Physics - 2

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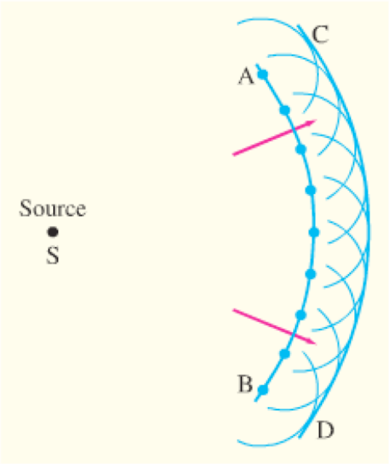
Light as a Wave

Huygen's Principle: Huygens (1629 - 1695) was the first person to proposed a wave theory of light.

- Huygens developed a technique by which we can predict the future position of a wave front.
- A wavefront is the imaginary surface that connects all points of a wave that are in the same phase (for example, all crests or all troughs). For example a 'wave' we see n the ocean is a wave front.
- Now, Huygens' principle can be stated as "*Every point on a wave front can be considered as a source of tiny wavlets that spread out in the forward direction at the speed of the wave itself. The new wave front then is the tangent line to all the wavelets.*"

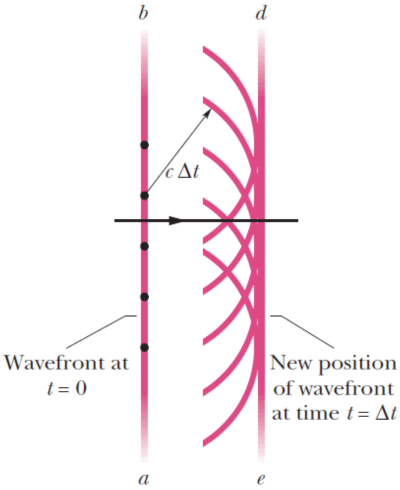
Light as a Wave

Huygens' principle



Light as a Wave

How can we predict the future position of a wave front?
Let's consider an example (shown in the figure below)



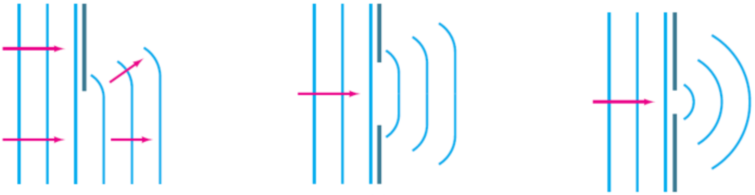
Light as a Wave

- The present location of a wavefront is represented by the plane ab ($t = 0$).
- Where will the wavefront be at a later time ($t = \Delta t$).
- Consider points on the wavelet ab serves as the source for secondary spherical wavelets.
- If the speed of the wave is c (speed of light), then the radius of the spherical waves will be $c\Delta t$ after time duration Δt.
- Then, we draw plane de, tangent to all the wavelets at time Δt.
- This plane represent the position of the wave at time Δt.

Diffraction

The bending of waves behind obstacles into the "shadow region" is known as **diffraction**.

- Diffraction can only occur for waves and not particles.
- Huygens principle is useful in explaining why the diffraction happens.
- The following figures depict diffraction of waves.



(a) (b) (c)

- This behavior (diffraction) of waves has been observed experimentally.

Diffraction

- Since diffraction can only occur for waves, it can serves as a means for identifying the nature of light.
- So, does light behave as a wave?
- Francesco Grimaldi (1618–1663) observed that when sunlight entered a darkened room through a tiny hole in a screen, the spot on the opposite wall was larger than would be expected from geometric rays.
- He also observed that the border of the image was not clear but was surrounded by colored fringes.
- Grimaldi attributed this to the diffraction of light.

Young's Interference Experiment

- Around 1801, many people thought that light had a particle-like nature.
- But, in 1801, Thomas Young experimentally proved that light is wave.
- He did so by demonstrating that light undergoes interference, just like water waves and sound waves.

Young's Interference Experiment

The figure below gives the basic arrangement of Young's experiment.

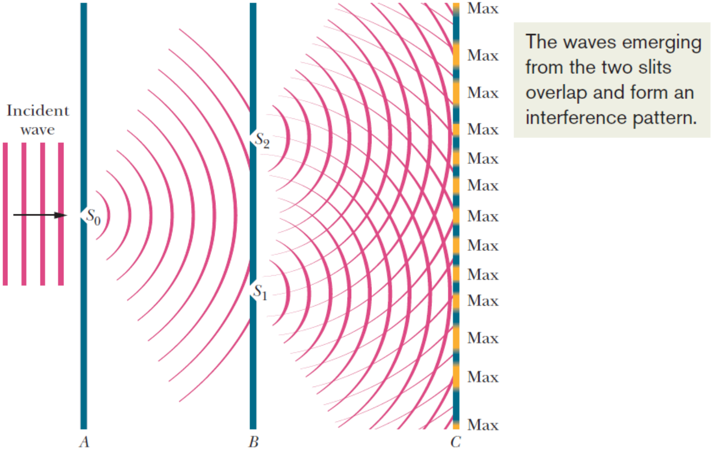


Figure 2: Figure Adopted from HRW

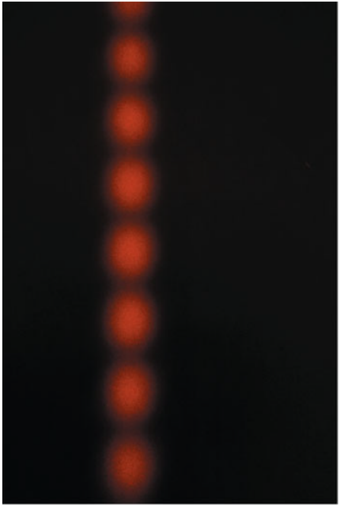
Young's Interference Experiment

- Light from a distant monochromatic source illuminates slit S_0 in screen A.
- The emerging light then spreads via diffraction to illuminate two slits S_1 and S_2 in screen B.
- Diffraction of the light by these two slits sends overlapping circular waves into the region beyond screen B, where the waves from one slit interfere with the waves from the other slit.

Young's Interference Experiment

- We cannot see the interference pattern in between screen B and C.
- When the waves hit the screen C, the points of interference maxima form visible bright rows.
- These visible bright regions are called **bright bands**, **bright fringes** or **maxima**.
- The dark regions are called **dark bands**, **dark fringes** or **minima**
- The pattern of bright and dark fringes on the screen is called an **interference pattern**

Young's Interference Experiment



Courtesy Jearl Walker

Figure 3: Figure adopted from HRW

Locating the Fringes:

- How can we find fringes location on the screen? Let's consider the figure below.

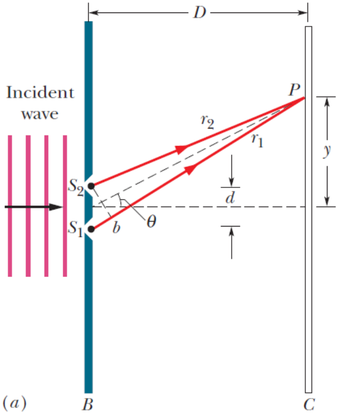


Figure 4: Figure adopted from HRW

Young's Interference Experiment

- In the figure, a plane wave of monochromatic light is incident on two slits S_1 and S_2 in screen B.
- We then draw a central axis from the mid point between S_1 and S_2, to the screen C.
- Let's consider a point P on the screen C, which is at an angle θ from the central axis.
- This point is at a distance r_1 from S_1 and r_2 from S_2.

Young's Interference Experiment

- At the screen B, the two waves are in phase because they are part of the same incident wave.
- But, when they reach point P, both waves travel different distances.
- This means The phase difference between two waves can change if the waves travel paths of different lengths.
- If, at some point the **path length difference** ΔL between the two waves is zero or integral multiple of the wavelength of the light, the waves will arriving at that point will be in phase and they will interfere fully constructively there.
- If ΔL is an odd multiple of half a wavelength, the waves will reach point P exactly out of phase and they interfere destructively.

Young's Interference Experiment

We can find exactly where each bright fringe and each dark fringe located by finding its angle θ.

- Let's draw a line from S_2 toward r_1, which is perpendicular to r_1. As shown in the figure below.

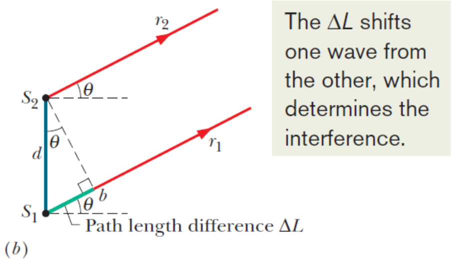


Figure 5: Figure adopted from HRW

- This will make sure that the distance from point b to point P on the screen and the r_2 are exactly the same.

- Then from the figure we can see that the path difference (ΔL) between the two waves is

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

- Now, if this path difference is integral multiple of wavelength, then at point P there will be a bright fringe (constructive interference).

$$\boxed{d\ sin\theta = m\lambda}, \quad for\ m\ =\ 0, 1, 2...\ \ (maxima\ or\ bright\ fringes)$$

- If the path difference is odd multiple of hald a wavelength.

$$\boxed{d\ sin\theta = (m + \frac{1}{2})\lambda}, \quad for\ m\ =\ 0, 1, 2...\ \ (minima\ or\ dark\ fringes)$$

Young's Interference Experiment

- For bright fringes, for $m = 0$, θ is also zero. Hence $\Delta L = 0$. Which represent the midpoint on the screen C. So, the mid point on the screen is a bright fringe and is called **central maximum**.
- For $m = 1$, called the **first-order bright fringes** have a ΔL of one wavelength, and it is located at (on both sides of the central maximum).

$$\theta = sin^{-1}(\frac{\lambda}{d})$$

- For $m = 2$, called the **second-order bright fringes** have a ΔL of two wavelength, and it is located at

$$\theta = sin^{-1}(\frac{2\lambda}{d})$$

Young's Interference Experiment

- For dark fringes, for $m = 0$, called the **first-order dark fringes** have a ΔL of $\frac{1}{2}\lambda$, and it is located at (on both sides of the central maximum)

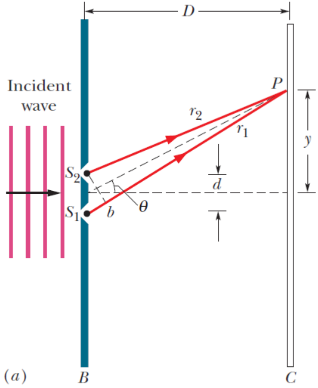
$$\theta = sin^{-1}(\frac{\lambda}{2d})$$

- For $m = 1$, called the **second-order dark fringes** have a ΔL of $\frac{3}{2}\lambda$, and it is located at

$$\theta = sin^{-1}(\frac{3\lambda}{2d})$$

Example

What is the distance on screen C in Fig below between adjacent maxima near the center of the interference pattern? The wavelength λ of the light is 546nm, the slit separation d is 0.12mm, and the slit–screen separation D is 55cm. Assume that θ in figure is small enough to permit use of the approximations $sin\theta \approx tan\theta \approx \theta$, in which θ is expressed in radian measure.



Example

- Since, for maxima

$$d\ sin\theta = m\lambda$$

- Or

$$sin\theta = \frac{m\lambda}{d}$$

- As from the figure

$$tan\theta = \frac{y_m}{D}$$

- Since $sin\theta \approx tan\theta \approx \theta$, then θ

$$\theta = \frac{m\lambda}{d}$$

- and

$$\theta = \frac{y_m}{D}$$

Example

- Combining both equations

$$y_m = \frac{m\lambda D}{d}$$

- This is an m-order maxima. The next maxima will be

$$y_{m+1} = \frac{(m+1)\lambda D}{d}$$

- The distance between these two will be

$$\Delta y = y_{m+1} - y_m = \frac{(m+1)\lambda D}{d} - \frac{m\lambda D}{d}$$

$$\Delta y = \frac{\lambda D}{d}$$

Example

- Putting values

$$\Delta y = \frac{(546 \times 10^{-9})(55 \times 10^{-2})}{0.12 \times 10^{-3}}$$

$$\boxed{\Delta y = 2.5\ mm}$$