10.1 Interference in Thin Films

You may have noticed the colours of reflected light in a thin layer of oil in a puddle on a road, like the one in **Figure 1**. To understand why reflection from a layer of oil produces this colourful pattern, you need to understand the interference of light waves when they are reflected from or transmitted through a thin layer of material, often called a **thin film**.

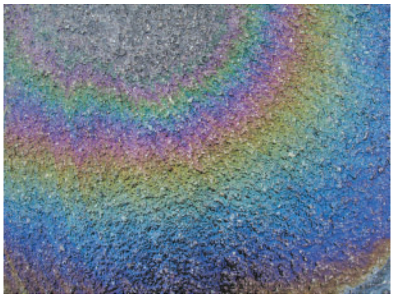

Figure 1 The colours in a thin film of oil on a road depend on the thickness of the oil layer.

thin film a very thin layer of a substance, usually on a supporting material

Phase Change Due to Reflection

When light rays travelling from air meet the upper surface of an oil layer, some light waves are reflected. Similar behaviour occurs at the lower surface of the oil layer, with the result that light rays from both surfaces are reflected. These rays interfere either constructively or destructively, depending on their phase difference. For example, if the ray travels from one medium into a more optically dense medium, the reflected wave is inverted so it will not constructively interfere.

You can see this effect for yourself by attaching one end of a string tightly to a wall, holding the other end of the string in your hand, and moving your wrist sharply to create a wave. The incident wave travels quickly down the string and hits the wall. The wall pushes against the string with a force that is equal in magnitude and opposite in direction, according to Newton's third law of motion. This causes the wave to be inverted when it is reflected. Now suppose that the string is not fixed at one end or the incident wave encounters another medium in which the wave can travel faster. Then the reflected wave will not be inverted. It will have the same phase as the incident wave.

A wave that goes right through the medium, or is transmitted, does not reflect, so it is never inverted. You can verify this by tying a long metal wire to the loose end of a string. Hold the other end of the wire in your hand, and move your wrist sharply as before. The incident wave will travel quickly down the wire and encounter the string. Since the string is more flexible than the wire, the string will offer little resistance to the incident wave, and some of the wave's energy will carry forward through the string. Whatever wave reflects back to the wire will have the same phase as the incident wave.

Similar to the waves in the string, light waves will also invert when they encounter the surface of more optically dense media. A more optically dense medium has a higher index of refraction, so light waves are slowed down by the medium. As you can see in **Figure 2(a)**, when an incident wave reaches a fixed end or the boundary of a medium in which its speed will decrease, the reflected wave is inverted. On the other hand, if the wave reaches a free end or the boundary of a medium in which its speed will increase (**Figure 2(b)**), the reflected wave is not inverted and no phase change occurs.

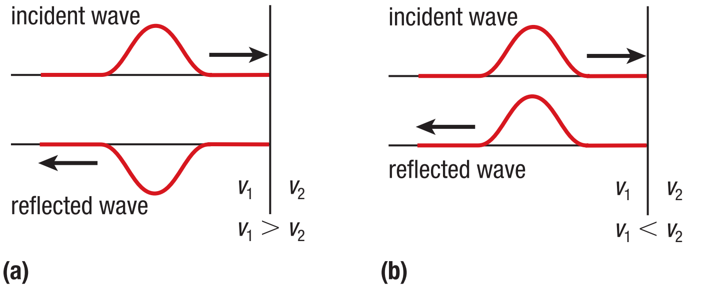

Figure 2 (a) A wave is inverted when it reflects from a fixed end or encounters a medium in which the speed of the wave decreases. (b) A wave is not inverted when it reflects from a free end or encounters a medium in which the speed of the wave increases.

Wavelength and the Index of Refraction

How does wavelength relate to the index of refraction? **Figure 3** shows a light wave striking a thin film of oil on a glass slide. The waves reflect from the top and bottom surfaces of the film of oil. Assume that the angle of incidence is zero. In the following figures, the incident ray is drawn with a larger angle of incidence so that the two reflected rays are easily visible.

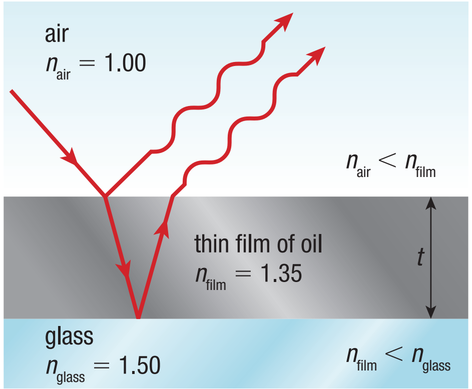

Figure 3 Light waves reflect from the top and bottom surfaces of a thin film of oil on glass. The indices of refraction are related as follows: $n_{air} < n_{film} < n_{glass}$.

For a film of thickness t, the distance travelled by the ray reflecting off the bottom layer is $2t$. This path difference will cause a phase difference between the rays reflected off the top and bottom layers of the film. To determine the total phase difference, however, you also need to account for the change in wavelength of the wave travelling through the film due to the index of refraction of the film.

The frequency, f, and wavelength, λ_{vac}, of a light wave in a vacuum are related by

$$c = \lambda_{vac} f$$

where $c = 3.0 \times 10^8$ m/s, the speed of light in a vacuum. When light travels through a substance with index of refraction n, its speed, v, is $\frac{c}{n}$. Since n for any substance is greater than 1, light travels more slowly in the substance than in a vacuum. The product of the wavelength in the film, λ_{film}, and the frequency of the light in the film, f_{film}, equals the wave speed. Thus,

$$\lambda_{film} f_{film} = \frac{c}{n_{film}}$$

Comparing the two previous equations shows that the wavelength, the frequency, or both must change when light travels from a vacuum into the thin film. **Figure 4** shows that as the light wave travels from one medium to the other, the wavelength changes but the frequency remains the same. If this were not the case, the waves just outside and just inside the film would not remain in phase, and the wave fronts would "pile up" at the boundary.

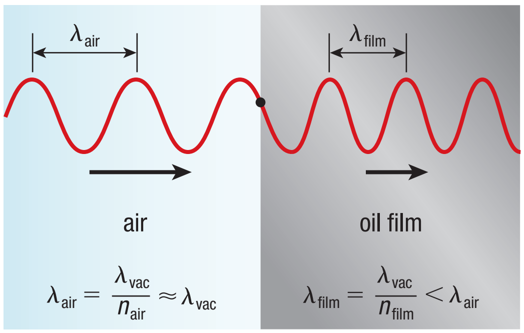

Figure 4 When light travels from air to a different medium, such as an oil film, the light waves are in phase. This can only happen if the frequency is the same on both sides of the boundary.

Although the frequency of light is unchanged as it enters the film, its wavelength changes. If we divide the previous equation by f, the wavelength inside the film becomes

$$\lambda_{\text{film}} = \frac{1}{f}\frac{c}{n_{\text{film}}}$$

Combining this with the relation between λ and f in a vacuum then leads to

$$\lambda_{\text{film}} = \frac{\lambda_{\text{vac}}}{n_{\text{film}}}$$

The wavelength of light inside the film is thus shorter by a factor of $\frac{1}{n_{\text{film}}}$. The same is true for light travelling in air, with $\lambda_{\text{air}} = \frac{\lambda_{\text{vac}}}{n_{\text{air}}}$. Given that n_{air} is very close to 1 ($n_{\text{air}} = 1.0003$), interference effects are not usually considered in air. Therefore, the wavelength of a light wave in air is close to its wavelength in a vacuum:

$$\lambda_{\text{air}} \approx \lambda_{\text{vac}}$$

The ray travelling through the oil film in Figure 3, on the previous page, travels the distance $2t$ inside the film. The extra number of wavelengths, N, this wave travels is thus

$$N = \frac{2t}{\lambda_{\text{film}}}$$

For example, if N has a value of 4, the ray will travel four complete, extra wavelengths compared with the ray reflecting off the top of the film.

To determine whether this combination of reflected rays produces constructive or destructive interference, you need to combine the phase change due to the path difference with phase changes due to reflection.

Thin Films and Interference

To understand what leads to the colours from a film such as the one in Figure 1, on page 502, consider a thin film between two glass slides. For simplicity's sake, assume that the light is monochromatic (single pure colour), so it has a single wavelength. When the light ray in **Figure 5** strikes the upper surface of the film, part of the light wave reflects and part of it transmits through the film. The transmitted part will then partially reflect from the boundary between the material under the film and the bottom surface of the film, and part of the wave will also transmit through the bottom surface. The intensity of transmitted and reflected light depends on the properties of the reflecting material. For a transparent material, much of the wave transmits and little reflects. For an opaque material, much of the wave reflects and little transmits.

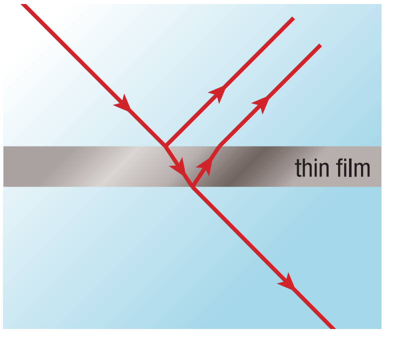

Figure 5 Both surfaces of a thin film reflect and transmit part of the incident light.

You will need to follow several steps to determine the relative phase of the interfering reflected waves. The difference in phase due to path difference depends on the difference in the lengths of the two paths and the wavelength of the light in the film. The phase change due to reflection depends on the relative sizes of the indices of refraction of the film and the surrounding substances.

Now suppose a thin film, for example a soap film, lies between air on one side and a substance with a higher index of refraction on the other, such as glass, so that $n_{air} < n_{film} < n_{glass}$ (**Figure 6**). Two phase changes occur when the index of refraction increases across each successive boundary, so both waves reflecting from the thin film invert upon reflection. Since they both change by the same amount, this change introduces no difference in phase between the two waves. If the number of extra wavelengths, N, is a whole number, light waves that travel along rays 2 and 3 in Figure 6 are in phase and interfere constructively with one another. If N is not a whole number, they are out of phase. For both waves having a phase change,

$$2t = \frac{n\lambda}{n_{film}} \text{ (constructive interference); } 2t = \frac{\left(m + \frac{1}{2}\right)\lambda}{n_{film}} \text{ (destructive interference)}$$

where $n = 1, 2, 3, \ldots$, and $m = 0, 1, 2, \ldots$.

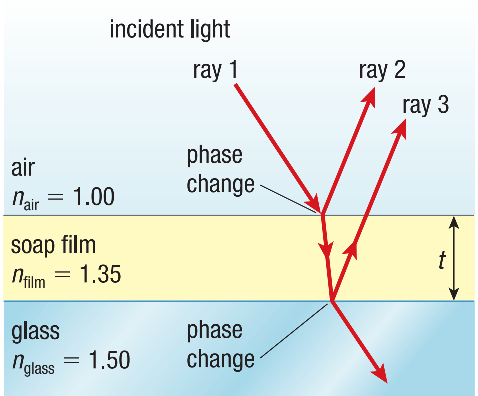

Figure 6 The incident light ray, ray 1, meets the boundary between the air and the soap film and is partially reflected (ray 2) and partially transmitted through the film. When it encounters the boundary between the soap film and the glass, it is partially reflected (ray 3) and partially transmitted.

Now we look at the case when only one of the two waves has a phase change on reflection, as, for example, in the case of a soap film with air on both sides (**Figure 7**). To simplify the analysis, we continue to consider the case where the incident and reflected rays are all approximately normal (perpendicular) to the film. This means that the rays that pass through the film travel a total distance of $2t$, where t is the thickness of the film. As before, the diagram does not show that the rays are perpendicular. The reason is that the rays would lie on top of each other, making the diagram difficult to understand and analyze.

The index of refraction of the soap film in Figure 7 is 1.35, so part of ray 1 reflects and becomes inverted (ray 2) when it encounters a medium with a higher index of refraction. Part of ray 1 transmits through the soap film, where it encounters the bottom layer of the film. It reflects and continues back through the soap film. There is no phase change when it encounters a medium with a lower index of refraction. The inverted phase change is equivalent to a shift of the wave by $\frac{\lambda}{2}$. Thus, when only one of the two waves undergoes an inverted phase change,

$$2t = \frac{\left(m + \frac{1}{2}\right)\lambda}{n_{film}} \text{ (constructive interference); } 2t = \frac{n\lambda}{n_{film}} \text{ (destructive interference)}$$

where $m = 0, 1, 2, \ldots$, and $n = 1, 2, 3, \ldots$.

These conditions depend on the thickness of the film. In other words, the thickness of the film determines the colour of light that will be strongly reflected. The thicker the thin film, the longer the wavelength of light that will produce constructive interference. The oil film in Figure 1 varies in thickness, so different colours of light are reflected. The following Tutorial shows you how to calculate the interference effects in thin films such as soap bubbles.

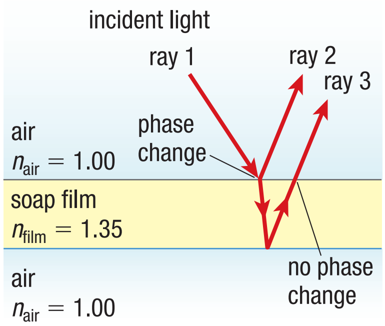

Figure 7 When ray 1 reflects at the air–film boundary, the reflected ray (ray 2) is inverted. The ray reflecting from the lower film–air boundary (ray 3) does not change phase at the upper film–air boundary.

Investigation 10.1.1

Investigating Interference Using Air Wedges (page 544)

Now that you have learned about thin films and interference, apply this knowledge to perform Investigation 10.1.1 to determine the thickness of a human hair.

Tutorial 1 Determining Interference Effects in Thin Films

In the following Sample Problems, you will determine the interference effects in thin films with one inverted reflection and two phase changes.

Sample Problem 1: Determining the Colour and Thickness of a Soap Film

Consider a soap film that is the thinnest film that will produce a bright blue light when illuminated with white light. The index of refraction of the soap film is 1.35, and the blue light is monochromatic with wavelength 411 nm (**Figure 8**).

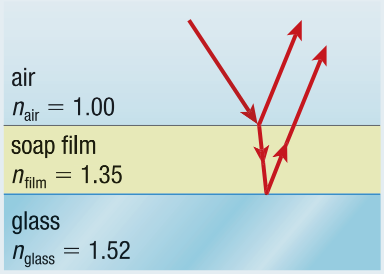

Figure 8 Interference from a soap film with air on one side depends on the substance on the other side of the film.

(a) Calculate the thickness of the film if the soap covers a piece of crown glass with index of refraction 1.52.

(b) Suppose the reflections occur instead from a soap film on water with index of refraction 1.33. Determine the thickness of the film on water that will produce the same blue colour of reflected light.

Solution

(a) **Given:** $n_{glass} = 1.52$; $n_{film} = 1.35$; $\lambda = 411 \text{ nm} = 4.11 \times 10^{-7}$ m

Required: t

Analysis: Both reflections involve inverted phases, since the index of refraction increases from layer to layer. Therefore, use the formula for constructive interference of the two waves when phase changes occur in both reflections. Let $n = 1$.

$$2t = \frac{n\lambda_{blue}}{n_{film}}$$

Solution:
$$2t = \frac{n\lambda_{blue}}{n_{film}}$$
$$t = \frac{n\lambda_{blue}}{2n_{film}}$$
$$= \frac{(1)4.11 \times 10^{-7} \text{ m}}{2(1.35)}$$
$$t = 1.52 \times 10^{-7} \text{ m}$$

Statement: The thickness of the film on the glass is 1.52×10^{-7} m.

(b) **Given:** $n_{water} = 1.33$; $n_{film} = 1.35$; $\lambda = 411 \text{ nm} = 4.11 \times 10^{-7}$ m

Required: t

Analysis: One ray is partially reflected from the upper surface and inverts because it is moving into a more optically dense medium. However, the second ray reflects from the bottom surface and does not change phase because it is moving into a less optically dense medium. Therefore, use the formula for constructive interference of two waves with one phase change. Set m equal to zero.

Solution:
$$2t = \frac{\left(m + \frac{1}{2}\right)\lambda_{blue}}{n_{film}}$$
$$2t = \frac{\lambda_{blue}}{2n_{film}}$$
$$t = \frac{\lambda_{blue}}{4n_{film}}$$
$$= \frac{4.11 \times 10^{-7} \text{ m}}{4(1.35)}$$
$$t = 7.61 \times 10^{-8} \text{ m}$$

Statement: The thickness of the film on water is 7.61×10^{-8} m.

Sample Problem 2: Making Solar Cells More Efficient

In solar cells, incoming light passes through an anti-reflective coating to increase the efficiency of the cell (**Figure 9**). Suppose the index of refraction of the coating is $n_1 = 1.45$ and the index of refraction of the material below the coating is $n_2 = 3.50$. In this case, you need to maximize the amount of transmitted light to minimize the reflected light. Determine the thickness of the anti-reflective coating that will minimize the reflection of light with a wavelength of 7.00×10^{-7} m.

Given: $n_1 = 1.45$; $n_2 = 3.50$; $\lambda = 7.00 \times 10^{-7}$ m

Required: t

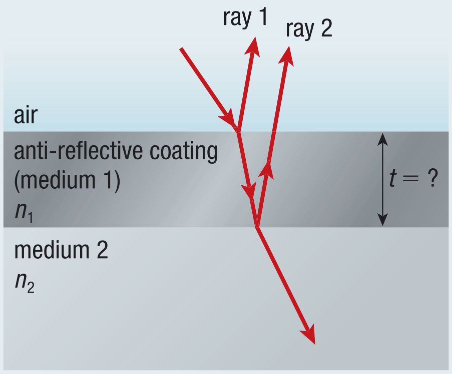

Figure 9

Analysis: An incident light ray moving from air into medium 1 will partially reflect at the upper surface of the coating. Since medium 1 is more optically dense than air, a light wave will be reflected and inverted at the upper surface. Similarly, at the lower surface of medium 1, a light wave will be reflected and inverted because medium 2 is more optically dense than medium 1. To maximize the amount of transmitted light through the coating, the two reflected rays from the upper and lower surface of the coating must undergo destructive interference. This means that the distance, $2t$, that ray 2 must travel compared to ray 1 is equal to $\frac{\lambda}{2}$. Therefore, use the formula for destructive interference when both waves change phase, which is the same as when both waves have no change of phase. Set m equal to zero.

$$2t = \frac{(m + \frac{1}{2})\lambda_{blue}}{n_{film}}$$

Solution: $2t = \dfrac{\lambda}{2n_{film}}$

$$t = \frac{\lambda}{4n_{film}}$$

$$= \frac{7.00 \times 10^{-7}\ \text{m}}{4(1.45)}$$

$$t = 1.21 \times 10^{-7}\ \text{m}$$

Statement: The thickness of the anti-reflective coating is 1.21×10^{-7} m.

Practice

1. A soap film produces constructive interference of light of wavelength 500.0 nm, and a second film produces constructive interference of light with a wavelength of 600.0 nm. Determine which film is thicker. Explain your answer. K/U C
2. Calculate the smallest thickness of a soap film on glass capable of producing reflective destructive interference with a wavelength of 745 nm in air. Assume that the index of refraction for soapy water is the same as that for pure water, which is 1.33. T/I A [ans: 1.40×10^{-7} m]
3. A 510 nm wavelength of yellowish light is incident on an oil slick with an index of refraction of 1.50 on top of a pool of pure water. Calculate the thickness the oil slick needs to be so that you cannot see the yellowish light. T/I A [ans: 1.70×10^{-7} m]
4. Most camera lenses have an anti-reflective coating made of magnesium fluoride (MgF_2). The magnesium fluoride coating has an index of refraction of 1.38. Determine the thickness of the anti-reflective magnesium fluoride coating needed for red light with a wavelength of 610 nm. K/U A [ans: 1.1×10^{-7} m]

Mini Investigation

Observing a Thin Film on Water

Skills: Performing, Observing, Analyzing, Communicating

SKILLS HANDBOOK A2.1

When white light is incident on a thin film, each different wavelength of light should have a different interference pattern. In this investigation, you will examine and compare the patterns for white, red, and blue light, and analyze the patterns in terms of the conditions for constructive and destructive interference.

Equipment and Materials: bright light source; black cloth or construction paper; a flat piece of glass; liquid dropper; water; light machine oil; red and blue filters; digital camera (optional)

1. Spread the cloth or construction paper on a flat table or desk.
2. Place the glass on top of the black surface. Using a liquid dropper, cover the surface of the glass with a thin layer of water.
3. Place a few drops of light machine oil on the water.
4. Direct a bright white light source at the surface. Darken the room. Observe the interference pattern on the surface of the water, and record your observations.

To unplug the lamp, pull on the plug, not the cord. Do not touch the lamp because it will be hot after use. Use caution when working in a darkened room.

5. Place a red filter in front of the light. Observe the changes in the pattern, and record your observations in labelled sketches or as digital images, if a digital camera is available.
6. Repeat Step 5 using a blue filter.

A. What did the dark areas in the film represent? K/U

B. What caused the patterns that you saw? K/U

C. Why did the pattern change when the colour of the light changed? K/U

Newton's Rings and Air Wedges

If you place a glass disc with a convex surface in contact with a flat glass surface, as shown in **Figure 10(a)**, and illuminate it with a beam of light, a phenomenon called Newton's rings occurs (**Figure 10(b)**). Light reflects from both the upper surface of the flat glass and the lower surface of the curved glass. The light reflecting from the flat glass plate changes phase because the air between the two glass surfaces has a lower index of refraction than the glass. However, the light reflecting from the lower surface of the curved glass does not change phase. The difference in path length, t, increases with the distance from the point of contact of the two glass surfaces. Therefore, monochromatic light of wavelength λ has a bright fringe at each location where the separation t is half a whole-number multiple of λ. It has a dark fringe from destructive interference at each location where the separation t is a whole-number multiple of λ.

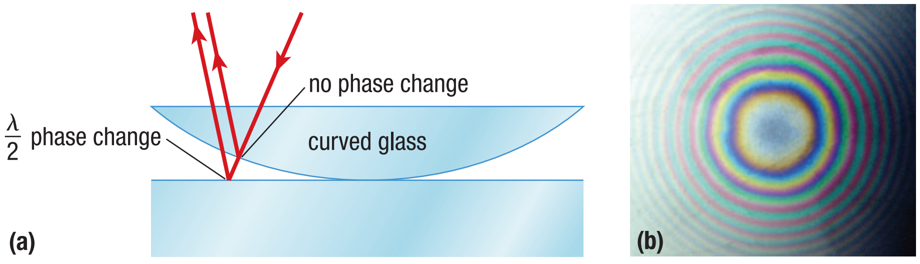

Figure 10 (a) Light reflects from both the upper surface of the flat glass and the lower surface of the curved glass. (b) Newton's rings, a series of concentric rings, form from light reflecting between a flat surface and an adjacent curved surface.

A practical application of Newton's rings is checking lenses for imperfections. Lenses are typically spherical in shape and, if shaped properly, will produce perfectly circular Newton's rings when illuminated with light (**Figure 11(a)**). However, if the lens is imperfectly shaped, it will produce a pattern that clearly indicates a defective lens shape, as shown in **Figure 11(b)**. CAREER LINK

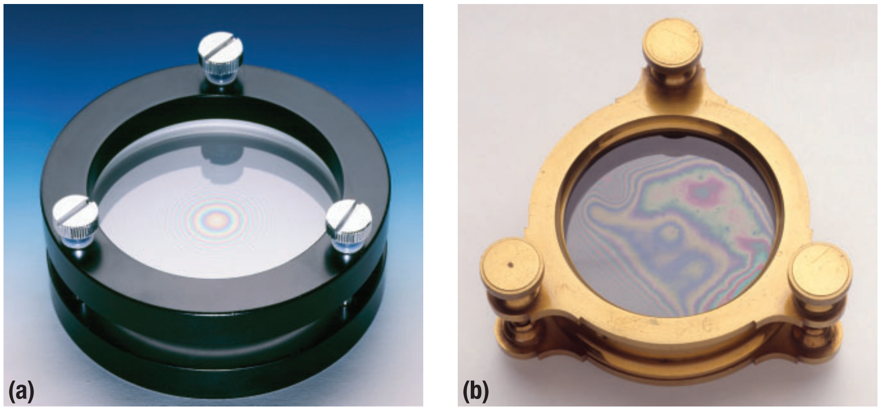

Figure 11 (a) A well-made lens has the shape of a section of the surface of a sphere. When illuminated with light, the interference patterns are circular Newton's rings. In this image, white light was used. (b) A defective lens produces non-circular Newton's rings that provide information on how to regrind the lens.

Air Wedges

air wedge the air between two sheets of flat glass angled to form a wedge

To create a measurable pattern of destructive and constructive interference, researchers often use an **air wedge**, which is a wedge of air between two sheets of flat glass that have been angled to form a wedge. The upper glass is slightly raised by a very small distance, t, and illuminated with monochromatic light, as shown in **Figure 12**. The interference patterns produced, such as the patterns in **Figure 13**, can be used to measure very small distances.

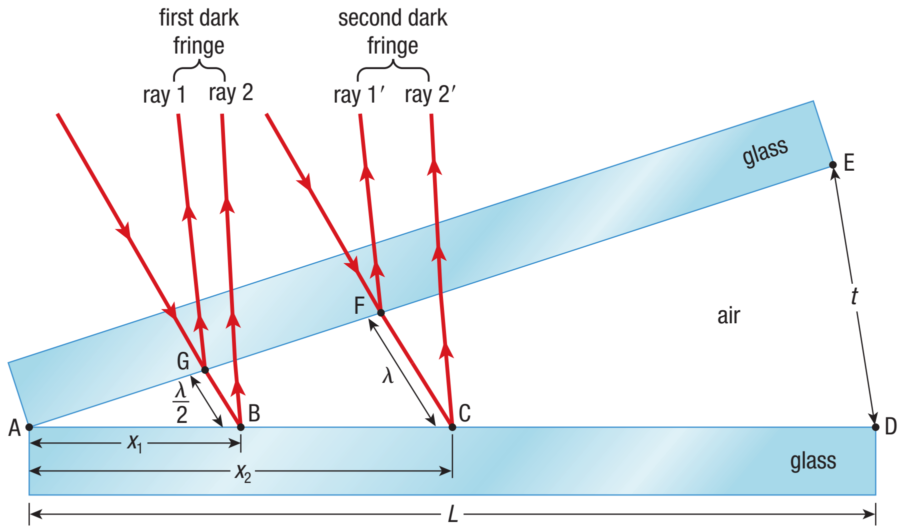

Figure 12 Two flat layers of glass separated at one end form an air wedge.

The measurable distance between fringes depends on the wavelength of light and the distance, t. Thus, if the distance is known, you can use the fringe pattern to determine the wavelength of light used. If you already know the wavelength, you can use the measurable pattern to determine the width of the very small object causing the separation of the layers of glass.

To calculate the fringe pattern from t, λ, and the length of the plate, L, you need to determine the relative phase of waves reflecting from the bottom surface of the upper glass plate (for example, point G in Figure 12) and the upper surface of the bottom glass plate (for example, point B). At point A, where the glass edges meet, the 180° phase change of just one reflected wave leads to destructive interference and a dark fringe. At point G, a light wave travelling through the first glass layer reaches a boundary where the index of refraction for air is less than that for glass. So light that reflects at point G has no phase change. The same reasoning applies at point F. The reflection of light at points B and C, however, undergoes a phase change of 180°. The reason is that light is travelling from air into glass, which is more optically dense than air. Thus, the dark fringes occur whenever the separation distance of the two plates at a particular location is a multiple of one wavelength.

To determine the first minimum, x_1, set the difference in path length to $\frac{\lambda}{2}$, which is the condition for destructive interference to occur. Triangles AGB and AFC in Figure 12 demonstrate that the first minimum meets the following condition:

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

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

The next fringe, x_2, occurs when the difference in path length for the reflection from the upper and the lower plates is λ:

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

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

Thus, the separation between the two fringes is

$$\Delta x = x_2 - x_1$$

$$\Delta x = \frac{L\lambda}{t} - \frac{L\lambda}{2t}$$

$$\Delta x = \frac{L\lambda}{2t}$$

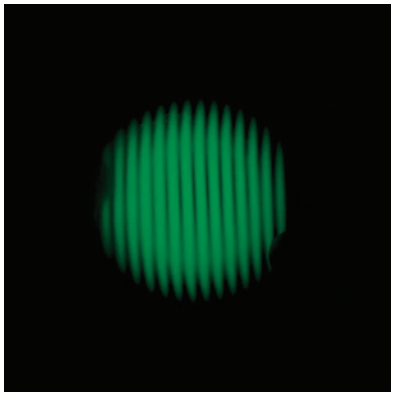

Figure 13 These dark fringes resulted from an air wedge experiment using $t = 546$ nm.

UNIT TASK BOOKMARK

You can apply what you have learned about interference in thin films to the Unit Task on page 556.

Tutorial 2 Calculating Interference Effects in an Air Wedge

This Sample Problem shows how to use interference effects to measure small distances.

Sample Problem 1: Interference Effects in an Air Wedge

Two glass plates are separated on one side by a human hair. The light shining on the plates has a wavelength of 6.00×10^{-7} m. The light intensity is zero at the point of contact of the two plates, followed by nine alternating bright and dark fringes (**Figure 14**). Estimate the thickness of the hair.

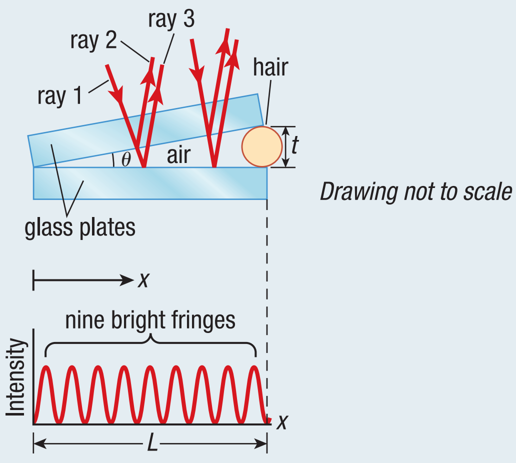

Figure 14

Given: $\lambda = 6.00 \times 10^{-7}$ m; nine complete cycles of passing from dark to light to dark areas along the wedge

Required: t

Analysis: Let $L = 9\Delta x$.

$$\Delta x = \frac{L\lambda}{2t}$$

$$2t = \frac{L\lambda}{\Delta x}$$

$$2t = \frac{9\cancel{\Delta x}\lambda}{\cancel{\Delta x}}$$

$$2t = 9\lambda$$

$$t = \frac{9\lambda}{2}$$

Solution: $t = \frac{9\lambda}{2}$

$$= \frac{9(6.00 \times 10^{-7}\text{ m})}{2}$$

$$t = 2.70 \times 10^{-6}\text{ m}$$

Statement: The estimated thickness of the hair is 2.70 μm.

Practice

1. A sheet of paper 0.012 cm thick separates two sheets of glass to form an air wedge 10.8 cm long. When the air wedge is illuminated with monochromatic light, the distance between the centres of the first and eighth dark bands is 2.4 mm. Determine the wavelength of the light. K/U T/I [ans: 7.6×10^{-7} m]
2. An air wedge 6.0 cm long is formed from two pieces of glass separated at one end by a piece of paper. When light of wavelength 730 nm is reflected from the wedge, interference fringes appear. Between the dark fringes at both ends of the wedge, 62 bright fringes appear. Calculate the thickness of the paper. K/U T/I [ans: 2.3×10^{-5} m]

Research This

Thin Films and Cellphones

Skills: Researching, Communicating

SKILLS HANDBOOK A4.1

A new thin-film technology ("green glow") uses several layers of thin films to detect and amplify infrared light, while other layers, which are called organic light-emitting diodes (OLEDs), convert infrared to visible light. This thin-film technology enables researchers to turn infrared light into visible light to create night vision. Some practical applications of green glow are cellphone cameras, and windshields and eyeglasses for night vision.

1. Choose one type of application either listed above or discovered through your own research as you learn more about OLEDs and thin films.
2. Research the application.

A. Explain how your chosen technology works and how the interference properties of thin films play a role. T/I C

B. Determine the current state of development of the application that you chose. T/I

C. Determine from your research what further improvements are needed to make the technology more usable, perhaps for another application. Discuss any concerns, hazards, or disadvantages of the technology that would need to be addressed. T/I C A

D. Prepare a brief presentation or a one-page written summary of the application that you researched. C

WEB LINK

10.1 Review

Summary

- Light waves become inverted when they reflect from the boundary of a medium that has a higher index of refraction than the original medium. No phase change occurs when light waves reflect from the boundary of a medium that has a lower index of refraction than the original medium.
- Light waves that reflect from the two surfaces of a thin film produce interference fringes that depend on the different path lengths travelled by the two waves, the wavelength of the light, any phase changes that occur from reflection, and the indices of refraction for the materials involved.
- If only one wave has a phase change,

  $$2t = \frac{\left(m + \frac{1}{2}\right)\lambda}{n_{\text{film}}} \quad \text{(constructive interference); } m = 0, 1, 2, 3, \ldots$$

  $$2t = \frac{n\lambda}{n_{\text{film}}} \quad \text{(destructive interference); } n = 1, 2, 3, \ldots$$

  where t is the thickness of the film, λ is the wavelength, and n_{film} is the index of refraction for the film.
- If both waves have a phase change,

  $$2t = \frac{n\lambda}{n_{\text{film}}} \quad \text{(constructive interference); } n = 1, 2, 3, \ldots$$

  $$2t = \frac{\left(m + \frac{1}{2}\right)\lambda}{n_{\text{film}}} \quad \text{(destructive interference); } m = 0, 1, 2, 3, \ldots$$
- Newton's rings and fringes in air wedges result from light reflecting, transmitting, and interfering with surfaces that have different separations at different locations.

Questions

1. A coating, 177.4 nm thick, is applied to a lens to minimize reflections. The refractive indices of the coating and the lens material are 1.55 and 1.48, respectively. Calculate the wavelength in air that is minimally reflected for light rays that strike the lens along the normal. Include a diagram. K/U T/I C
2. A transparent film of $n = 1.29$ spills onto the surface of water, with $n = 1.33$, producing a maximum of reflection with normally incident orange light, with a wavelength of 7.00×10^{-7} m in air. Assuming that the maximum occurs in the first order, determine the thickness of the film. Include a diagram in your solution. K/U T/I C
3. An extremely thin film of soapy water of $n_{\text{film}} = 1.35$ sits on top of a flat glass plate of $n_{\text{glass}} = 1.50$. The soap film has a red colour when the incident light reflects perpendicularly off the surface of the water. Determine the thickness of the film when $\lambda_{\text{red}} = 6.00 \times 10^{-7}$ m. T/I
4. Change the index of refraction for the glass plate in Question 3 to 1.10. Determine the thickness of the film when $\lambda_{\text{red}} = 6.00 \times 10^{-7}$ m. T/I
5. **Figure 15** shows the bands of reflected colour produced by exposing a thin soap-bubble film to white light. What produces the colours? Is the bubble of uniform thickness? Explain. K/U T/I A

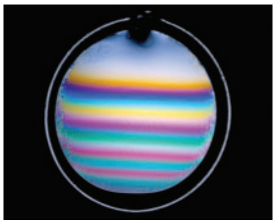

Figure 15

6. Use diagrams to explain why the top of a soap film appears bright from one side and dark from the other side when light is transmitted through it. K/U C
7. A very thin sheet of glass of $n_{\text{glass}} = 1.55$ floats on the surface of water of $n_{\text{water}} = 1.33$. When illuminated with white light at normal incidence, the reflected light consists predominantly of the wavelengths 5.60×10^{-7} m and 4.00×10^{-7} m. Determine the thickness of the glass. T/I