Optics

Branch of physics which deals with the study of light – behavior and property of light; how light interacts with matter and construction of optical instruments. The term light in optics include visible light, ultraviolet light and infrared light. We define light as a form of energy which is treated as a particle and as a wave (wave – particle duality). Light can therefore be perceived as a stream of energy particles from the source to the target object. A single particle of light is a massless packet of energy referred as photon. Light is also considered as an electromagnet wave which is transverse in nature. There are three branches of optics depending on the definition of light.

Branches of optics

Geometric optics: Light is considered as a ray – path along which light energy travels. This is the earliest branch of optics which involved ray tracing. The laws of reflection was stated by Euclid around 300 BC. The law of refraction was experimentally determined by Snell in 1621. This led to development of optical devices like Mirrors, lenses, glasses, Telescope and Microscope.

Physical Optics: Light is considered as a wave – an electromagnetic wave. Light wave is described using wavelength, frequency, speed, intensity (power) and energy. The main personalities behind this study included Thomas Young, Joseph Frounhofer and Augustin Fresnel. Three properties of light are studied in wave optics; Interference, Diffraction and Polarization. The study led to development of antireflection coating, high reflection coating, light polarizers, holograms, and interferometers among others.

Quantum Optics: Light is considered as a particle – photon or stream of particles. This development led to explanation of photoelectric effect – ejecting electrons from some metals surfaces by shining a beam of light on them. The main personalities include Einstein in 1905.

Some Uses of light

Light plays a vital role in our daily lives. These are just a few of uses of light.

1. Laser rays of light is used in compact disc (CD) players to retrieve stored information (music and videos).
2. Laser beams are used to read bar codes for prices in the supermarkets.
3. Laser printers use light to print images on paper.
4. Digital cameras use light to capture images of objects.
5. Fiber-optic cables are used to connect computers to transfer digital information.
6. Lasers are used to perform surgery and in non-invasive diagnostic tools.
7. Laser fabric cutting machines
8. Infrared security systems

Photonics is based on the science of optics and electronics. Photonics is defined as the generation, manipulation, transport, detection, and use of light information.

Properties of light

What is light? Light is a form of energy that is propagated inform of electromagnetic wave with a constant speed of $2.999\ x\ 10^8\ m/s$ in a vacuum. It travels in a straight line as it transfer energy from one place to another.

When light falls on an object, a fraction of light energy is reflected back in the same medium, another fraction is absorbed by the object and the rest of the energy is transmitted through the object.

$$E = E_{reflected} + E_{Absorbed} + E_{transmitted}$$

Radiometry is the field of detecting and measuring electromagnetic radiated energy, where visible light energy is included. It gives the distribution of the light's power in space.

Photometry is the concerned in the measurement of light, in terms of its perceived brightness to the human eye. Photometer – instrument used to measure the intensity of light. It has a spectra response similar to that of a human eye.

Luminous sources radiate their own light. Non-luminous sources reflect light.

Luminous intensity, I is the measure of power emitted by a source in a particular direction per unit solid angle.

SI unit of Luminous intensity the candela (cd). The intensity of a light source is commonly referred as candlepower.

Luminous flux, F is the amount of the energy of the light emitted per second in all directions.

The SI unit of luminous flux is lumen (lm).

Consider a point source of light emitting uniform light in all directions. A distance of 1 m from the source, the enclosed space is spherical in shape with a total surface area $4\pi\ m^2$.

$$Luminous\ flux\ =\ area\ x\ luminous\ intensity$$

$$Luminous\ flux, F\ =\ 4\pi I$$

Illuminance, E is the amount of luminous flux per unit area. The SI unit is the lumen/m^2.

Laws of reflection of light

1. Angle of reflection equals to the angle of incidence.
2. The incident ray, the normal line and the reflected ray must meet on the reflecting surface.

Characteristics of images formed by a flat reflecting surfaces

1. Image has the same size as the object
2. The image and the object have the same distance from the reflecting surface.
3. Image is laterally inverted
4. The image is virtual

Refraction of light

When light travels from one medium to another, two properties will change;

1. Velocity. (Frequency remains the same but wavelength will change)
2. Direction (given in terms of angles)

Light moving along the normal is not deflected.

The index of refraction of a transparent medium is the ratio between the velocity of light in free space and light velocity in a given medium.

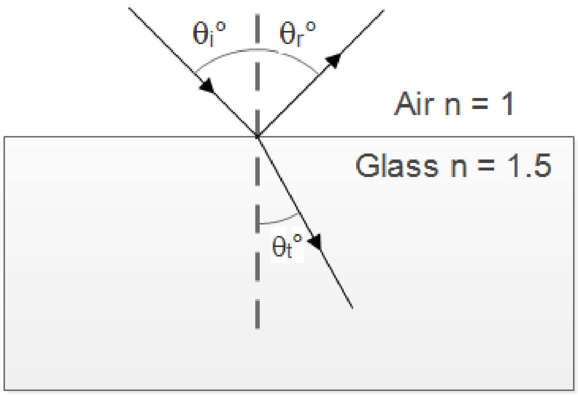
$$Index\ of\ refractio, n\ = \frac{c}{v}$$

The greater the value of index, n the more the light is deflected on entering the medium from the air.

Snell's law

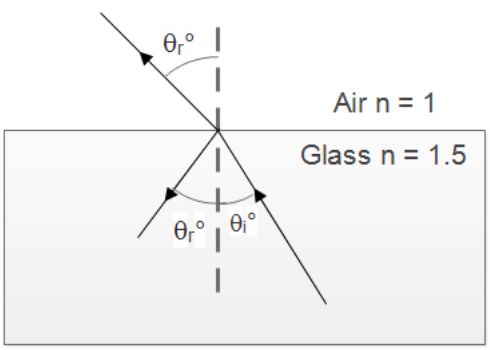
This predicts the direction of light as it travels through different transparent mediums. Equation law is stated by the following equation where n is the refractive index, i for incident, t for transmitted.

$n_i \sin \theta_i = n_t \sin \theta_t$



The principle of reversibility

If light passes from medium one to the second, it traces a path. When the source of light comes from the second medium to medium one, the same path is traced but in reverse.



When light comes from glass to air, the diffraction is more; high index medium to a low index medium. A small increase in θ_i results to big refraction in θ_r. At some point $\theta_i = \theta_c$ will give $\theta_r = 90°$.

Critical angle, $\boldsymbol{\theta_c}$

This is a particular angle of incidence when the angle of refraction is equal to 90°.

The consequence of this to the Snell's law;

$n_i \sin\theta_c = n_t \sin 90°$

If the transmission medium is air, $n_t = 1$ and $\sin 90° = 1$. Therefore;

$n_i = \frac{1}{\sin\theta_c}$ A relationship used to find critical angel when refractive index is known.

Total internal reflection

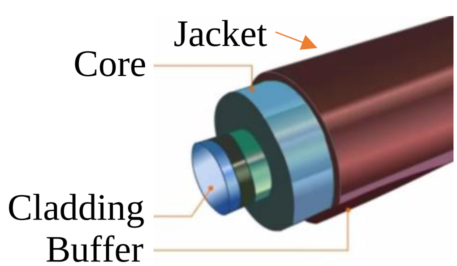
This is a phenomena that occur when $\theta_i > \theta_c$. Total incident ray is reflected back to the same incident medium and none is transmitted to the second medium.

This phenomena is most applied in transmission of information inform of light - fiber optic cables.

Optic fibres cables

They are used to direct or guide light as it move from one point to another. They are long tiny threads made of very pure glass with a diameter almost to that of human hair. They are arranged in bundles called optical cables used to transmit light communication signals over long distances.

Optical fibres consist of three layers;



Core is the thin glass material through which light travels. Cladding surround the core and reflects light into the core. Buffer coating protects the fibres from moisture and any kind of external damage. The jacket is the cable's outer covering.

Optical fibres uses total internal reflection to confine light in the transmitting core. The core has a high reflecting index than the cladding hence the right suffers total internal reflection. The cladding maintain the constant critical angle of incidence throughout the fibres such that no light escape through the cladding. Light signals may degrade due to impurities within the fibres.

When light is directed into the core at small enough angle, total internal reflection will occur between the core and the cladding interface.

Angle of acceptance is the maximum angle in air for which total incident light is reflected into the core.

Fibres attenuation loss of light energy during transmission due to absorption and scattering by impurities in the optical fibres.

Other uses of optical fibres; in endoscope to view internal organs and in photometers – instruments used to measure the intensity of light.

When the diameter of the fiber is too small enough, waves travel in one path. Such fiber single – mode fiber. At larger diameters, wave coming in at different angles travel in different paths (Multi – mode paths).

Lenses

They are transparent medium bound between two curved surfaces. They are transmissive optical device that focus or collimate light using refraction. It can be concave or convex or a combination of the two. To collimate is to make rays of light aligned accurately parallel to one another. To eliminate divergence and convergence of light rays. A lens can focus light to form an image clearly on a screen.

There are two types of lenses; convex and concave.

A convex lens is thicker at the center than at the edges. The side receiving light is curved outward. We have bi-convex, Plano-convex and concavo-convex.

A concave lens is thinner at the center than at the edges. The side receiving light is inward outward. We have bi-concave, Plano-concave and convexo-concave.

Parts of a lens

Optical center; geometrical center of the lens.

Centre of curvature; The Centre of the sphere from which the surface of the lens was cut.

Principal axis; Imaginary line joining the optical center and the centre of curvature.

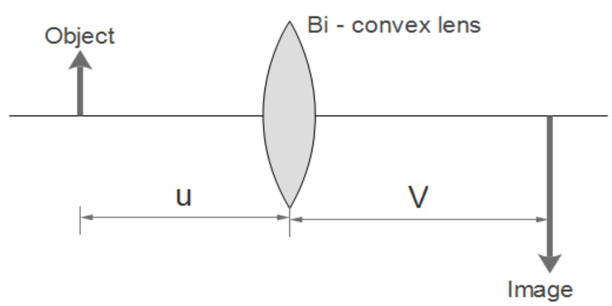
Principal focus: A point that is halfway between the optical centre and centre of curvature. For a convex lens, this point can be projected on a screen hence it's a real principal focus despite being on the other side of the lens.

The relationship between ***f***, focal length *u*, Object distance and *v*, Image distance for a convex or converging lenses.

$$\frac{1}{f} = \frac{1}{u} + \frac{1}{v}$$

Sign convection

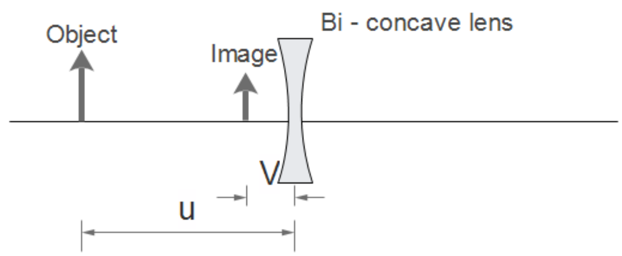
1. Optical centre is the reference point of all measurements.
2. Distances for real objects and real images are positive regardless of the side of the mirror.
3. Distances of virtual images and objects are negative.
4. The focal length of a convex lens is positive and that of a concave lens is negative.



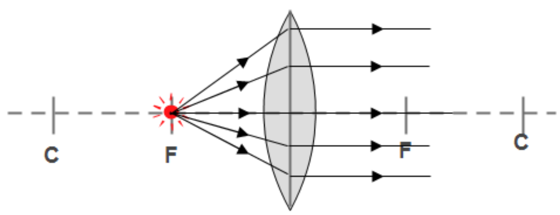
But for concave lenses, the relation changes slightly;

$$\frac{1}{-f} = \frac{1}{u} + \frac{1}{-v}$$

The focal length and the image are virtual. They cannot be formed on a screen.



A point source of light positioned at the focal length collimates light.



Magnification of the lens is given by;

$$M = \frac{v}{u}$$

Power of the lens $P = \frac{1}{f}$ It can also be obtained by $P = \frac{v}{f} - 1$

The SI unit of lens power is diopter, D. The focal length is in metres and the optical power in dioptres (inverse metres).

Lens maker's Equation

For a thin lens, the lens maker's equation is given by:

$$\frac{1}{\mathrm{f}} = (n-1)\left(\frac{1}{R_1} + \frac{1}{R_2}\right)$$

Where, n is the index of refraction, R_1 and R_2 are radii of curvature. R_1 is for the side closest to the source of light and R_2 for the side furthest from the source of light. Both R_1 and R_2 are considered positive for the convex lens.

Questions

a) i. State Snell's law. (1 mark)

ii. The refractive index of diamond is 2.42. Give the velocity of light in a diamond material? (2 marks)

b) Describe three characteristic of an image formed by a diverging lens of a real object? (3 marks)

Solution

Virtual, Erect/Upright and smaller/diminished.

c) i. What is optic fiber? (1 mark)

ii. Explain **two** advantage of optic fiber over metal conductors in transfer of electrons. (2 marks)

Solution

1. Attenuation is low compared to current signal through a wire
2. Interference with magnetic and electric field to distort the signal

d) A lens form an image that is four times the size of an object on a screen. The distance between the object and the screen is 100 cm when the image is sharply focused.

i. State with reasons what type of lens was used. Explain your answer. (2 marks)

ii. Calculate the focal length of the lens. (4 marks)

e) State the *laws of reflection*. Show with appropriate drawings how it applies to light rays falling on a plane surfaces. (3 marks)

f) Explain the dual nature of light. (2 marks)

g) The refraction of diamond is 2.42.

i. What is the velocity of light in diamond? (3 marks)

ii. A beam of light strikes a pane of glass at an angle of incidence of 50. If the angle of refraction is 30, find the index of refraction of the glass? (3 marks)

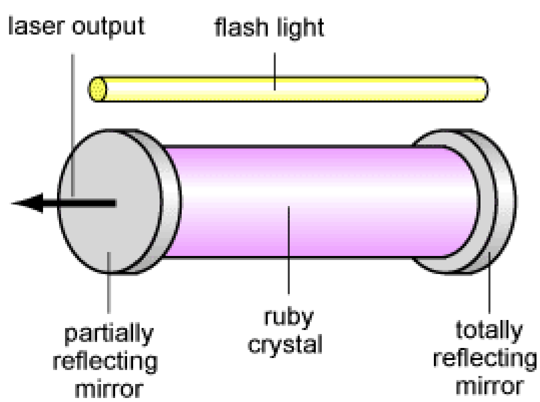
Laser

They are devices that generate an intense beam of coherent and monochromatic light. They are light sources used in laboratory or in the industries to create light of specific wavelength and power.

Coherent means light waves with a constant phase difference and the same frequency. All the wavelength are in phase in specific space and time. Ordinary light bulb which use heating element to create light produce incoherent light with a wide range of wavelengths.

Laser is the acronym of; **L**ight **a**mplification by **s**timulated **e**mission of **r**adiation. Light photons are emitted from excited atoms or molecules as they settle back to their unexcited state.

The figure below shows a ruby laser. It consist of gain medium between reflecting mirrors. The original light is provided by the flash light and amplified by the laser.



Ruby which is $AL_2O_3 + Cr$ is the gain medium. The medium determines the wavelength of the light beam produced. Solid Laser (e.g Ruby) Gas lasers (e.g He-Ne) and liquid (dye) lasers.

The flash light lamp are used to excite the gain medium into a higher than usual energy state. When flash light goes off, excited gain medium loses the gained energy inform of photon at a specific wavelength and return to normal energy state. The mirrors reflect the light back to cause stimulated emission. The mirror with the partial reflection allow a narrow beam out.

Lasers are dangerous because they have a potential to have a very high power. Laser beams can deposit a great amount of energy within a very small area.

Properties of Laser light

1. They are highly directional – narrow beams in specific directions.
2. Monochromatic – One colour and one wavelength.
3. Coherent – All waves have a constant phase difference.

Light Emitting Diodes (LED)

Light is produced through the same process as lasers but there are no reflecting mirrors to cause the stimulated emission. There is only spontaneous emission rather than stimulated. LED produce incoherent light which are less harmful to human eye.

Questions

a) Describe three properties of laser light? (3 marks)

b) Define the following properties of laser light:
   i. Mono-chromaticity (1 mark)
   ii. Directionality (1 mark)
   iii. Coherence (1 mark)

c) i. What is a laser? (2 marks)
   ii. Laser is an acronym for what? (5 marks)
   iii. Explain any three uses of lasers. (3 marks)