Wave Optics

Wave theory of light, properties of light wave, refraction of light waves, dispersion of light waves, interference of light waves, Young's experiment, diffraction.

Lecture Four

بصريات الموجه Wave Optics

4.1 Wave Theory of light:

Energy light can be transferred from one point to another in two different ways.

(1) Through a particle
(2) Through a wave (i.e. vibration of particles in the medium)

There are two theory to interpreted light propagation:

Newton corpuscular theory: نظرية نيوتن الجسيمية

According to Newton light energy, light propagate from one point to another in the form of particle. In this case, very small tiny particles are emitted from source of light in all directions, in speed $3 x 10^8$ m/sec. when these corpuscles strike the retina of eye we feel the sensation of light.

Newton attributed different colors to the different size of the corpuscles. With the help of corpuscular theory, Newton can explain both the phenomenon of ***reflection*** and ***refraction,*** but while explaining *refraction* Newton proved that the light would travel faster in a denser medium. But experimental results showed that light would travel slower in the denser medium. After few years phenomenon of **interference** and **diffraction** were discovered. *Newton's corpuscular theory could not explain this phenomenon. Due to this failures Newton's corpuscular theory was discarded.*

Wave theory of light (Huygens's theory):

Huygens put his wave theory, according to its theory, light energy propagated in the form of wave, could successfully explain the phenomenon of ***reflection*** and ***refraction***, ***interference*** and ***diffraction*** all. One of principle of wave theory its requires a material medium for its propagation, But light also travel through vacuum, Huygens had to assume existence of pervading hypothetical medium known as **ether**.

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The question was raised about the nature of light wave whether it is ***longitudinal*** or ***transverse***.

We can define ***longitudinal* Wave**, if the direction of vibration is along the direction of propagation. ***Transverse Wave*** is known if the direction of vibration is perpendicular to the direction of propagation.

Since the phenomenon of reflection, refraction, interference and diffraction all could be explained by longitudinal as well as transverse nature of wave .

Then phenomenon of polarization was discovered and **Fresnel,** showed that ***polarization*** could be explained by ***transverse nature*** of wave and not by longitudinal nature. Hence it was concluded that light is a transverse wave.

Maxwell suggested "*A Dynamical Theory of the Electromagnetic Field*" in 1865, Maxwell demonstrated that electric and magnetic fields travel through space as waves moving at the speed of light. He proposed can be applied on light, and an wave in the same medium is the causes of electric and magnetic phenomena.

Maxwell said, light is travel through vacuum with a speed $3*10^8$ m/s, it must be electromagnetic wave. Thus light is an electromagnetic wave which can travel through vacuum, and is transverse in nature.

4.2 Dual Nature of Light

Scientists observed that light energy can behave like a wave as it moves through space, or it can behave like a discrete particle with a discrete amount of energy (quantum) can be absorbed and emitted.

For example in case of discrete particle, **nature of light is modeled with photons**. A photon has no mass and no charge. It is a carrier of electromagnetic energy and interacts with other discrete particles (e.g., electrons, atoms, and molecules). A beam of light is modeled as a stream of photons, each carrying a well-defined energy that is dependent upon the wavelength of the light. The energy of a given photon can be calculated by:

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$$\boxed{\text{Photon energy } (E) = hc/\lambda}$$

where E is in joules

h = Planck's constant = $6.625\ 10^{-34}$ J•s

c = Speed of light = 2.998×10^{8} m/s

λ = Wavelength of the light in meters

4.3 Properties of light waves:

What is light? This question has been debated for many centuries. The answer, in short, light is a special kind of electromagnetic energy. The speed of light, although quite fast, is not infinite. The speed of light in a vacuum is expressed as $\boldsymbol{c = 2.99 \times 10^{8}}$ **m/s**., and this speed is considered a universal constant. It is important to note that speed changes for light traveling through **non-vacuum media** such as air (0.03% slower) or glass (30.0% slower).

In a vacuum, light travel in a straight line at fixed speed, carrying energy from one place to another. Two key properties of light interacting with a medium are:

1. It can be deflected upon passing from one medium to another (refraction).

2. It can be bounced off a surface (reflection).

The tool to detection and measurement of light energy is called ***radiometry***. It uses a standardized system for characterizing radiant energy. The next paragraph show some properties of light:

4-4 Reflection

When a ray of light reflects off a surface (such as a mirror), its new direction depends on only the angle of incidence. The law of reflection states that the angle of incidence on a reflecting surface is equal to the angle of reflection.

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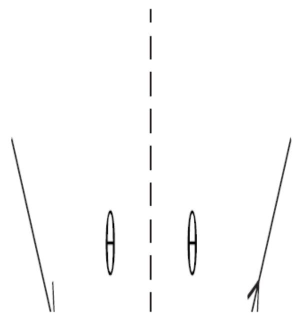
Wave theory of light, properties of light wave, refraction of light waves, dispersion of light waves, interference of light waves, Young's experiment, diffraction.



Law of reflection: Angle of incidence = Angle of reflection

4.5 Refraction of light waves: (الانكسار)

When a ray of light passes from one medium to another, it changes direction (**bends**) at the interface because of the difference in speed of the wave in the media. The ratio of this speed difference is called ***the index of refraction (n).*** The ratio of the indices of refraction and the direction of the two rays of light for the two media are expressed in ***Snell's law*** as shown in Figure 4-1 and Equation 4-2.

$$\boxed{\frac{n_2}{n_1} = \frac{\sin\theta}{\sin\phi}}$$

where n_1 and n_2 are the indices of refraction for the two media

θ is the angle of incidence

ϕ is the angle of refraction.

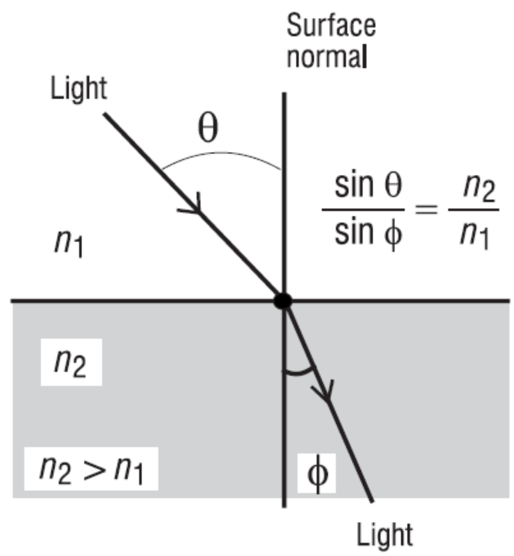


Figure 4.1: show the refraction of light

4.6 Diffraction: (الحيود)

Conclusive evidence of the correctness of a **wave model** came with the explanation of observed ***diffraction*** and ***interference***. When light passes an obstacle, the shadow is not sharp as geometrical ray theory direction would predict, but rather diffracted a little into the dark region behind the obstacle, thus giving the shadow an unclear edge.

The barrier has an opening points, Every point on the incident wave front that arrives at the slot can be viewed as the site of an expanding spherical wavelet.

For holes that are small compared to the wavelength, the hole becomes like a source and spherical waves result. **As the slit width d increases**, the diffracted wave becomes more and more like the incident plane wave except for the edges at the shadow.

Wave theory of light, properties of light wave, refraction of light waves, dispersion of light waves, interference of light waves, Young's experiment, diffraction.

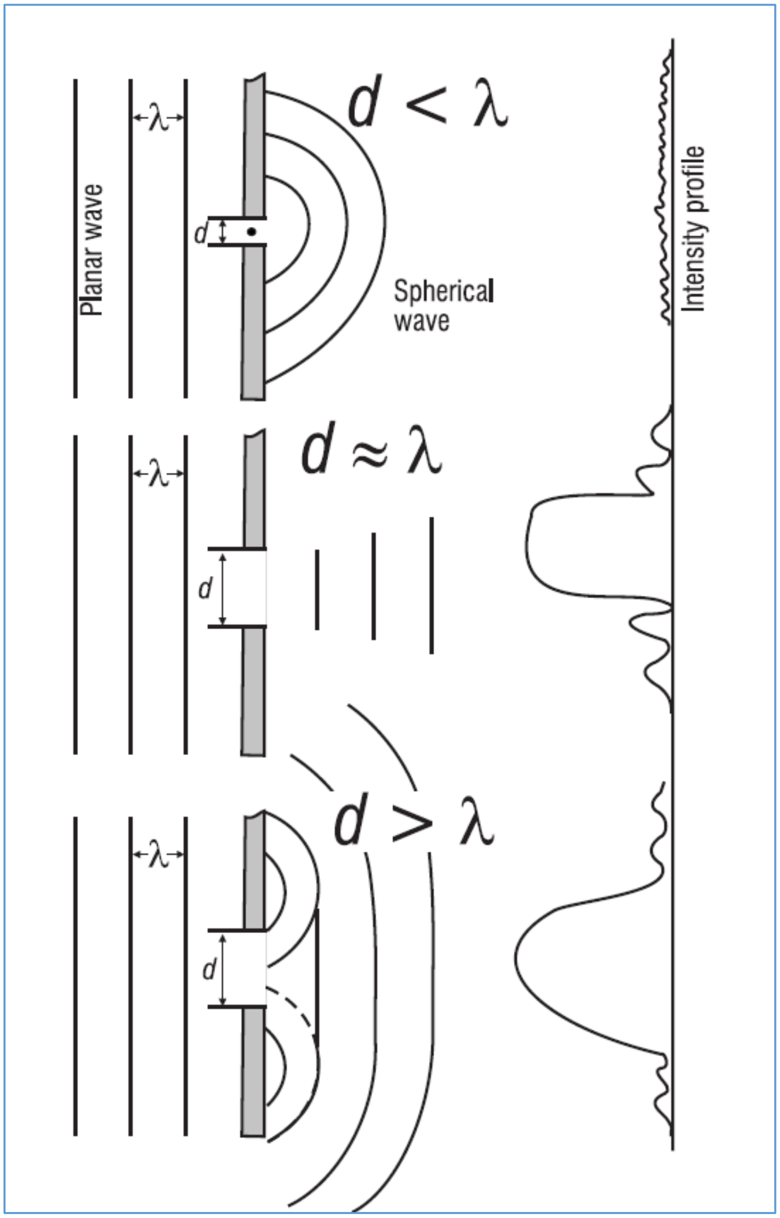


Figure 4-2: Show the diffraction theory

4.7 Interferences of light waves:

The first definitive demonstration of the **wavelike nature of light** was the classical two-slit experiment performed by ***Thomas Young*** in 1801. The two slits are very small compared to their separation distance. Thus, each slit produces diffracted spherical waves that overlap as they expand into the space to the right of the barrier.

When they overlap, they interfere with each other, producing regions of **mutually reinforcing waves**. These appear on the screen as regions of maximum intensity. Between adjacent maxima is a region of minimum intensity. See Figure 4-3. The resulting pattern on the screen shows where constructive interference occurs ***(maxima, labeled B, (Brightness))*** and where destructive interference occurs ***(minima, labeled D, (Dark))***.

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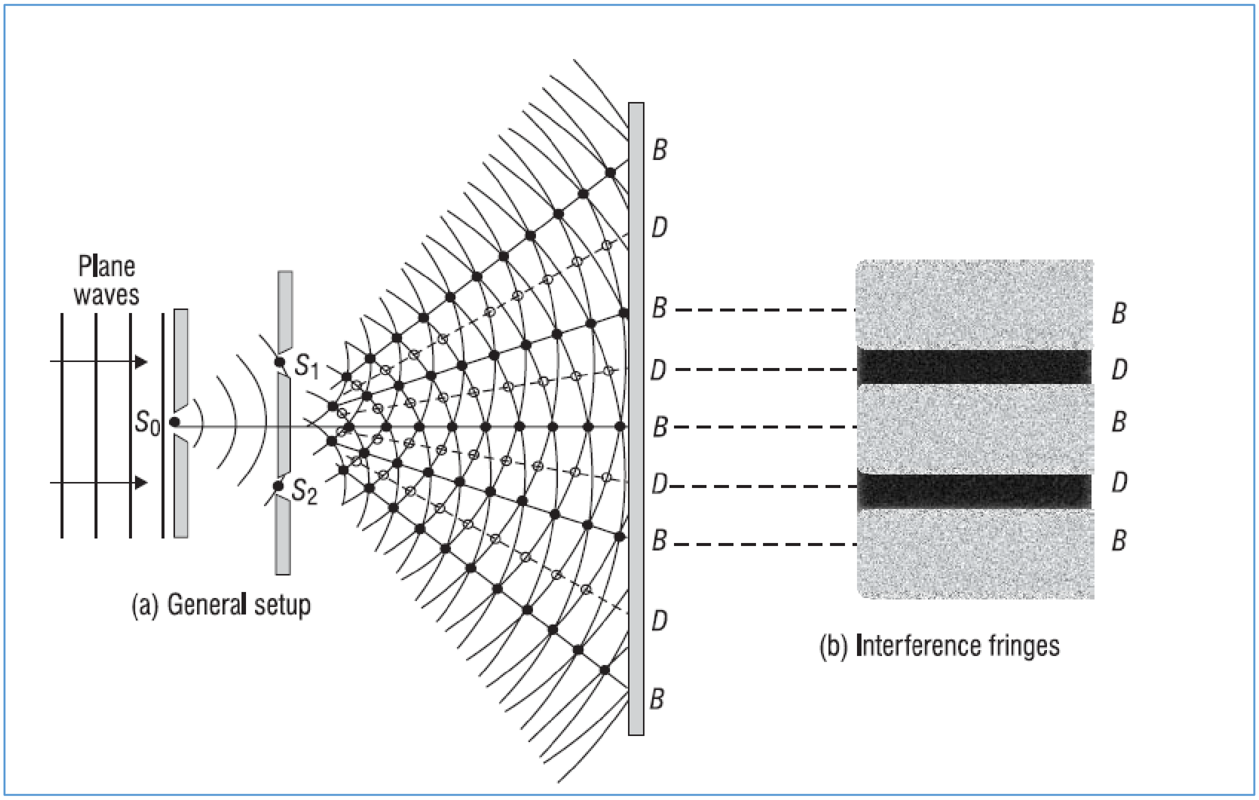

Figure 4-3: show the interferences wave

4.8 Superposition التراكب

For many categories of waves, including electromagnetic, two or more waves can traverse the same space at the same time independently of one another.

This means that the electric field at any point in space is simply the vector sum of the electric fields that the individual waves alone produce at the point. This is the **superposition principle**. Both the electric and magnetic fields of an electromagnetic wave satisfy the superposition principle. When two or more waves are superimposed, the resulting physical effect is called ***interference***.

Suppose two waves, y_1 and y_2, have nearly the same wavelength and phase (i.e., the maxima occur at nearly the same time and place). Superposition of these waves results in a wave ($y_1 + y_2$) of almost twice the amplitude of the individual waves. See Figure (4-4)a. This is called constructive interference. If the maximum of one wave is near the minimum of the other wave, the resultant (y_1 + y_2) has almost no amplitude, as shown in Figure (4-4)b. This is called destructive interference.

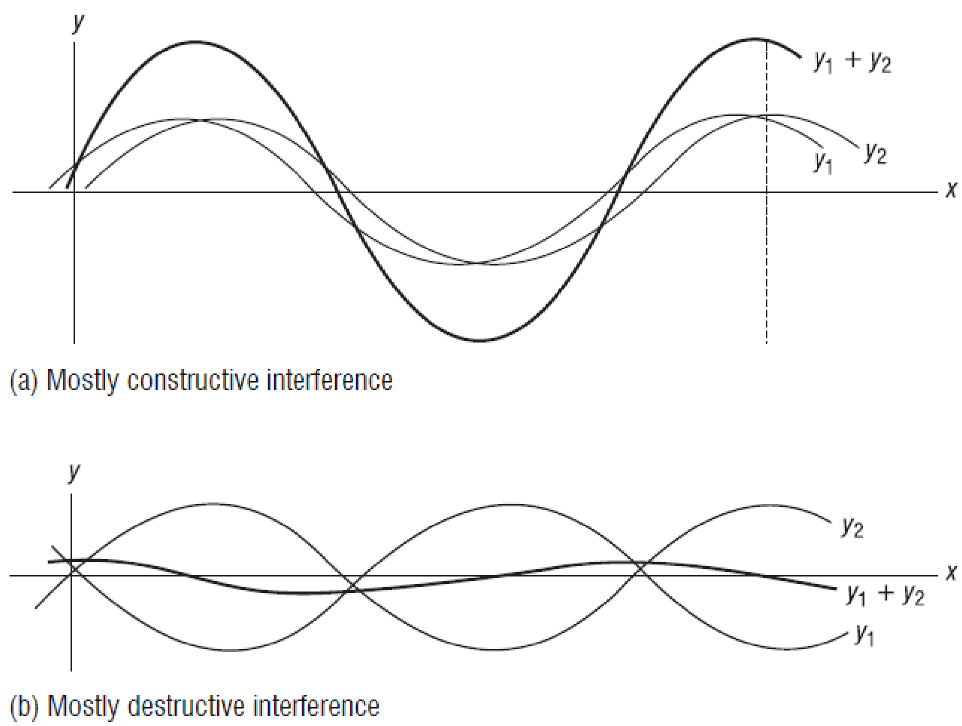

Figure 4-4: ***the principle of superposition to add individual waves***

4.6 Young's experiment:

Huygens' Principle

In the seventeenth century, Christian Huygens proposed a principle that can be used to predict, where a given wave front. His principle assumes that each point along a wave front can be considered a point source for production of secondary spherical wavelets. After a period of time, the new position of the wave front will be the surface tangent to these secondary wavelets. Huygens’principle is illustrated in Figure 4-5, for five point sources on a wave front.

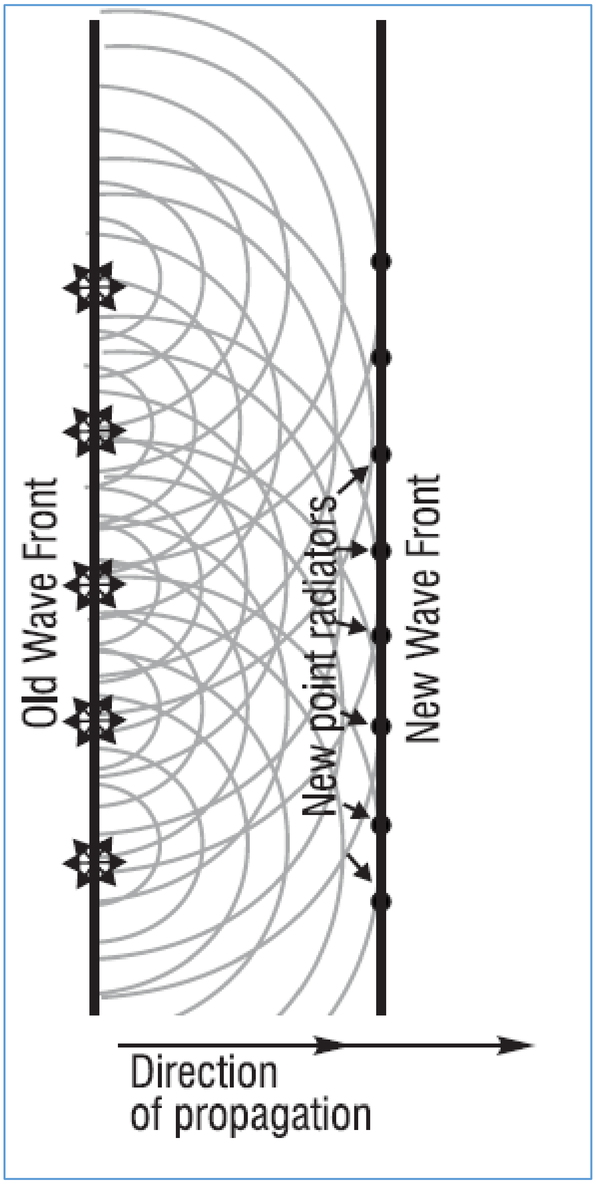

Figure 4-5 Using Huygens’ principle to establish new wave fronts

Wave theory of light, properties of light wave, refraction of light waves, dispersion of light waves, interference of light waves, Young's experiment, diffraction.

4-4 Polarization

Polarization arises from the direction of the **E-field vector** with respect to the direction of the light's propagation. Since a light wave's electric field vibrates in a direction perpendicular to its propagation motion figure (4-6), it is called a transverse wave and is **polarizable.** A sound wave, by contrast, vibrates back and forth along its propagation direction and thus is not polarizable.

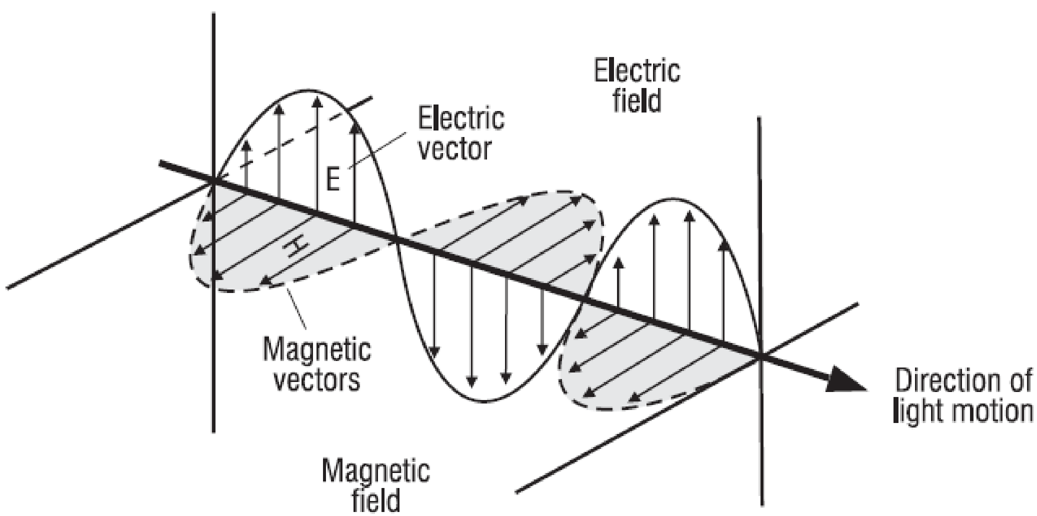

Figure (4-6) Electric and magnetic fields in a light wave

Light is unpolarized if it is composed of vibrations in many different directions, with no preferred orientation. See Figure (4-7)(a).

Many light sources (e.g., incandescent bulbs, arc lamps, the sun) produce unpolarized light. Vertically polarized light is shown in Figure (4-7)(b) and horizontally polarized light in Figure (4-7)(c). Each is an example of linearly polarized light.

Figure (4-7)(d) shows linearly polarized light making an angle of θ with the vertical. In this case, the tilted E-vector can be described by its components, E_x and E_y.

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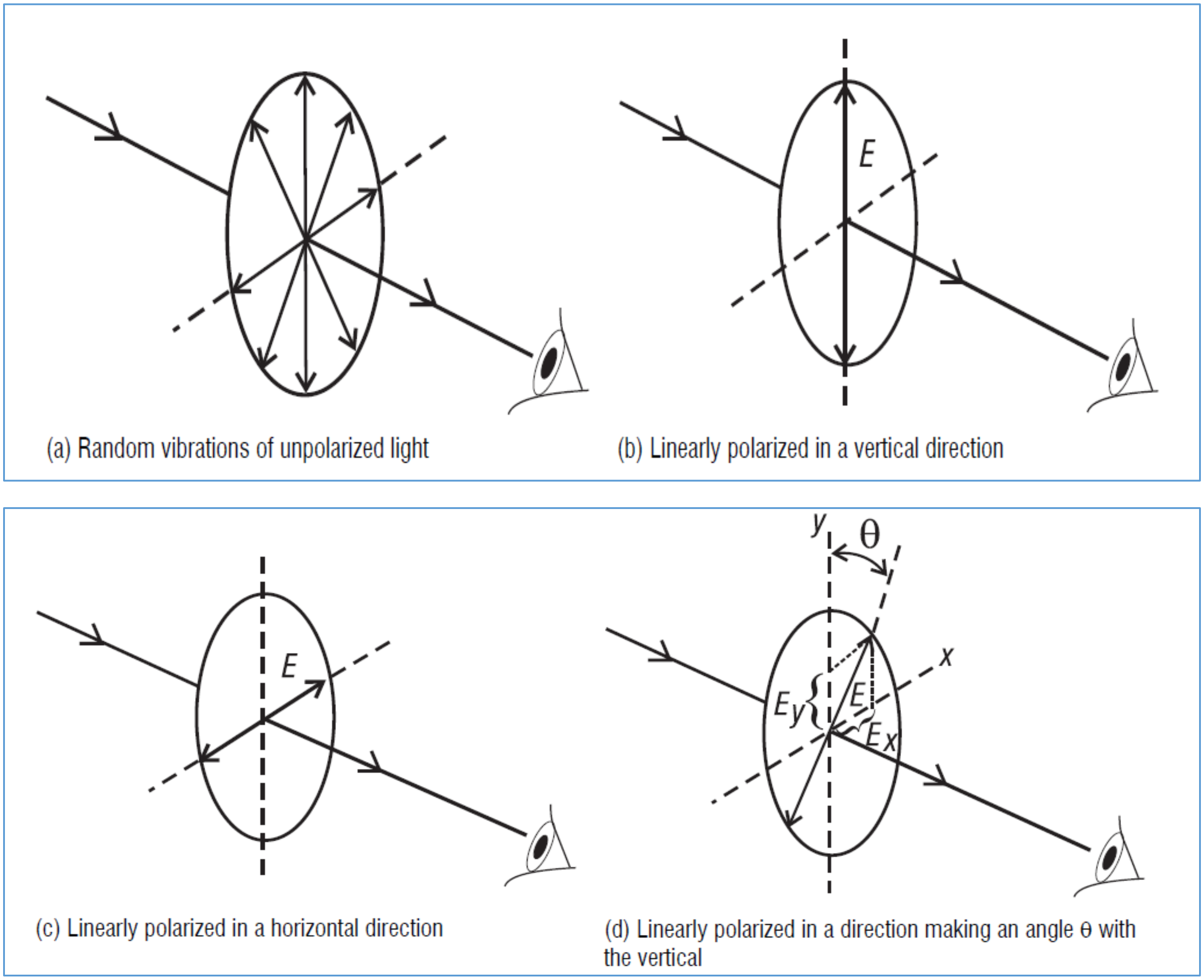

Figure 4-7 ***Unpolarized and linearly polarized light***

Last figure can happened in some cases when E_x and E_y are not in the same phase—they do not reach their maxima and minima at the same time—the E-field does not remain oriented in a fixed, linear direction. the amplitude maxima of the two components do not occur at the same time and so-called *elliptically* polarized light is exhibited.

This means that, light exhibits differing polarization orientations. A special case of elliptical polarization—called *circular* polarization—occurs when E_x equals E_y and they are out of phase by 90°.

There is a Certain materials transmit only selected polarizations. They are called polarizers—or analyzers—and have many uses. With randomly polarized light, a polarizer will pass light of one polarization and absorb or reflect other polarizations.

A common example of the use of polarization in our daily life is found in polarizing sunglasses. The material in the lenses passes light whose electric field vibrations are perpendicular to certain molecular orientations and absorbs light whose electric field vibrations are parallel to the molecular orientations.

Sometime the major component of light reflecting from a surface, such as a lake or car hood, is horizontally polarized, parallel to the surface. Thus, polarization in sunglasses, with the *transmission axis* in a vertical direction, rejects horizontally polarized light and therefore reduces glare.

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Questions

Q1) compare between the following: reflection, refraction, defraction

Q2) compare between the constrictive and destructive interference

Short Questions and Answers on Wave Theory of Light and Newton's Corpuscular Theory

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Q1: What are the two ways energy in light can be transferred?

A1:

1. Through a particle.
2. Through a wave (vibration of particles in the medium).

Q2: What is Newton's corpuscular theory?

A2: Newton's corpuscular theory states that light propagates in the form of tiny particles called corpuscles, emitted from the source of light in all directions at a speed of 3×10^8 m/s[3]

Q3: How did Newton explain colors in his corpuscular theory?

A3: Newton attributed different colors to the different sizes of the corpuscles.

Q4: What phenomena could Newton's corpuscular theory explain?

A4: The theory could explain reflection and refraction.

Q5: What experimental result contradicted Newton's explanation of refraction?

A5: Newton's theory suggested that light travels faster in denser media, but experiments showed that light travels slower in denser media.

Q6: Why was Newton's corpuscular theory discarded?

A6: The theory failed to explain the phenomena of interference and diffraction, which were later discovered.

Questions and Answers on Wave Theory of Light and Electromagnetic Theory

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Q1: What does Huygens's wave theory state about light propagation?

A1: Huygens's wave theory states that light propagates in the form of waves and successfully explains the phenomena of reflection, refraction, interference, and diffraction.

Q2: What is the principle of wave theory regarding the propagation medium?

A2: Wave theory requires a material medium for propagation. To explain light traveling through a vacuum, Huygens proposed the existence of a hypothetical medium called ether.

Q3: What is the difference between longitudinal and transverse waves?

answer

- **Longitudinal Wave:** The direction of vibration is along the direction of propagation.
- **Transverse Wave:** The direction of vibration is perpendicular to the direction of propagation.

Q4: What phenomenon led to the conclusion that light is a transverse wave?

A4: The phenomenon of polarization, demonstrated by Fresnel, showed that light must be a transverse wave, as polarization cannot be explained by longitudinal waves.

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Wave theory of light, properties of light wave, refraction of light waves, dispersion of light waves, interference of light waves, Young's experiment, diffraction.

Q5: What was Maxwell's contribution to the understanding of light?

A5: Maxwell proposed the "Dynamical Theory of the Electromagnetic Field" in 1865, demonstrating that electric and magnetic fields propagate as waves at the speed of light. He concluded that light is an electromagnetic wave.

Q6: What is the speed of light according to Maxwell's theory?

A6: Maxwell stated that light travels at a speed of 3×10^8 m/s^3 \times 10^8, in a vacuum.

Q7: Why can light travel through a vacuum according to Maxwell's theory?

A7: Light can travel through a vacuum because it is an electromagnetic wave and does not require a material medium for propagation.

Q8: What is the nature of light according to Maxwell's electromagnetic theory?

A8: Light is a transverse electromagnetic wave that can travel through a vacuum.

Questions and Answers on Light Properties and Behavior

Q1: How does light behave in terms of wave and particle models?

A1: Light can behave like a wave as it moves through space and like a discrete particle, called a photon, that carries energy in quantized amounts.

Q2: What is a photon?

A2: A photon is a massless and chargeless carrier of electromagnetic energy. It interacts with discrete particles, such as electrons, atoms, and molecules.

Q3: How is the energy of a photon determined?

A3: The energy of a photon is determined by its wavelength and can be calculated using the formula:
$E=h\nu$, where:

- E: Energy of the photon,
- h: Planck's constant (6.626×10^{-34} J.s),
- ν: Frequency of the light.

Q4: What is light in the context of electromagnetic energy?

A4: Light is a special kind of electromagnetic energy that travels at a constant speed in a vacuum.

Q5: What is the speed of light in a vacuum, and is it constant?

A5: The speed of light in a vacuum is $c=2.99\times10^{8}$ m/s, and it is considered a universal constant.

Q6: How does the speed of light change in non-vacuum media?

A6: In non-vacuum media:

- Light is 0.03% slower in air.
- Light is 30.0% slower in glass.

Q7: What happens to light when it interacts with a medium?

A7: Two key interactions occur:

1. Light is deflected upon passing from one medium to another (refraction).
2. Light bounces off a surface (reflection).

Wave theory of light, properties of light wave, refraction of light waves, dispersion of light waves, interference of light waves, Young's experiment, diffraction.

Q8: What is radiometry?

A8: Radiometry is the tool for detecting and measuring light energy. It uses a standardized system for characterizing radiant energy.

Q9: How does light travel in a vacuum?

A9: In a vacuum, light travels in a straight line at a constant speed, carrying energy from one place to another.

Questions and Answers on Reflection and Refraction

Q1: What happens to light when it reflects off a surface?

A1: When light reflects off a surface, its direction changes based on the angle of incidence, following the law of reflection.

Q2: What does the law of reflection state?

A2: The law of reflection states that the angle of incidence is equal to the angle of reflection.

Q3: What kind of surface is commonly associated with reflection?

A3: A mirror is a common example of a surface where reflection occurs.

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Refraction

Q4: What is refraction?

A4: Refraction is the bending of light as it passes from one medium to another due to a difference in the speed of light in the two media.

Q5: Why does light bend when it passes from one medium to another?

A5: Light bends because the speed of light changes in different media, causing a change in direction at the interface.

Q6: What is the index of refraction?

A6: The index of refraction (nn) is the ratio of the speed of light in a vacuum to the speed of light in a given medium.

Q7: What is Snell's Law?

A7: Snell's Law describes the relationship between the angles of incidence and refraction and the indices of refraction of the two media. It is expressed as:

$n1\sin\theta1=n2\sin\theta2$

Where:

- $n1,n2$: Indices of refraction of the two media,
- $\theta1,\theta2$: Angles of incidence and refraction.

Q8: How is refraction related to the speed of light in different media?

A8: Refraction occurs because the speed of light is different in each medium, with light traveling slower in media with higher indices of refraction.

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Q9: What happens to the light ray when it passes from a medium with a lower index of refraction to a higher index?

A9: The light ray bends toward the normal when passing from a medium with a lower index of refraction to one with a higher index.

Q10: What happens when light passes from a medium with a higher index of refraction to a lower index?

A10: The light ray bends away from the normal when passing from a medium with a higher index of refraction to one with a lower index.

Questions and Answers on Diffraction

Q1: What is diffraction?

A1: Diffraction is the bending of light waves around obstacles or through small openings, causing light to spread into the region behind the obstacle or slit.

Q2: What evidence supports the wave model of light through diffraction?

A2: Diffraction provides conclusive evidence for the wave model of light because it shows that light bends around obstacles and creates patterns that cannot be explained by geometrical ray theory.

Q3: How does light behave when passing an obstacle or slit?

A3: When light passes an obstacle or slit, it does not create sharp shadows as predicted by ray theory. Instead, light bends slightly into the shadow region, resulting in unclear edges.

Q4: What happens when a wave encounters a small slit compared to its wavelength?

A4: If the slit is small compared to the wavelength of light, the slit behaves like a point source, emitting spherical waves.

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Q5: How does the slit width d affect the diffracted wave?

A5:

- For small slit widths (dd), the light spreads widely, producing spherical waves.
- As dd increases, the diffracted wave becomes more similar to the original plane wave, with diffraction effects noticeable only near the edges of the shadow.

Q6: What is the role of wavelets in diffraction?

A6: According to Huygens's principle, every point on the incident wavefront that reaches the slit acts as the source of expanding spherical wavelets, which collectively form the diffracted wave.

Q7: What happens to the shadow of an obstacle due to diffraction?

A7: The shadow of an obstacle becomes unclear at the edges due to the bending of light into the shadow region.

Q8: Why does diffraction occur more prominently for longer wavelengths?

A8: Diffraction effects are more pronounced when the wavelength of light is comparable to or larger than the size of the obstacle or slit. Longer wavelengths bend more around small obstacles.

Questions and Answers on Interference of Light Waves

Q1: What was the first definitive demonstration of the wavelike nature of light?

A1: The first definitive demonstration of the wavelike nature of light was Thomas Young's classical two-slit experiment in 1801.

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Q2: What happens when light passes through two slits in Young's experiment?

A2: When light passes through two slits, it produces diffracted spherical waves from each slit. These waves overlap and interfere with each other, creating regions of maximum intensity (constructive interference) and minimum intensity (destructive interference).

Q3: What are the regions of maximum intensity and minimum intensity in interference?

A3:

- **Regions of maximum intensity (B)** occur where constructive interference takes place.
- **Regions of minimum intensity (D)** occur where destructive interference happens.

Q4: What is the principle of superposition?

A4: The principle of superposition states that when two or more waves occupy the same space at the same time, the resulting effect is the vector sum of the individual waves' effects. This principle applies to both the electric and magnetic fields of electromagnetic waves.

Q5: What happens when two waves are superimposed?

A5: When two waves are superimposed:

- **Constructive interference** occurs if the maxima of the waves align, resulting in a wave with nearly twice the amplitude of the individual waves.
- **Destructive interference** occurs if the maximum of one wave aligns with the minimum of another, resulting in nearly no amplitude.

Q6: What is constructive interference?

A6: Constructive interference occurs when two waves are in phase, and their maxima align, resulting in a wave with a larger amplitude (almost twice the amplitude of the individual waves).

Q7: What is destructive interference?

A7: Destructive interference occurs when the maximum of one wave coincides with the minimum of another wave, leading to cancellation and nearly no resulting amplitude.

Q8: What is the significance of the interference pattern observed in Young's experiment?

A8: The interference pattern observed in Young's experiment demonstrates that light behaves as a wave, with regions of constructive and destructive interference confirming the wavelike nature of light.

Q9: How does the superposition principle relate to interference?

A9: The superposition principle is the foundation of interference. It explains how two or more waves can combine to form a new wave, resulting in constructive or destructive interference depending on how the waves overlap.

Q10: How are constructive and destructive interference represented in a diagram?

A10:

- **Constructive interference** is represented by two waves combining to form a wave with larger amplitude (peak aligning with peak).
- **Destructive interference** is represented by two waves canceling each other out, forming a wave with minimal or no amplitude (peak aligning with trough).

Questions and Answers on Polarization of Light

Q1: What is polarization of light?

A1: Polarization of light refers to the orientation of the electric field vector with respect to the direction of light's propagation. Light is a transverse wave, and its electric field vibrates perpendicular to its direction of travel, making it polarizable.

Q3: What is unpolarized light?

A3: Unpolarized light is light that consists of vibrations in many different directions, with no preferred orientation. Common light sources, such as incandescent bulbs, arc lamps, and the sun, produce unpolarized light.

Q4: What is linearly polarized light?

A4: Linearly polarized light is light in which the electric field vibrations occur in a single, fixed direction. Examples include vertically or horizontally polarized light, as shown in Figure 4-7(b) and 4-7(c).

Q5: What happens when the electric field of linearly polarized light is tilted at an angle?

A5: When the electric field of linearly polarized light is tilted at an angle θ with respect to the vertical, it can be described by its components Ex and Ey. These components are part of the overall field in the tilted direction, as shown in Figure 4-7(d).

Q6: What is elliptical polarization?

A6: Elliptical polarization occurs when the components of the electric field, Ex and Ey, are not in phase with each other—i.e., they do not reach their maxima and minima at the same time. As a result, the electric field does not stay oriented in a fixed, linear direction.

Q7: What is circular polarization?

A7: Circular polarization is a special case of elliptical polarization that occurs when the amplitudes of the electric field components, Ex and Ey, are equal and are 90° out of phase. This results in a circular movement of the electric field vector.

Q8: What are polarizers?

A8: Polarizers (or analyzers) are materials that transmit only selected polarizations of light. They allow light of a specific polarization direction to pass through while absorbing or reflecting other polarizations.

Q9: How do polarizing sunglasses work?

A9: Polarizing sunglasses use lenses made from polarizing materials that only transmit light with electric field vibrations perpendicular to certain molecular orientations. They block horizontally polarized light (such as glare from a surface), reducing glare and improving visibility.

Q10: Why does polarization play a role in reducing glare from surfaces like water or car hoods?

A10: When light reflects from surfaces such as water or car hoods, the reflected light is often horizontally polarized. Polarizing sunglasses block this horizontally polarized light by having their transmission axis oriented vertically, effectively reducing glare.

Multiple-Choice Question (MSQ) on Huygens' Principle

Q1: According to Huygens' Principle, each point along a wave front acts as:

A) A fixed point in space
B) A point source for the production of secondary spherical wavelets
C) A detector for measuring wave speed
D) A point where interference occurs

Answer:
B) A point source for the production of secondary spherical wavelets

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Q2: According to Huygens' Principle, the new position of the wave front after a certain period of time is:

A) A straight line perpendicular to the original wave front
B) The surface tangent to the secondary wavelets

C) A circle of radius equal to the wavelength
D) The same as the original wave front

Answer:
B) The surface tangent to the secondary wavelets

Q3: What is the significance of Huygens' Principle in wave propagation?

A) It helps explain the reflection of waves at boundaries
B) It describes the behavior of light as particles
C) It predicts future wave front positions by considering each point as a point source
D) It shows that waves only travel in one direction

Answer:
C) It predicts future wave front positions by considering each point as a point source

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Q4: In the context of Huygens' Principle, what happens after a period of time?

A) The wave front remains stationary
B) The wave front travels in a straight line
C) The wave front is formed by the tangent to the secondary wavelets
D) The wave front is reflected back to its origin

Answer:
C) The wave front is formed by the tangent to the secondary wavelets

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Q5: What type of wave propagation does Huygens' Principle apply to?

A) Only sound waves
B) Only light waves
C) All types of waves (e.g., light, sound, water)
D) Only mechanical waves in solids

Answer:
C) All types of waves (e.g., light, sound, water)