Chapter 5: Optics

At the end of the lesson, students should be able to:

- Know the characteristics of lights
- Understand the dual behaviour of lights
- Understand the Law of Reflections and its applications
- Understand the Law of Refractions and its applications
- Describe how an image is formed using ray diagram
- State Len's equation with respect to an image
- Know the setup of fibre optics communications
- Understand total internal reflection in relation to fibre optics
- Introduction to LiDAR and vision camera sensors in autonomous vehicles

5.1 Introduction to light and its characteristics

Optics is the branch of Physics that deals with light. In this chapter, we shall study its characteristics, generation, propagation and applications.

Light is a transverse electromagnetic wave (TEM) and it has a frequency or electromagnetic spectrum.

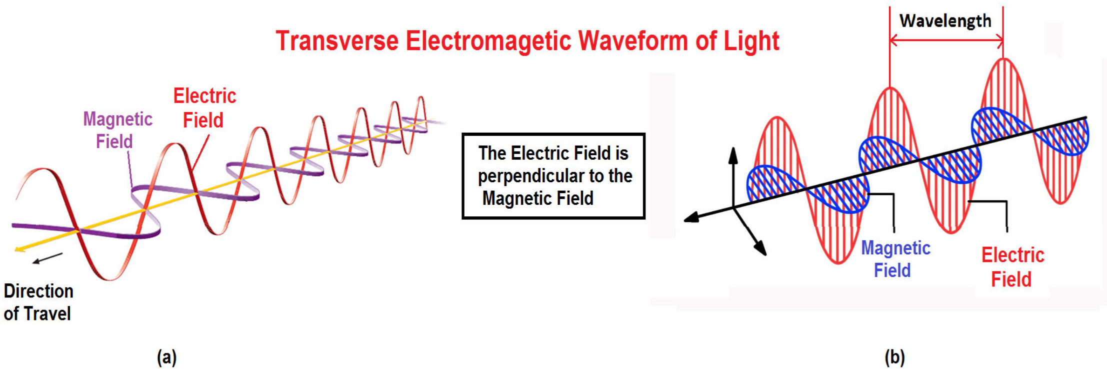
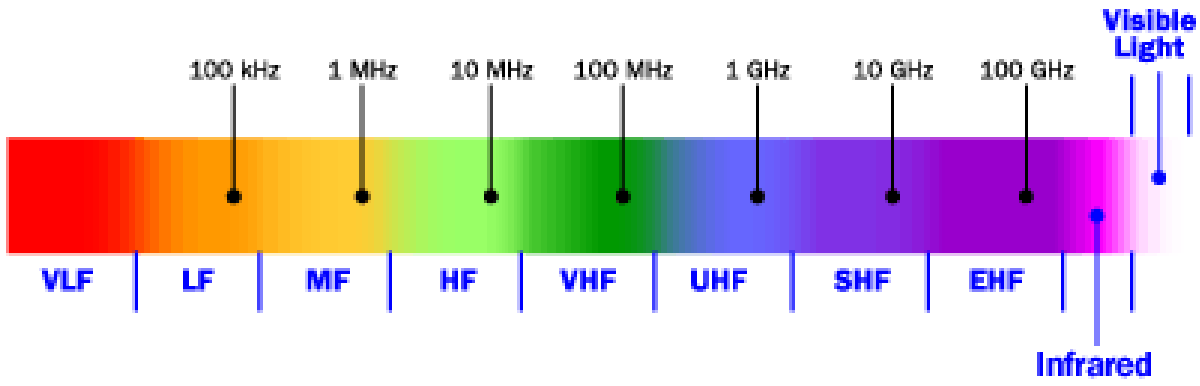


Figure 5.1: Transverse Electromagnetic Waveform of Light



RF Band	Range		Use
VLF	3 KHz	30 KHz	Navigation (NAV)
LF	30 KHz	30 KHz	NAV, broadcast, maritime
MF	300 KHz	3 MHz	AM Broadcast, maritime
HF	3 MHz	30 MHz	CB, broadcast, maritime
VHF	30 MHz	300 MHz	FM, TV, NAV
UHF	300 MHz	3 GHz	TV, radar, NAV, space, meteorological
SHF	3 GHz	30 GHz	Space, satellite, NAV, radar

Table 5.1: Electromagnetic Spectrum

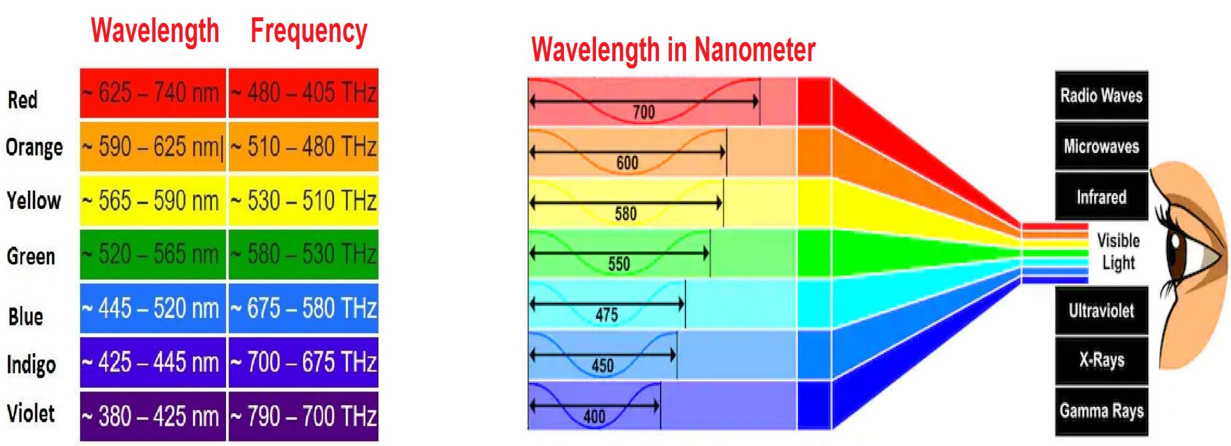


Figure 5.2: Electromagnetic Visible Light Spectrum

The three most important **characteristics of light** are brightness, colour, and temperature. Brightness does not need much explanation, but colour and temperature are slightly more subtle concepts. **Light** is also an electromagnetic radiation visible to the human eye.

The velocity of light in any frequency, in vacuum, is one of the fundamental constants of nature. Light propagates at a velocity, c, **of 3 x 10^8 m/s** in vacuum

The frequency (f), wavelength (λ) and velocity (c) of light in a medium are related by

$$c = f\,\lambda$$

When propagating in a medium, light of a particular frequency slows down but its frequency is unchanged. So, it has to be the wavelength that becomes shorter while light propagates in a medium. In which case, we have **$c = f\,\lambda$** .
Monochromatic light is a light of single frequency or single wavelength

https://www.youtube.com/watch?v=pj_ya0e20vE

5.2 Dual Behaviour of Light

Light has dual nature. It behaves either as wave or as particle depending on its interaction. Light being a wave is used to explain double slit experiment and light being a particle is used to explain by photoelectric effect.

The following are the theories that support the dual nature (reference only).

- **Newton's corpuscular theory**
  - Explains the rectilinear propagation of light
  - Made up of particles that are hurled at a great velocity.
- **Huygens's wave theory of light**
  - Wave behaviour of light.
- **Maxwell's electromagnetic theory**
  - Light behaves like an electromagnetic wave.
  - Light and radio waves are similar.
- **Planck's quantum theory**
  - Light consists of photons.
  - Each photon has an energy, $E = hf = hc/\lambda$ where h is known as the Planck's constant.

5.3 Reflection of Light

Light can be reflected off a surface. Among other things, this gives rise to the images we see in mirrors. The reason that we see an image in a mirror as apparently coming from behind the mirror is that our eyes interpret the reflected light as originally coming from a point behind the mirror, as indicated in the figure. The image we see is upright, the same size as the original object and laterally inverted.

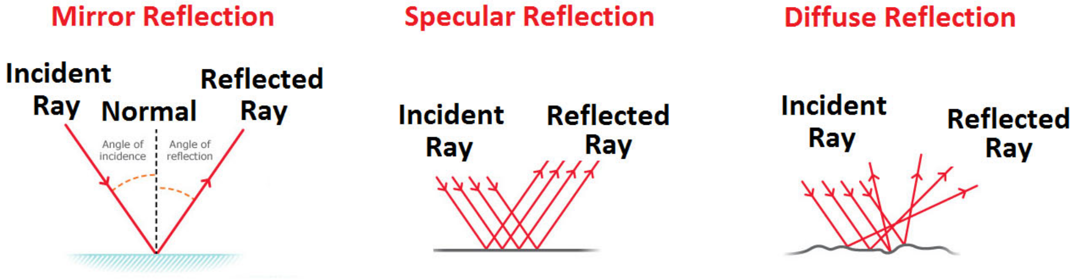


Figure 5.3: Reflection of Light on surfaces

Mirror and **specular reflection** are also known as **regular reflection**, is the mirror-like reflection of waves, such as light, from a surface. The law of reflection states that for each incident ray the angle of incidence equals the angle of reflection, and the incident, normal, and reflected directions are coplanar.

Diffuse reflection is the reflection of light or other waves or particles from a surface such that a ray incident on the surface is scattered at many angles rather than at just one angle as in the case of specular reflection. Many common materials exhibit a mixture of specular and diffuse reflection.

Reflection of light satisfies the following relation:

Angle of incidence (i) = Angle of reflection (r)

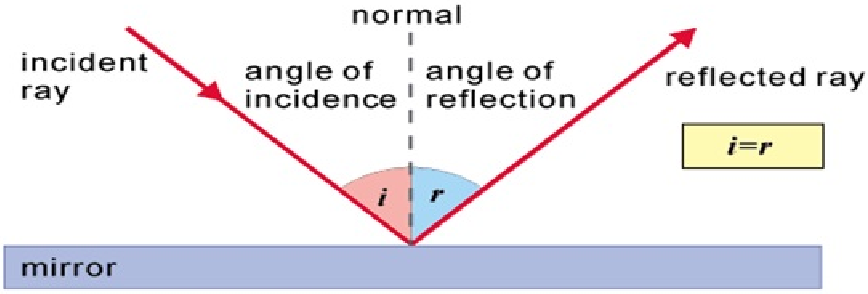


Figure 5.4: Angle of incident, angle of reflection and normal of light

This is known as the **Law of reflection.** Reflective materials can be used to reflect the light off approaching vehicles to warn the drivers that there are repair works ahead. No energy is required to be generated from the materials.

https://www.youtube.com/watch?v=WDBtOeXUdWQ

5.4 Refraction of Light

As light travels from one medium to another medium, the

- Speed of the light changes.
- Direction of the light changes.
- Wavelength of the light changes.

However, the frequency remains same.

Refraction is the bending of a wave when it enters a medium where its speed is different. The refraction of light when it passes from a fast medium to a slow medium bends the light ray toward the normal to the boundary between the two media.

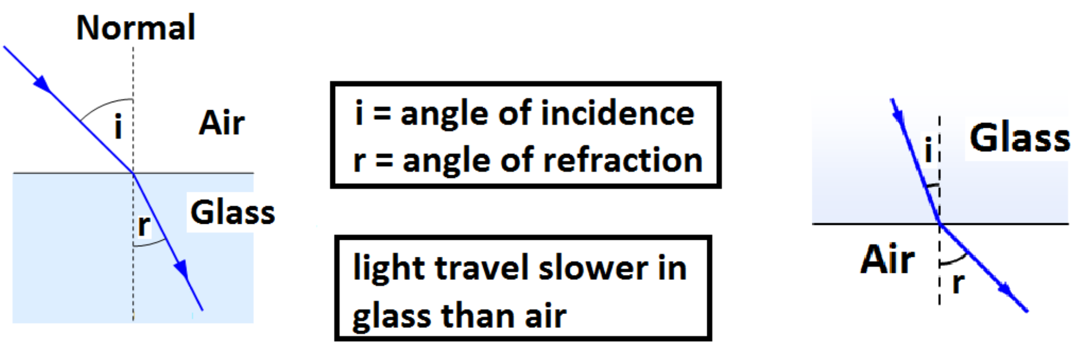


Figure 5.5: Refraction of Light between two different media

The Snell's law of refraction governs the refraction of light. It states that:

$$n1 \times \sin(i) = n2 \times \sin(r)$$

Where

i is the angle of incidence
r is the angle of refraction
n1 & n2 are the refractive indices of two different media.

https://www.youtube.com/watch?v=4l2thi5_84o

Example 5.1

If a light ray (in air, $n_1 = 1$) is incident upon a piece of glass ($n_2 = 1.5$) at an angle of 30^0 (i), then the angle of the refracted ray (r) is:

$$r = \sin^{-1}(1 \times [\sin 30^\circ]/1.5) = 19.47^\circ$$

The index of refraction of light is given as:

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

c = velocity of light in vacuum

v = velocity of light in the medium

n is always greater than or equal to 1.

Table 5.2 shows the refractive indices of various materials.

Media	Refractive Index
Water	1.33
Fused Quartz	1.46
Crown Glass	1.52
Flint Glass	1.62
High-Index Plastic Lenses	1.74
Diamond	2.42

Table 5.2 Refractive Indices

White light can be dispersed into many colours. Each colour has different wavelength.

Variation of index of refraction with wavelength is known as dispersion.

Because of this index change versus wavelength, when white light is refracted, it is separated into its component colours. This is shown in Figure 5.6

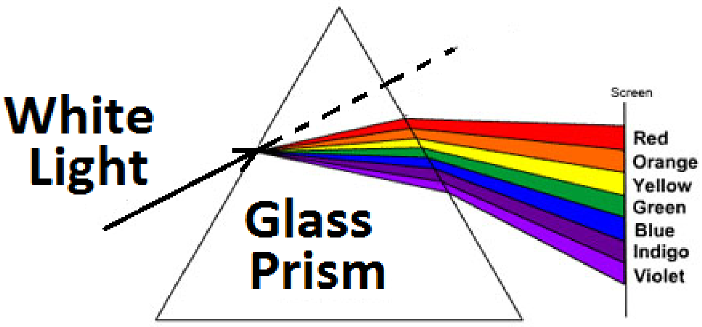


Figure 5.6: Dispersion of light through a glass prism

The explanation for this phenomenon is simple: the white light consists of literally all the colours in the rainbow. The various colours are refracted through different angles by the glass prism, and are ``dispersed'', or spread out. From Figure 5.6, we see that violet light gets bent more by the glass than red light.

Air has an index of refraction of about 1.0003. However, it is convenient to use a value of 1.0 for most optical calculations.

The greater the density difference between the two materials, the more the light bends. One place where this is used is in lenses for a variety of optical devices, such as microscopes, magnifying glasses, and glasses for correcting vision.

Many types of optical illusions are due, at least in part, to the refraction of light. The following Figure 5.7.

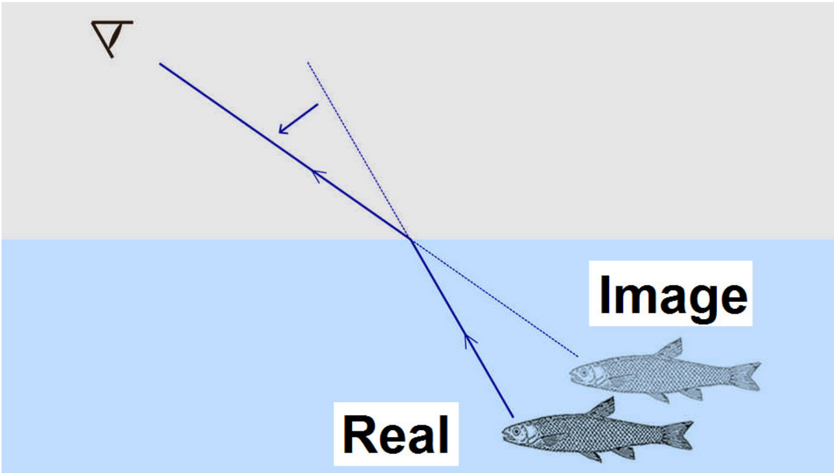


Figure 5.7: Apparent depth of an object under water

5.5 How images are formed in mirrors and lenses

In this section, we shall understand how images are formed in mirrors and lenses.

To study mirrors and lenses, we need to know the **focal point**. The focal point of a lens or mirror is the point in space where parallel light rays meet after passing through the lens or bouncing off the mirror. A "perfect"lens or mirror would send all light rays through one focal point, which would result in the clearest image. (refer to Figure 5.8 and Figure 5.9)

5.5.1 Convex and Concave mirrors

Figure 5.8 shows how a convex and a concave mirror form images. Note how the distance of the object and the curvatures of the mirrors affect the images being formed.

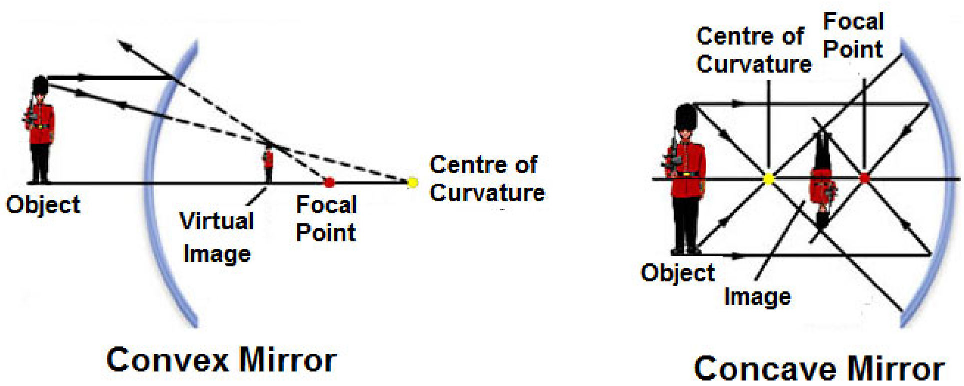


Figure 5.8: Focal point and Image formation in Mirrors

5.5.2 Focal point and focus length of convex and concave lenses

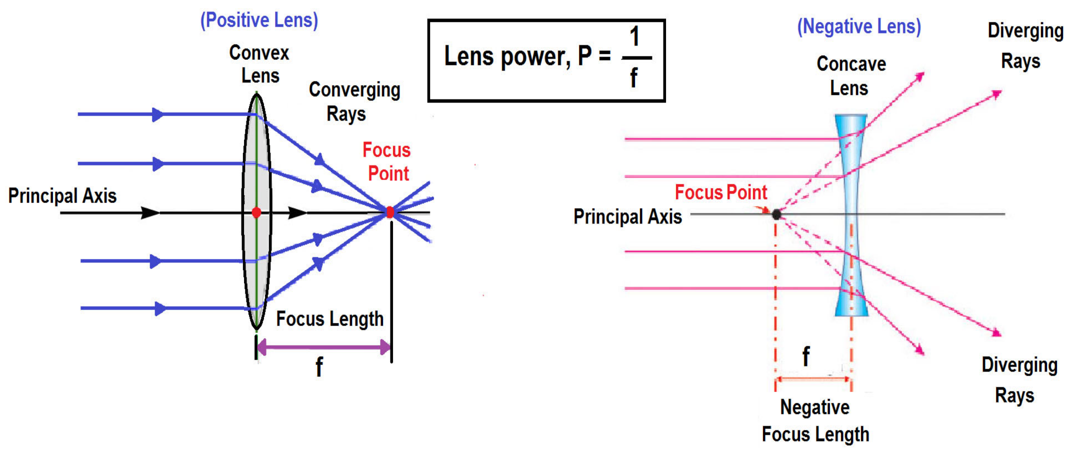


Figure 5.9: Focal point in lenses

Figure 5.10 and Figure 5.11 show how an image is formed in a convex and a concve lens. Note the object is placed at a distance greater than the focal length away from the lenses. For the convex lens, the image is inverted and real. The image of the concave lens is virtual. The image position may be found from the **Len's equation** or by using a ray diagram.

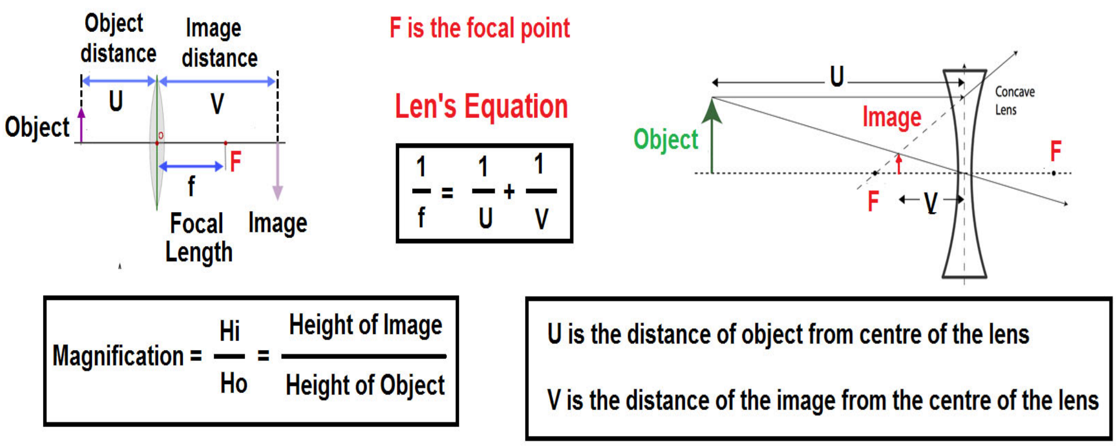


Figure 5.10: Image formation in a Convex and a Concave Lens

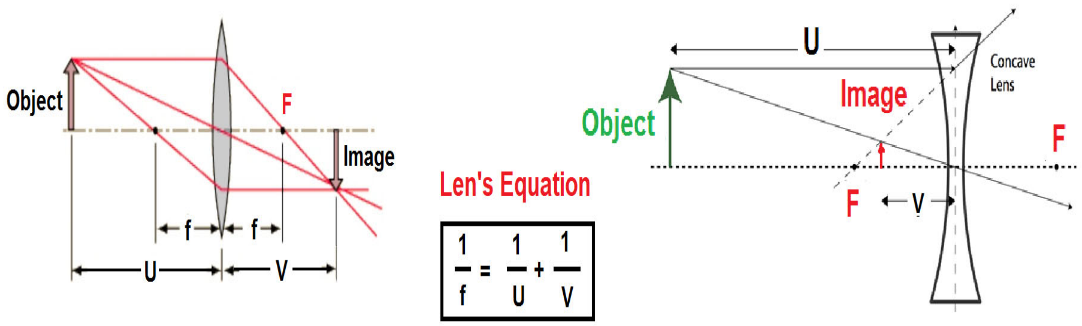


Figure 5.11: Image formation using ray diagrams

Figure 5.12 shows how virtual images are formed in a convex and a concave lens. Note that the object distance is shorter than the focal length for the convex lens. Although a virtual image does not form a visible projection on a screen, it is no sense "imaginary", i.e., it has a definite position and size and can be "seen" or imaged by the eye, camera, or other optical instrument. Concave lens always produces virtual images.

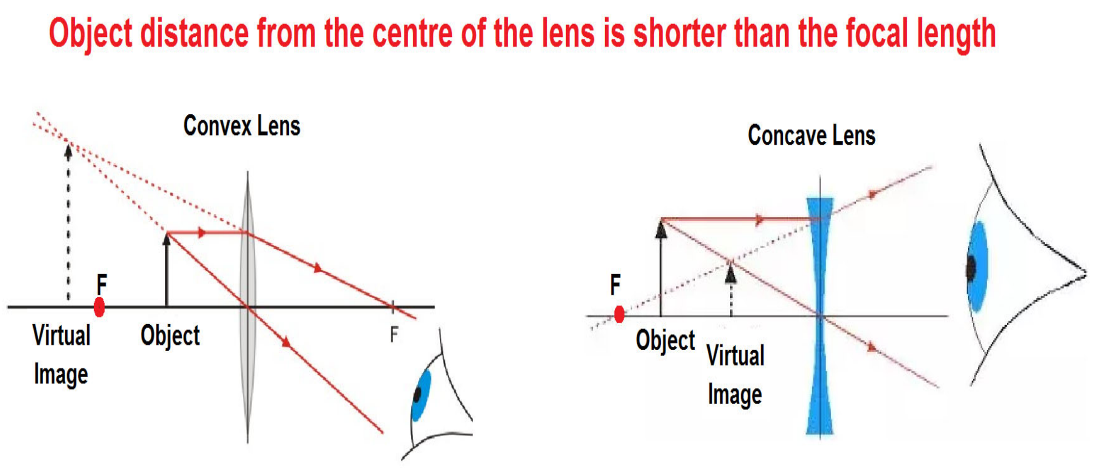


Figure 5.12: Virtual Image formation in Convex and Concave Lenses

https://www.youtube.com/watch?v=xpcX3B4xE7Q

5.6 Vision Camera

Vision cameras are installed in autonomous vehicles. They function like human eyes. By careful selection, we can increase the field of view. Generally, stereo vision or systems with 2 cameras is able to provide the distance of an object from the camera accurately. Without proper lightings, the cameras either cannot see clearly or are not reliable.

5.6.1 Fiber Optic Communications

In recent years, world demand for communications facilities carrying many different types of real-time and non-real-time signals such as voice, data and video has been growing very rapidly during the past few decades. The continuing increasing demand and resulting large amount of worldwide communication traffic naturally calls for communications links with very large transmission bandwidth. Higher transmission bandwidth allows more information to be transferred at a faster rate.

Fiber optics cable networks are able to satisfy this increasing demand.

Moreover, it has become apparent that fiber optics is steadily replacing copper co-axial cables as a transmission medium of choice for high bandwidth long distance communications applications. They span the long distances between local phone systems as well as providing the backbone for many network systems. Other system users include cable television services, university campuses, office buildings, industrial plants, and electric utility companies.

Power companies are an emerging group that has begun to utilize fiber optics in their communication systems. Most power utilities already have fiber-optic communication systems in use for monitoring their power grid systems.

Figure 5.13 shows the layout of a typical cable television (CATV) network using a Hybrid Fiber Co-axial (HFC) because the trunk transmission is by fiber optic cable and the local transmission, down to the subscriber's home, is by co-axial copper cable. The CATV trunk network, head end to hub sites and hub sites to node, is fiber optic cable.

Such a hybrid allows for the integration of fiber and coaxial at a neighborhood location. This location, called a node, would provide the optical receiver that converts the light impulses back to electronic signals. The signals could then be fed to individual homes via coaxial cable.

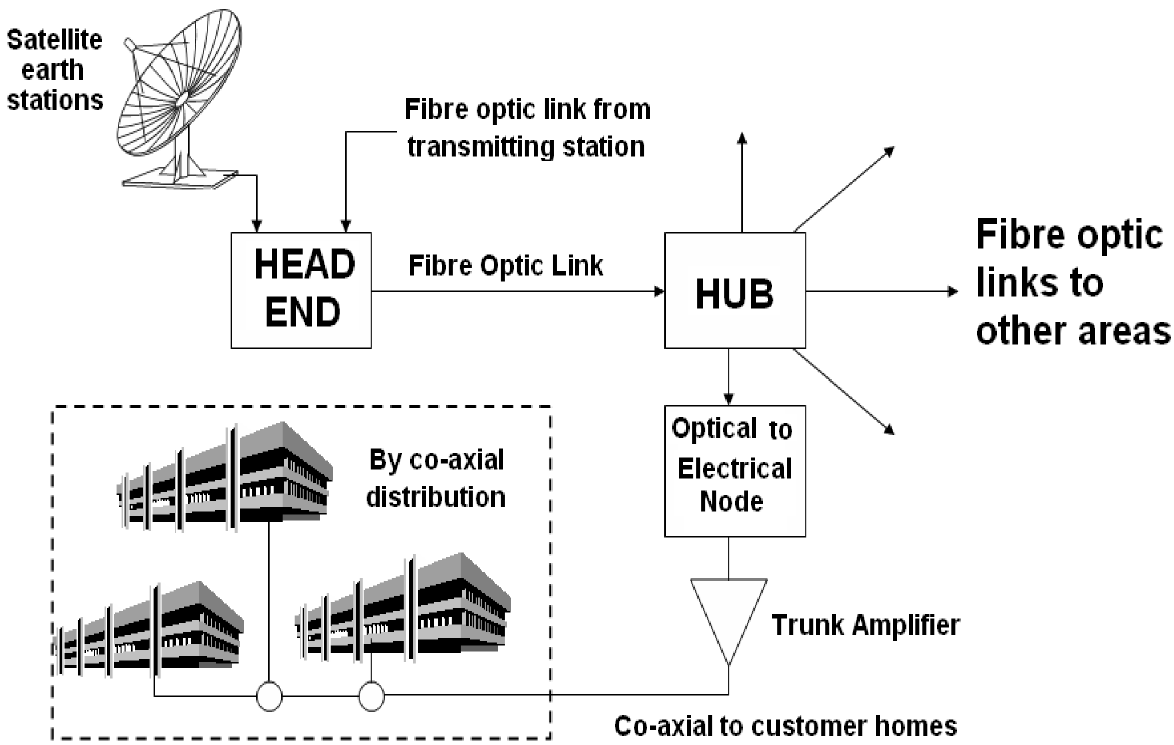


Figure 5.13: Fibre Optic Distribution System

5.6.2 Advantages and disadvantages of using Fiber Optics in data communications

The **benefits** of a fiber optic communication system as compared to traditional copper systems are:

- **Very wide bandwidth** - very high information carrying capacity. It can carry information at up to 2.5 Gigabits per second, enough to carry 40,000 telephone conversations or 250 television channels. Experts predict larger bandwidths than this as light frequency separation becomes available. Commercials fiber optics can be modulated up to 40 Gigabits per second and a single fiber-optic cable can carry data at rates as high as 14444 Tb/s.
- **Low transmission loss / attenuation** – signal losses can be as low as 0.2 dB/km! (depends on type of fiber used) It needs fewer optical repeaters to boost the transmitting light pulses than copper coaxial systems. (A copper co-axial communication system needs more **signal regenerators** to boost the signals to prevent it from losing energy during transmission.) Hence, data can be transmitted much further with lower losses.
- **Lightweight and smaller diameter cables** - Being about the same diameter as a human hair, a fiber is much smaller than a copper wire. Fibers can be installed in cable ducts that have no room for copper cables and hundreds of fibers will take up the same space as one piece of coaxial cable.
- **Very high-speed communication** – travel at the speed of light.
- **Low crosstalk** - Optical fibers do not generate external electromagnetic fields so the light in one fiber will not interfere in an adjacent fiber. Hence, also lower transmission errors.
- **Electromagnetic immunity** - No Electromagnetic Interference (EMI) issues. This may be an important consideration when laying cables near electromagnetic sensitive instruments or equipment. E.g. Primary and Navigational displays.
- **Radio Frequency immunity** - no Radio Frequency Interference (RFI) issues. This may be an important consideration when laying cables near radio frequency sensitive instruments or equipment. E.g. Antenna.
- **Electrical noise immunity** (no voltage or current surges) – no sudden increase in voltages or current (spikes). It does not produce electric sparks that can be an obvious fire hazard. Hence, greater safety.
- **Greater security** – It is difficult (but not impossible) for someone to tap an optical fiber. This is because the light does not radiate outside the fiber and any tapping into the fiber would be detected because of the associated power loss.
- **Abundant of raw materials** - Glass is made from silicon which is an abundant and easily extracted element, whereas, copper is relatively rare and difficult to mine.
- **Environmental Friendly**
- **Resistant to radiation, corrosion and temperature variations**
- **No grounding or shorting concerns**

- **Easy upgrading** - upgradeable without ripping out & replacing cable harnesses
- **Lower maintenance cost**.

The **major disadvantages** of a fiber optic communication system as compared to traditional copper systems are:

- **Incompatibility with the existing electronic hardware systems**. Hence, current communication hardware systems must be somewhat retrofitted to the fiber-optic networks.
- **Bottle neck problem**. Much of the speed that is gained through optical fiber transmission can be inhibited at the conversion points of a fiber-optic chain. When a portion of the chain experiences heavy use, information becomes jammed in a bottleneck at the points where conversion to, or from, electronic signals is taking place. Bottlenecks like this should become less frequent as microprocessors become more efficient and fiber-optics reach closer to a direct electronic hardware interface.
- **Expensive components**. Because of the relative newness of the technology, fiber optic components are expensive. Fiber optic transmitters and receivers are still relatively expensive compared to electrical interfaces.
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5.7 Total Internal Reflection in Optical Fiber Communication

To understand how optical fiber can transmit data (signal), let us recall reflection and refraction of light travelling between 2 different mediums.

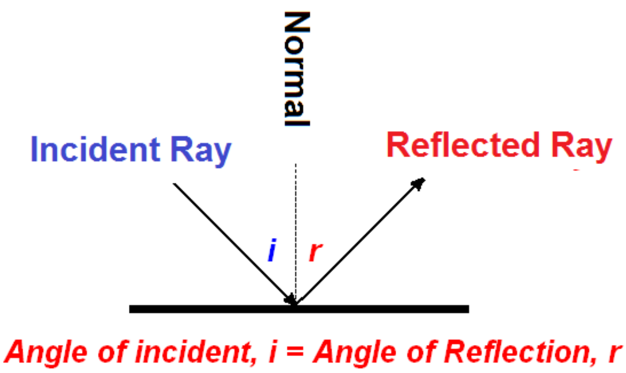

Figure 5.14: Reflection of Light on a smooth surface

Light is an electromagnetic wave, hence, the speed at which it travels is determined by the electrical and magnetic properties of the material in which it travels. If the light travels in different materials then the light will change speed and will bend in a different direction. This bending is known as **refraction**. The speed of light in a material is determined by the following equation:

$$v = \frac{c}{n} \quad \text{(m/s)}$$

Where v is the velocity of the light ray, c is the velocity of light in free space (3×10^8 m/s) and n is the refractive index of the material in which the light is traveling. Figure 5.15 shows how light are bent when traveling between two different materials.

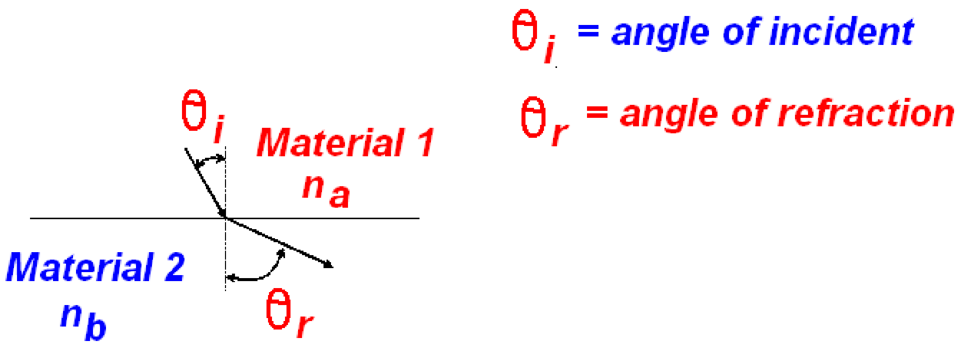

Figure 5.15: Refraction of Light on a smooth surface

https://www.youtube.com/watch?v=k1mrNrjDJwc

5.7.1 Critical angle

Consider what happens if the angle of incident, θ_i is increased. Eventually, the angle of diffraction, θ_r will reach 90^0 and the angle θ_i that gives θ_r = 90^0 is known as the critical angle θ_c. If θ_i is increased beyond θ_c, then the light is no longer refracted into the second material. Instead, the light is **Totally Internally Reflected** in the first material.

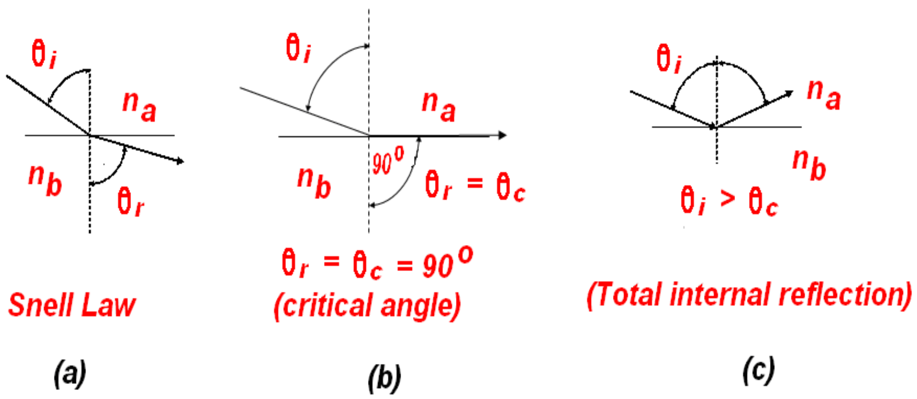

Figure 5.16: Reflection of Light on a smooth surface

It can be proven that

$$\theta_c = Sin^{-1}\frac{n_b}{n_a}$$

and

$$n_a > n_b$$

In short, total internal reflection **occurs** because the angle of refraction reaches a 90-degree angle before the angle of incidence reaches a 90-degree angle. Since light only bends away from the normal when passing from a more dense medium into a less dense medium, then this would be a necessary condition for total internal reflection.

5.7.2 Total Internal Reflection

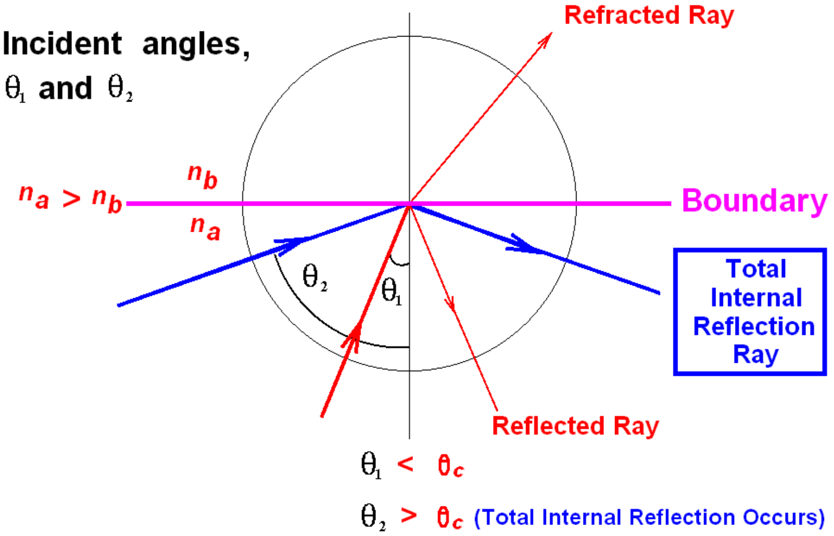

Figure 5.17: Total Internal Reflection of Light on a smooth surface

To recall, when light crosses a boundary between materials with different refractive indices, the light beam will be partially refracted at the boundary surface, and partially reflected.

Total internal reflection is an optical phenomenon that occurs when light strikes a medium boundary at an angle larger than the **critical angle**, θ_r, with respect to the normal to the surface. If the reflective indexes, n_b, is lower than n_a, no light can pass through, so effectively all of the light is reflected back to the first medium with reflective index, n_a. The **critical angle**, θ_c, is the angle of incidence, θ_i, above which the total internal reflection occurs.

During total internal reflection, 100% of the light is reflected back into the denser medium, as long as the angle at which it is incident to the surface is large enough.

Total internal reflection occurs:

- When light travel from denser medium to less dense medium and
- When the angle of incidence is greater than a minimum value.

The minimum angle of incidence is known as the critical angle θ_C. θ_C is given by:

$$\text{Sin } \theta_C = \frac{\text{Refractive index of the less dense medium}}{\text{Refractive index of the denser medium}}$$

Example 5.2

Find the critical angle when two media being glass and water.

$$\text{Sin } \theta_C = 1.33 / 1.5 = 0.887$$

Therefore critical angle is = $\sin^{-1}$ 0.887 = 62.49^0

5.7.3 Principle of optic fiber communication

An optical fiber communication system is similar to the copper wire communication it is replacing. The difference is that fiber-optics use light pulses to transmit information (data) down fiber lines instead of using electronic pulses (digital data) to transmit information down copper lines. With copper cables, larger size means less resistance and therefore more current, but with fiber, the opposite is true.

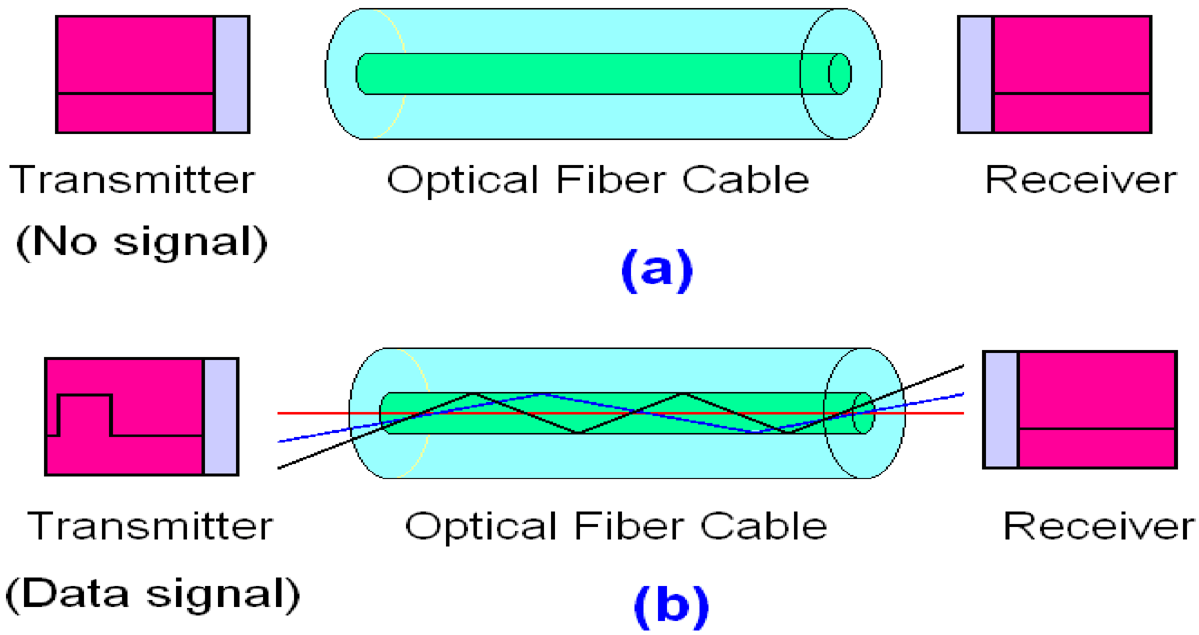

Figure 5.18: Total Internal Reflection of Light in an optical fibre

5.8 Introduction to machine vison and LIDAR sensors in autonomous vehicle

An autonomous vehicle needs many sensors to manoeuvre safely around. These sensors include camera, radar, LIDAR, ultrasonic and infrared. These sensors work in conjunction with each other to control the driverless vehicle. Radar sensors dotted around the car monitor the position of vehicles nearby. Camera are the 'eyes' that help the vehicle to see far. LIDAR sensors help to detect the edges of roads and identify lane markings by bouncing pulses of light off the car's surroundings. Ultrasonic sensors make use of sound reflection and infrared can be used for near distance detection of objects.

RADAR stands for Radio Detection and Ranging

LIDAR stands for Light Imaging Detection and Ranging

LIDAR works much like radar, but instead of sending out radio waves, it emits pulses of infrared light or laser. Laser is invisible to the human eye. It measures how long the laser take to come back after hitting nearby objects. It does this millions of times a second, then compiles the results into a so-called point cloud, which works like a 3-D map of the world in real time—a map so detailed it can be used not just to spot objects but to identify them. Once it can identify objects, the car's computer can predict how they will behave, and thus how it should drive.

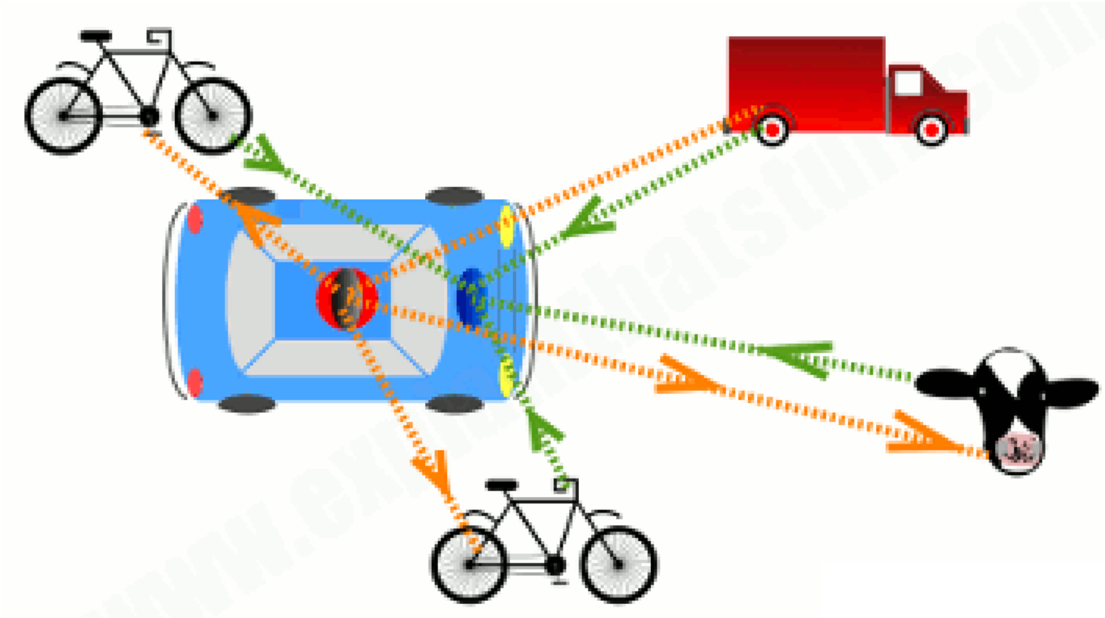

Figure 5.19: How LIDAR detects object around an autonomous vehicle

The YouTube video will help us to understand the driverless car better.

https://www.youtube.com/watch?v=JC94Y063x58 (How is LiDAR remote sensing used for Autonomous vehicles?)

https://www.youtube.com/watch?v=zREAEdXzOcw **(**What are the Top 5 uses of Lidar? Why is Lidar so important?)

https://www.youtube.com/watch?v=e6C3m-mZ40Y (A solution for camera-based autonomous driving? | Niko Eiden | HT Summit 2017)

https://www.youtube.com/watch?v=gEy91PGGLR0 **(Autonomous car/how it works)**

https://www.youtube.com/watch?v=tiwVMrTLUWg **(How driverless car see the road)**