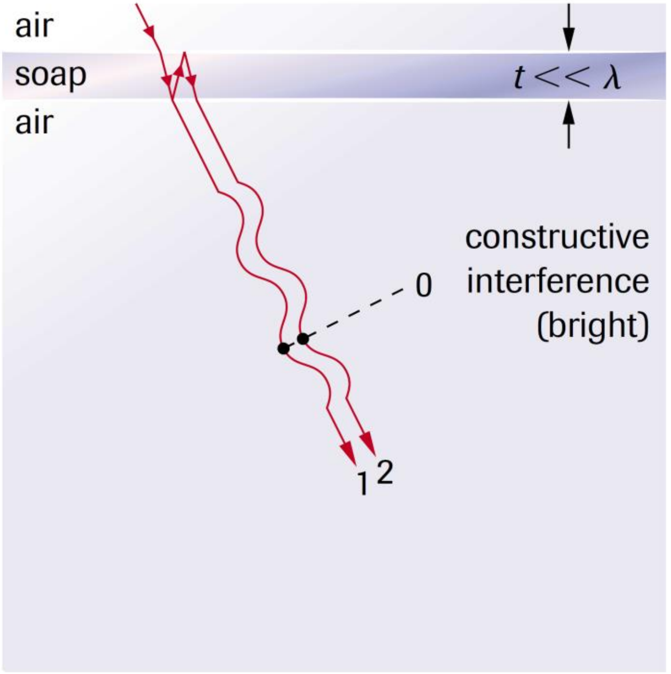


INTERFERENCE IN THIN FILMS – COLOURS OF LIGHT

- Recall that the wavelengths for different colours of light are different lengths
- The film thickness that gives constructive interference for red light will cause destructive interference for another colour
- This causes the rainbow dispersion of light we see on bubble, oil spills, etc.

INTERFERENCE IN THIN FILMS – TRANSMITTED LIGHT

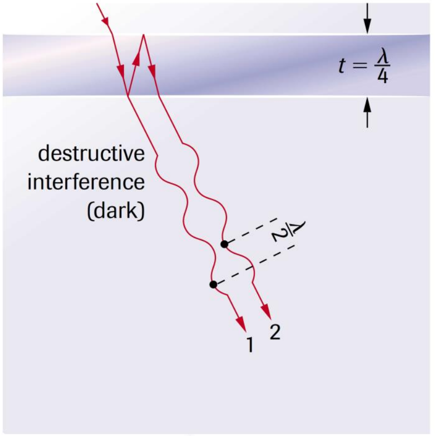
- When light is transmitted through the bubble there is no change in phase
- Some of the light that reflected inside the film reflects back off the upper surface and back through the lower side of the bubble
  - All reflections behaved as free ends, so there is no inversion of the waves
- When the film is very thin, the distance the reflected light travelled is negligible
  - There is no phase change, so we see constructive interference
- This is why there is a bright spot if you are looking at the bubble from the other side
  - Think of a bubble wand before you blow a bubble



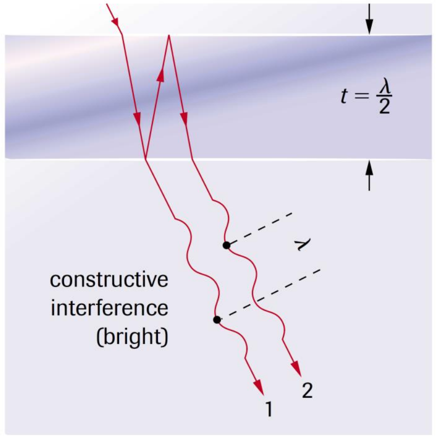
path difference approaches zero

INTERFERENCE IN THIN FILMS – TRANSMITTED LIGHT CONT.

- When the film is a thickness of $t = \frac{\lambda}{4}$, the reflected light travels a distance of $2t = \frac{\lambda}{2}$
  - The transmitted waves have a path difference of half a wavelength, so they are out of phase and have destructive interference
- When the film thickness is $t = \frac{\lambda}{2}$, the reflected light travels a distance of $2t = \lambda$
  - The transmitted waves have a path difference of a wavelength, so they are in phase and have constructive interference
- NOTE: λ is the wavelength <u>within the film</u>; recall $\lambda_2 = \frac{\lambda_1 n_1}{n_2}$



path difference is $\frac{\lambda}{2}$



path difference is λ

PROBLEM 1

In summer months, the amount of solar energy entering a house should be minimized. Window glass is made energy-efficient by applying a coating to maximize reflected light. Light in the midrange of the visible spectrum (at 568 nm) travels into energy-efficient window glass, as in **Figure 5**. What thickness of the added coating is needed to maximize reflected light and thus minimize transmitted light?

PROBLEM 1 – SOLUTIONS

Reflection occurs both at the air–coating interface and at the coating–glass interface. In both cases, the reflected light is 180º out of phase with the incident light, since both reflections occur at a fast-to-slow boundary. The two reflected rays would therefore be in phase if there were a zero path difference. To produce constructive interference the path difference must be $\frac{\lambda}{2}$. In other words, the coating thickness t must be $\frac{\lambda}{4}$, where λ is the wavelength of the light in the coating.

$n_{coating} = 1.4$

$t = ?$

$$n_{coating} = \frac{\lambda_{air}}{\lambda_{coating}}$$

$$\lambda_{coating} = \frac{\lambda_{air}}{n_{coating}}$$

$$= \frac{568 \text{ nm}}{1.4}$$

$$\lambda_{coating} = 406 \text{ nm}$$

$$t = \frac{\lambda_{coating}}{4}$$

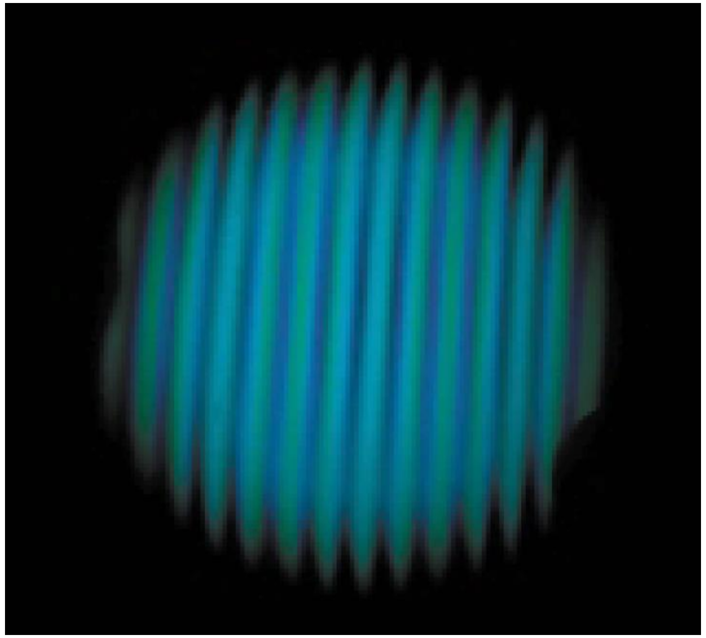
$$= \frac{406 \text{ nm}}{4}$$

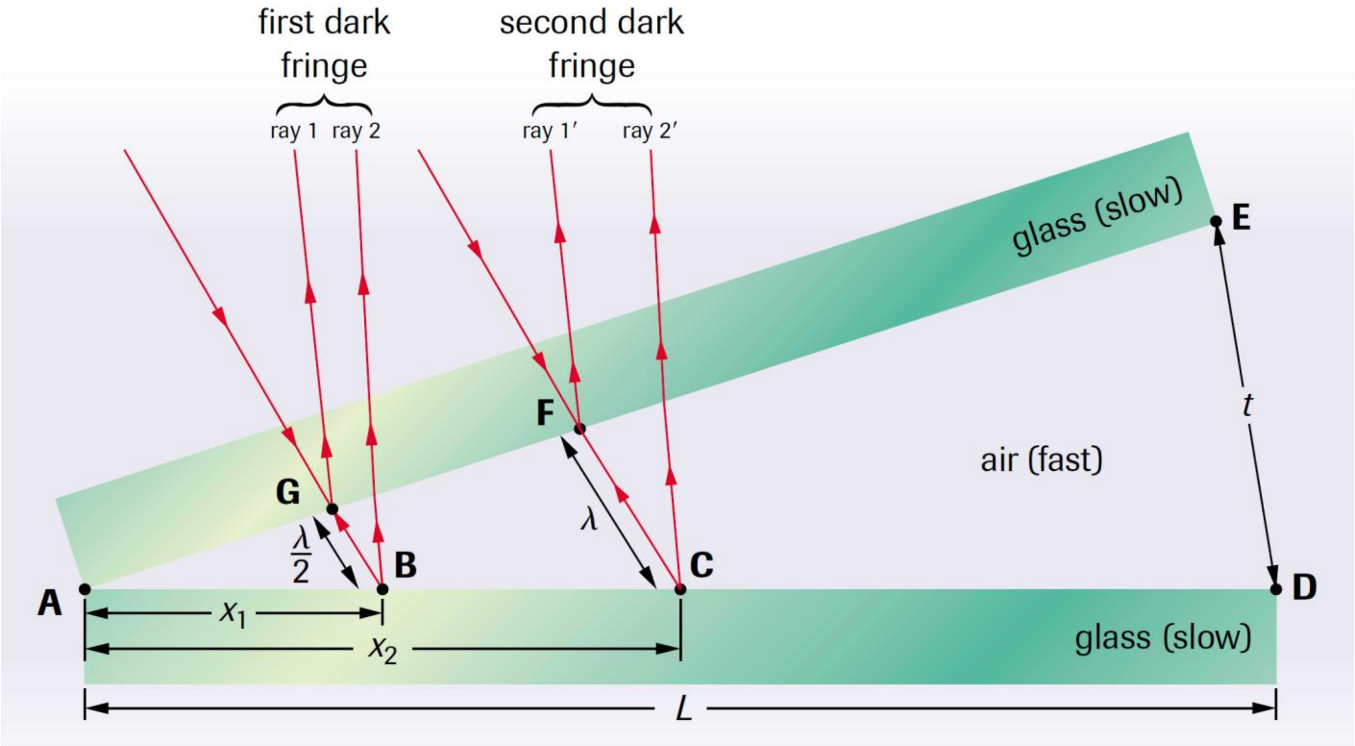
$$t = 101 \text{ nm, or } 1.0 \times 10^{-7} \text{ m}$$

The required thickness for the coating is 1.0×10^{-7} m.

INTERFERENCE IN AN AIR WEDGE

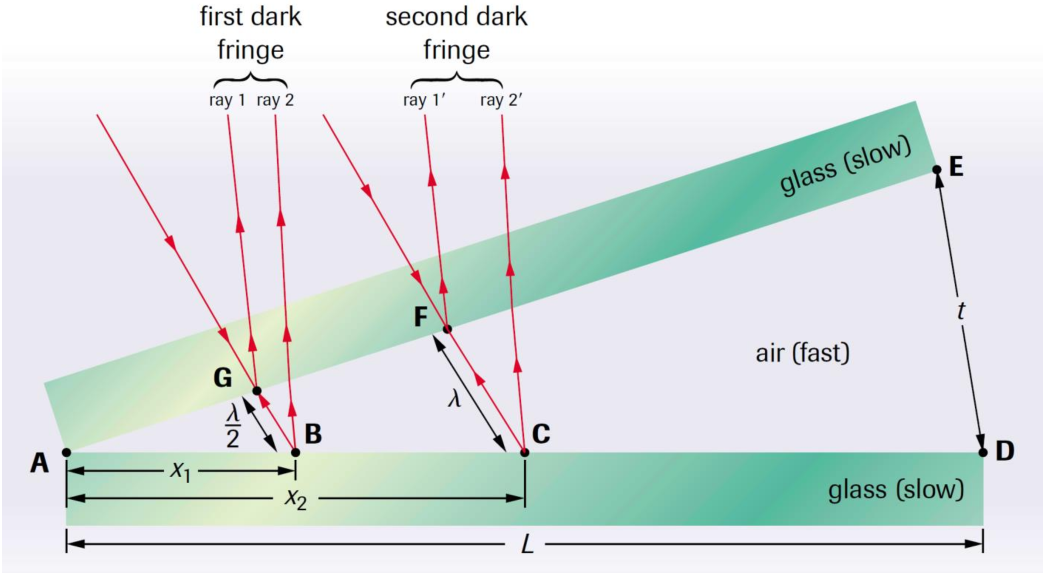
- **Air Wedge:** the air between two pieces of optically flat glass angled to form a wedge





INTERFERENCE IN AN AIR WEDGE – CONT.

- NOTE: the diagram is not to scale; in reality, angles of incidence approach zero
- We can use the air wedge to determine the wavelength of incident light by measuring the interference pattern it creates
- Since the angle of incidence is so small and the wedge is so narrow, we can assume segments GB, FC, and ED are parallel



INTERFERENCE IN AN AIR WEDGE – CONT.

- This gives us the following similar triangles

$$\triangle ABG \cong \triangle ACF \cong \triangle ADE$$

- Comparing $\triangle$ ABG to $\triangle$ ADE:

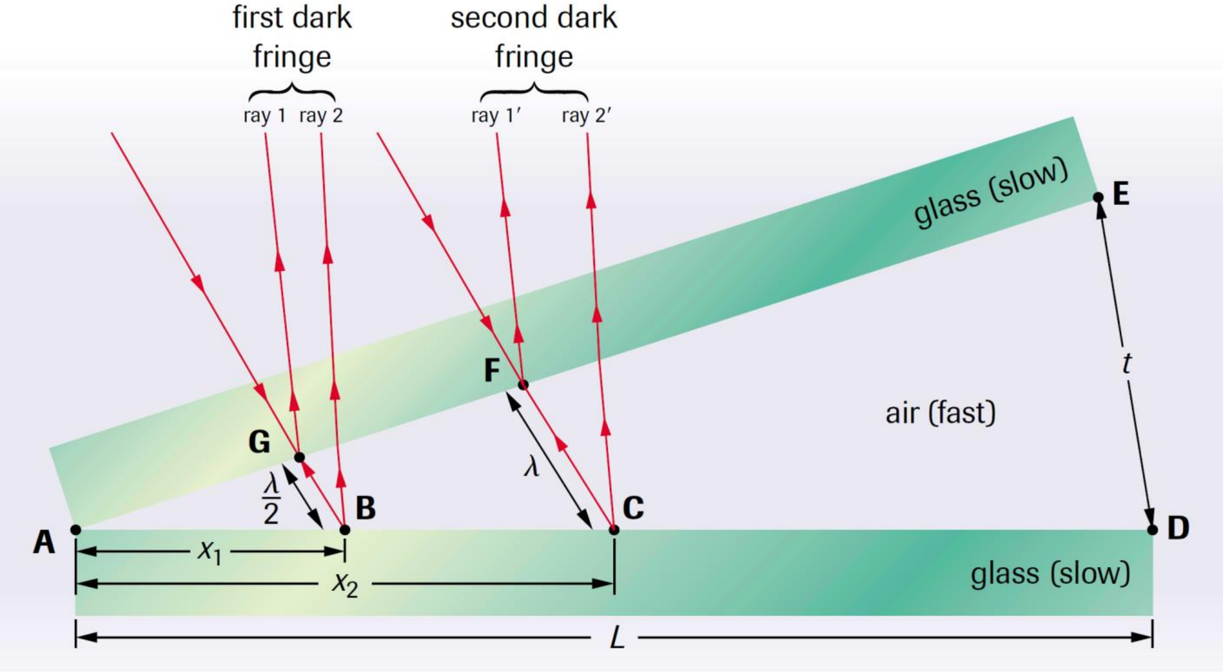
$$\frac{x_1}{L} = \frac{\left(\frac{\lambda}{2}\right)}{t}$$

$$x_1 = \frac{L\lambda}{2t}$$

- Comparing $\triangle$ ACF to $\triangle$ ADE:

$$\frac{x_2}{L} = \frac{\lambda}{t}$$

$$x_2 = \frac{L\lambda}{t}$$



INTERFERENCE IN AN AIR WEDGE – CONT.

- The distance between dark fringes is Δx

$$\begin{aligned}\Delta x &= x_2 - x_1 \\ &= \frac{L\lambda}{t} - \frac{L\lambda}{2t}\end{aligned}$$

$$\boldsymbol{\Delta x = L\left(\frac{\lambda}{2t}\right)}$$

  - L – length of the air wedge
  - λ – wavelength of light in the wedge
  - t – thickness of the base of the wedge

PROBLEM 2

(a) An air wedge between two microscope slides, 11.0 cm long and separated at one end by a paper of thickness 0.091 mm, is illuminated with red light of wavelength 663 nm. What is the spacing of the dark fringes in the interference pattern reflected from the air wedge?

(b) How would the spacing change if the wedge were filled with water ($n = 1.33$)?

PROBLEM 2 – SOLUTIONS

$$L = 11.0 \text{ cm} \qquad t = 0.091 \text{ mm} = 9.1 \times 10^{-3} \text{ cm}$$

$$\lambda = 663 \text{ nm} = 6.63 \times 10^{-5} \text{ cm} \qquad \Delta x = ?$$

(a) In air:

$$\Delta x = L\left(\frac{\lambda}{2t}\right)$$

$$= 11.0 \text{ cm}\left(\frac{6.63 \times 10^{-5} \text{ cm}}{2(9.1 \times 10^{-3} \text{ cm})}\right)$$

$$\Delta x = 4.0 \times 10^{-2} \text{ cm}$$

The spacing between the dark fringes in air is 4.0×10^{-2} cm.

PROBLEM 2 – SOLUTIONS CONT.

(b) If the air were replaced by water:

$$\frac{n_w}{n_a} = \frac{\lambda_{air}}{\lambda_{water}}$$

$$\lambda_{water} = \left(\frac{n_a}{n_w}\right)\lambda_{air}$$

$$= \frac{1.00}{1.33}(6.63 \times 10^{-5}\ \text{cm})$$

$$\lambda_{water} = 4.98 \times 10^{-5}\ \text{cm}$$

$$\Delta x = L\left(\frac{\lambda}{2t}\right)$$

$$= 11.0\ \text{cm}\left(\frac{4.98 \times 10^{-5}\ \text{cm}}{2(9.1 \times 10^{-3}\ \text{cm})}\right)$$

$$\Delta x = 3.0 \times 10^{-2}\ \text{cm}$$

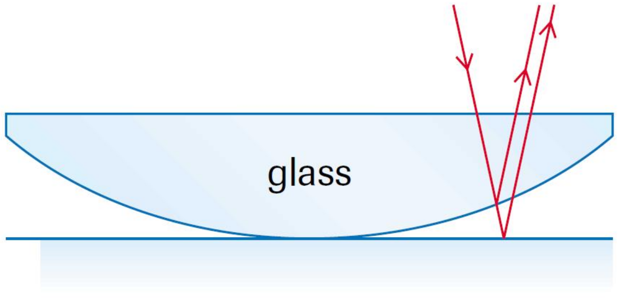
The spacing of the dark fringes in water would be 3.0×10^{-2} cm.

HELPFUL VIDEOS

- Khan Academy – Thin Film Interference Parts 1 & 2
  - https://www.youtube.com/watch?v=oXowkdgJPO4
  - https://www.youtube.com/watch?v=yWkga94iBzU

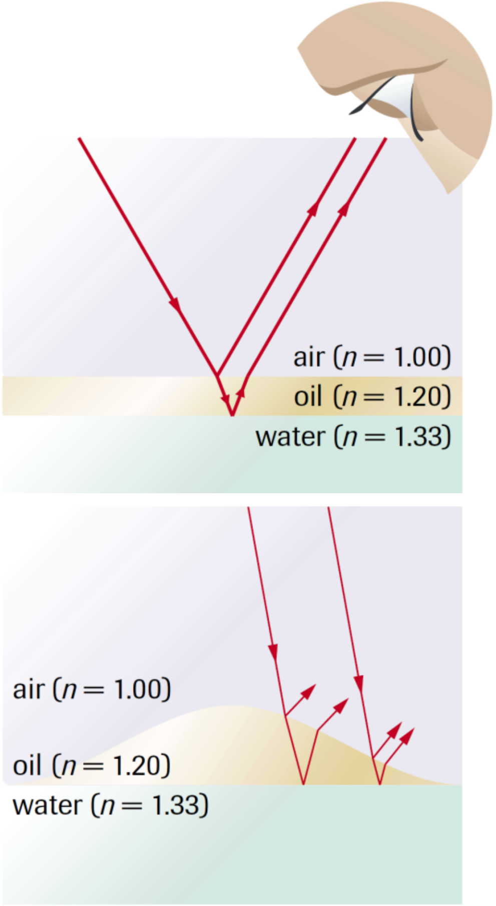
NEWTON'S RINGS

- **Newton's Rings:** a series of concentric rings, produced as a result of interference between the light rays reflected by the top and bottom of a curved surface
- This is useful in:
  - Verifying that a newly ground lens has the proper curvature
  - Verifying if a piece of metal is indeed flat



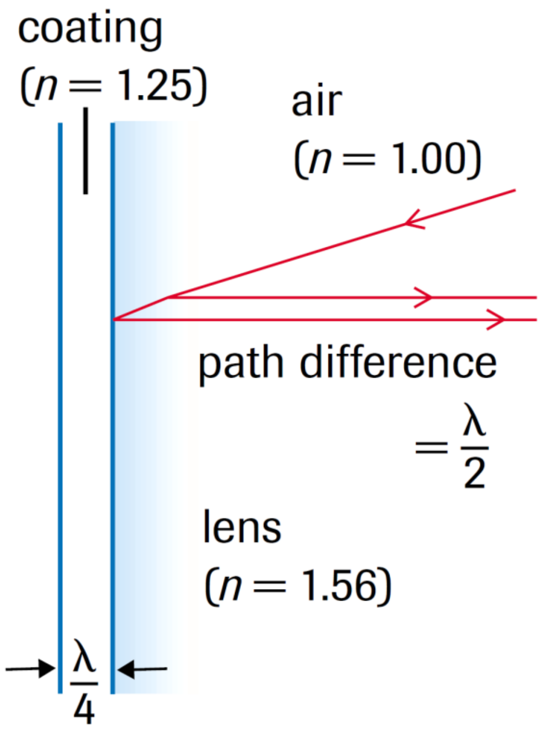
OIL ON WATER

- Since $n_{\text{air}} < n_{\text{oil}} < n_{\text{water}}$, both reflected rays are phase-inverted
- Different thicknesses of oil will cause constructive interference with different wavelengths of light
- This is what gives the swirling rainbow effect



EYEGLASSES AND LENSES

- A common problem with eyeglasses is back-glare
  - **Back-glare:** the reflection of light from the back of eyeglass lenses into the eyes
- Significant reduction of back-glare is found when a coating of $t = \frac{\lambda}{4}$ is applied to the lens
  - A wavelength near the centre of the visible spectrum is usually chosen
  - Multiple coatings of varying thickness can help reduce glare from different wavelengths of light

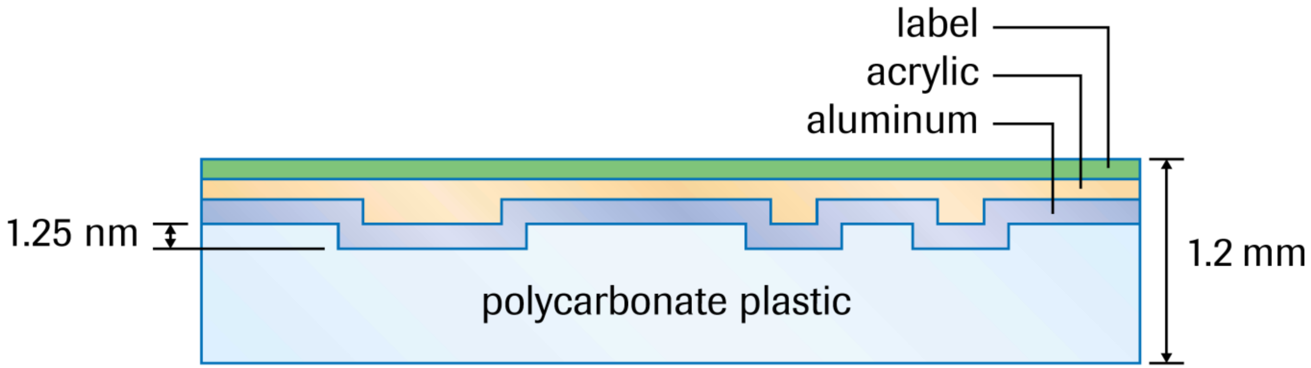


CDS AND DVDS

- CDs store information as a long track of bumps read by a laser
- This track is very thin (0.5 μm) and is printed in a spiral on a disk, allowing the tracks to be very long (can be over 5 km)
- Tracks start at the inside of the disk and wind their way to the outside

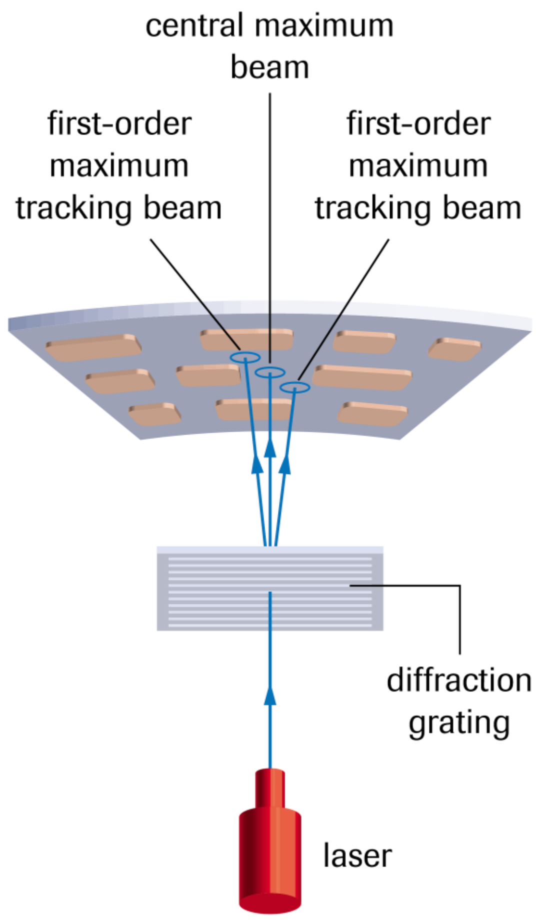
CDS AND DVDS – CONT.

- A CD is composed of layers
  - Polycarbonic plastic has the track bumps moulded in
  - An aluminum layer protects the track
  - An acrylic layer protects the aluminum from exposure
  - A label is usually printed onto the acrylic



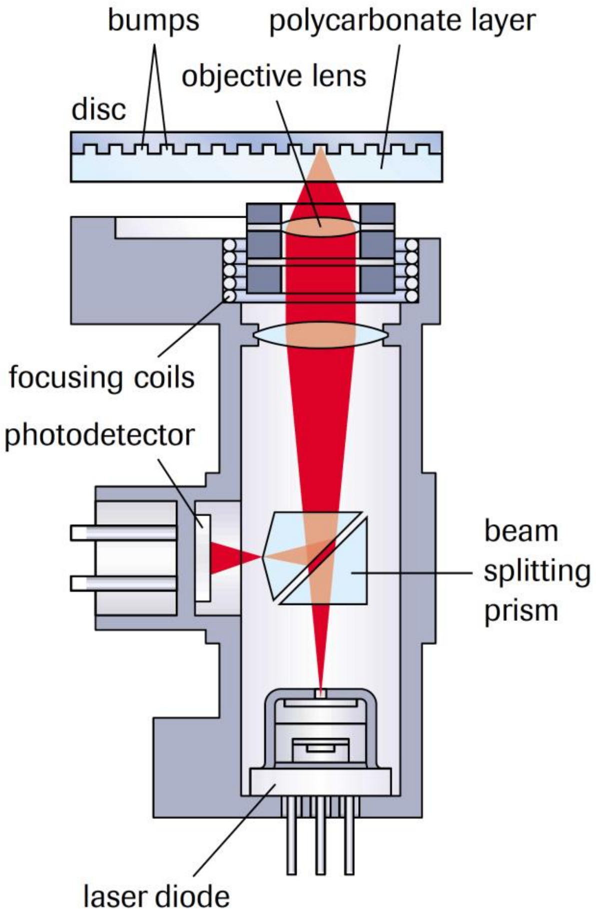
CDS AND DVDS – CONT.

- To read the track, a laser is sent through a diffractions grating
- The central maximum beam reads the track
- The first-order maximum beams run along either side of the track, ensuring the beam stays along the track
- The track must be read at a constant speed, so the drive motor must slow down as the laser moves outward, ranging from 500 to 200 rpm



CDS AND DVDS – CONT.

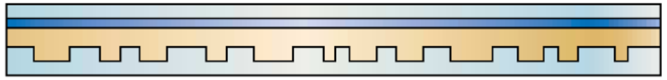
- Laser light is polarized vertically to prevent reflection off the polarized beam splitter
  - This allows nearly all returning light to be reflected into the photodetector
- The bumps are made to be $t = \frac{\lambda}{4}$, so the light travels half a wavelength further where there is a space
  - This causes destructive interference, reducing the intensity of spaces between bumps
- This information is a physical representation of binary electrical signals



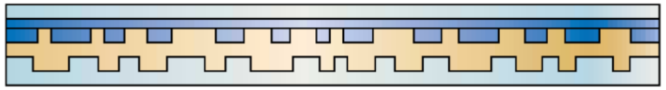
CDS AND DVDS – CONT.

- DVDs are similar to CDs, but have increased capacity
  - Track thickness is only 320 nm, rather than a CD's 500 nm
  - Laser wavelength is shorter; 635 nm instead of 780 nm
  - Semireflective gold is used instead of aluminum
- Because of the gold used, DVDs can have double-layer tracks
- Using both sides of the disk, along with the double layer, allows storage of up to 17 GB of information

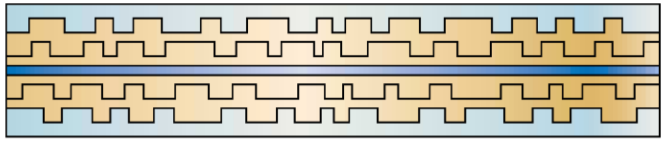
single-sided, single layer (4.7 GB)



single-sided, double layer (8.5 GB)



double-sided, double layer (17 GB)



SUMMARY – INTERFERENCE IN THIN FILMS

- For reflected light in thin films, destructive interference occurs when the thin film has a thickness of $0, \frac{\lambda}{2}, \lambda, \frac{3\lambda}{2}, \ldots$, and constructive interference occurs at thicknesses of $\frac{\lambda}{4}, \frac{3\lambda}{4}, \frac{5\lambda}{4}, \ldots$, where λ is the wavelength in the film.
- For transmitted light in thin films, destructive interference occurs at $\frac{\lambda}{4}, \frac{3\lambda}{4}, \frac{5\lambda}{4}, \ldots$, and constructive interference occurs at $0, \frac{\lambda}{2}, \lambda, \frac{3\lambda}{2}, \ldots$, where λ is the wavelength in the film.
- Air wedges can be used to determine the thicknesses of very small objects through the relationship $\Delta x = L\left(\frac{\lambda}{2t}\right)$.

SUMMARY – APPLICATIONS OF THIN FILMS

- Newton’s rings can be used to determine the “flatness” of objects.
- Thinly coated lenses reduce or eliminate unwanted reflections and UV radiation. If the coating is $\frac{\lambda}{4}$ thick, destructive interference effectively reduces reflected light.
- CDs and DVDs use principles of thin-film interference and polarization.
- DVDs have a much higher capacity than CDs: their tracks are narrower; they can record data on two levels; and they use both sides of the disc.

PRACTICE

Readings

- Section 10.4 (pg 512)
- Section 10.5 (pg 520)

Questions

- pg 519 #1-6
- pg 524 #1-3,5,7