# Material Science

Prof. Satish V. Kailas

Associate Professor
Dept. of Mechanical Engineering,
Indian Institute of Science,
Bangalore – 560012
India

Chapter 17. Optical properties

- Optical property of a material is defined as its interaction with electro-magnetic radiation in the visible.
- Electromagnetic spectrum of radiation spans the wide range from γ-rays with wavelength as 10^{-12} m, through x-rays, ultraviolet, visible, infrared, and finally radio waves with wavelengths as along as 10^5 m.
- Visible light is one form of electromagnetic radiation with wavelengths ranging from 0.39 to 0.77 μm.
- Light can be considered as having waves and consisting of particles called photons.

- Energy E of a photon $E = h\nu = \dfrac{hc_0}{\lambda}$

    o h – Planck's constant (6.62×10^{-34} J.sec),
    o ν – frequency,
    o c_0 – speed of light in vacuum (3×10^8 m/sec), and
    o λ – wavelength.

Electro-magnetic radiation
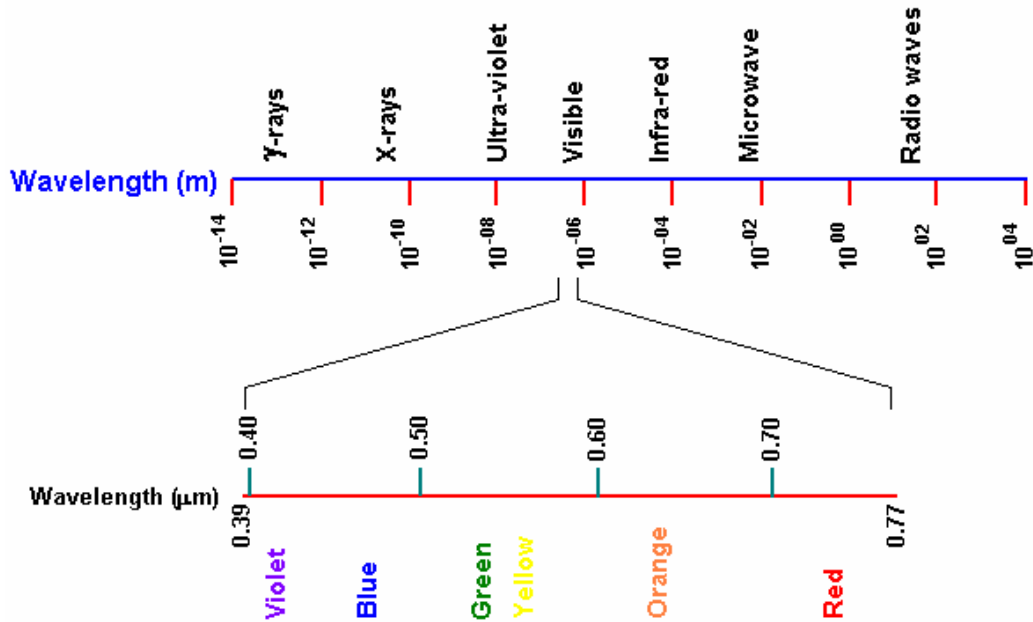
Material – Light interaction

- Interaction of photons with the electronic or crystal structure of a material leads to a number of phenomena.
- The photons may give their energy to the material (absorption); photons give their energy, but photons of identical energy are immediately emitted by the material (reflection); photons may not interact with the material structure (transmission); *or* during transmission photons are changes in velocity (refraction).
- At any instance of light interaction with a material, the total intensity of the incident light striking a surface is equal to sum of the absorbed, reflected, and transmitted intensities.

$$I_0 = I_A + I_R + I_T$$

- Where the intensity '*I* 'is defined as the number of photons impinging on a surface per unit area per unit time.

Optical materials

- Materials are classified on the basis of their interaction with visible light into three categories.
- Materials that are capable of transmitting light with relatively little absorption and reflection are called *transparent materials* i.e. we can see through them.
- *Translucent materials* are those through which light is transmitted diffusely i.e. objects are not clearly distinguishable when viewed through.
- Those materials that are impervious to the transmission of visible light are termed as *opaque materials*. These materials absorb all the energy from the light photons.

Optical properties – Metals

- Metals consist of partially filled high-energy conduction bands.
- When photons are directed at metals, their energy is used to excite electrons into unoccupied states. Thus metals are opaque to the visible light.
- Metals are, however, transparent to high end frequencies i.e. x-rays and γ-rays.
- Absorption of takes place in very thin outer layer. Thus, metallic films thinner than 0.1 μm can transmit the light.
- The absorbed radiation is emitted from the metallic surface in the form of visible light of the same wavelength as reflected light. The reflectivity of metals is about 0.95, while the rest of impinged energy is dissipated as heat
- The amount of energy absorbed by metals depends on the electronic structure of each particular metal. For example: with copper and gold there is greater absorption of the short wavelength colors such as green and blue and a greater reflection of yellow, orange and red wavelengths.

Optical properties of non-metallic materials

- Non-metallic materials consist of various energy band structures. Thus, all four optical phenomena such as absorption, reflection, transmission and refraction are important for these materials.

Refraction
- when light photons are transmitted through a material, they causes polarization of the electrons and in-turn the speed of light is reduced and the beam of light changes direction.
- The relative velocity of light passing through a medium is expressed by the optical property called the index of refraction (*n*), and is defined as

$$n = \frac{c_0}{c}$$

- where c_0 – speed of light in vacuum, c – speed of light in the concerned material.
- If the angle of incidence from a normal to the surface is θ_i, and the angle of refraction is θ_r, the refractive index of the medium, *n*, is given by (provided that the incident light is coming from a phase of low refractive index such as vacuum or air)

$$n = \frac{\sin \theta_i}{\sin \theta_r}$$
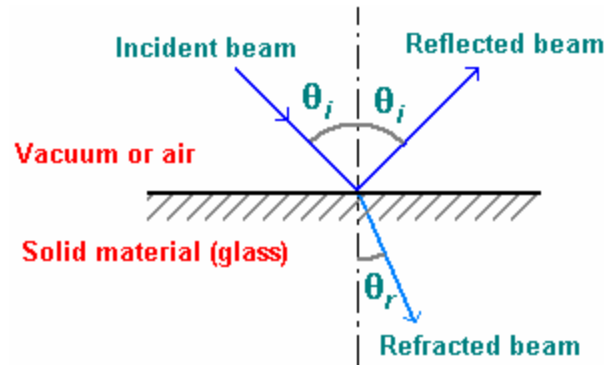
- speed of light in a material can be related to its electrical and magnetic properties as

$$c = \frac{1}{\sqrt{\mu.\varepsilon}}$$

- where ε – electrical permittivity, and μ – magnetic permeability. Thus,

$$n = \frac{c_0}{c} = \frac{\sqrt{\mu.\varepsilon}}{\sqrt{\mu_0.\varepsilon_0}} = \sqrt{\mu_r.\varepsilon_r}$$

- Since most materials are only slightly magnetic i.e. $\mu_r \approx 1$, Thus

$$n \cong \sqrt{\varepsilon_r}$$

- Thus, for transparent materials, index of refraction and dielectric constant are related.

Refractive indices of some materials

Material	Refractive index	Material	Refractive index
Air	1.00	Epoxy	1.58
Ice	1.309	Polystyrene	1.60
Water	1.33	Spinel, $MgAl_2O_3$	1.72
Teflon	1.35	Sapphire, Al_2O_3	1.76
Silica glass	1.458	Rutile, TiO_2	2.68
Polymethyl methacrylate	1.49	Diamond	2.417
Silicate glass	1.50	Silicon	3.29
Polyethylene	1.52	Gallium arsenide	3.35
NaCl	1.54	Germanium	4.00

- Snell's law of light refraction: refractive indices for light passing through from one medium with refractive index n through another of refractive index n' is related to the incident angle, θ, and refractive angle, θ', by

$$\frac{n}{n'} = \frac{\sin \theta'}{\sin \theta}$$

Reflection

- Reflectivity is defined as fraction of light reflected at an interface.

$$R = \frac{I_R}{I_0}$$

- Where I_0 and I_R are the incident and reflected bean intensities respectively.
- If the material is in a vacuum or in air then

$$R = \left(\frac{n-1}{n+1}\right)^2$$

- If the material is in some other medium with an index of refraction of n_i, then

$$R = \left(\frac{n-n_i}{n+n_i}\right)^2$$

- The above equations apply to the reflection from a single surface and assume normal incidence. The value of R depends upon the angle of incidence.
- Materials with a high index of refraction have a higher reflectivity than materials with a low index. Because the index of refraction varies with the wavelength of the photons, so does the reflectivity.
- In metals, the reflectivity is typically on the order of 0.90-0.95, whereas for glasses it is close to 0.05. The high reflectivity of metals is one reason that they are opaque. High reflectivity is desired in many applications including mirrors, coatings on glasses, etc.

Absorption

- When a light beam in impinged on a material surface, portion of the incident beam that is not reflected by the material is either absorbed or transmitted through the material.
- Bouguer's law: The fraction of beam that is absorbed is related to the thickness of the materials and the manner in which the photons interact with the material's structure.

$$I = I_0 \exp(-\alpha.x)$$

- where I – intensity of the beam coming out of the material,
- I_0 – intensity of the incident beam,
- x – path through which the photons move, and
- α – linear absorption coefficient, which is characteristic of a particular material.
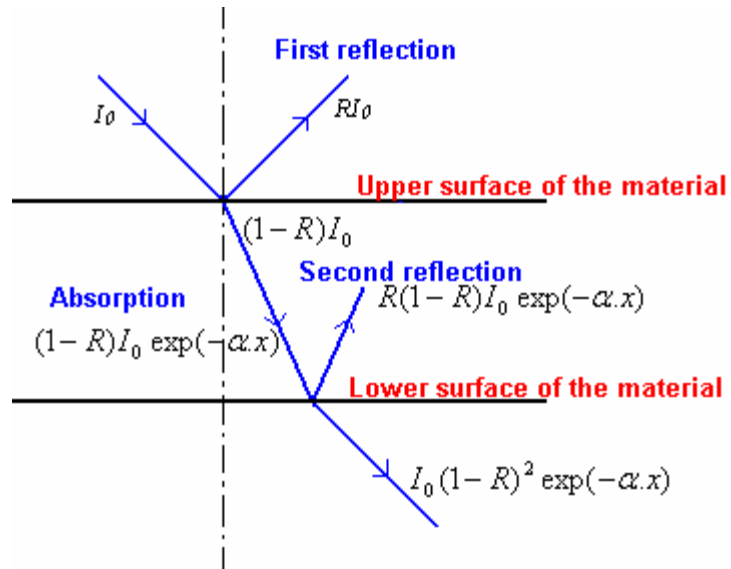
Absorption mechanisms

- Absorption occurs by two mechanisms: Rayleigh scattering and Compton scattering.
- **Rayleigh scattering:** where photon interacts with the electrons orbiting an atom and is deflected without any change in photon energy. This is significant for high atomic number atoms and low photon energies. Ex.: Blue color in the sunlight gets scattered more than other colors in the visible spectrum and thus making sky look blue.
- **Tyndall effect** is where scattering occurs from particles much larger than the wavelength of light. Ex.: Clouds look white.
- **Compton scattering:** interacting photon knocks out an electron loosing some of its energy during the process. This is also significant for high atomic number atoms and low photon energies.
- **Photoelectric effect** occurs when photon energy is consumed to release an electron from atom nucleus. This effect arises from the fact that the potential energy barrier for electrons is finite at the surface of the metal. Ex.: Solar cells.

Transmission

- Fraction of light beam that is not reflected or absorbed is transmitted through the material.

$$I_t = I_0 (1 - R)^2 \exp(-\alpha.x)$$

- The process of light transmission is as follows

First reflection

I_0 RI_0

Upper surface of the material

$(1-R)I_0$

Second reflection

$R(1-R)I_0 \exp(-\alpha.x)$

Absorption

$(1-R)I_0 \exp(-\alpha.x)$

Lower surface of the material

$I_0(1-R)^2 \exp(-\alpha.x)$

Optical applications

- Light interacts with a material in many ways.
- Depending on the material, its crystal-/micro-structure, and also on the characteristics of incident light, there are many peculiar phenomena occurs, which are known as optical phenomena. These include:
  - luminescence
  - lasers
  - thermal emission
  - photo-conductivity
  - optical fibers
- All these find quite many applications in technology for every day life

Luminescence

- It is the process where a material absorbs energy and then immediately emits visible or near-visible radiation. It consists of electron excitation and then dropping down to lower energy states.
- If the emission of radiation occurs within 10^{-8} sec after excitation, the luminescence is called *fluorescence*, and if it takes longer than 10^{-8} sec, it is known as *phosphorescence.*
- Ordinarily pure materials do not display this phenomenon. Special materials called *phosphors* have the capability of absorbing high-energy radiation and spontaneously emitting lower-energy radiation. Ex.: some sulfides, oxides, tungstates, and few organic materials.
- The intensity of luminescence is given as:

$$I = I_0 \exp(-\frac{t}{\tau})$$

- where I_0 – initial intensity of luminescence,
  - I – fraction of luminescence after time, t,
  - τ - relaxation time, constant for a material.

- Luminescence process is classified based on the energy source for electron excitation as *photo-luminescence, cathode-luminescence,* and *electro-luminescence*.

Photo-luminescence

- *Photo-luminescence* occurs in fluorescent lamps.
- Here ultra-violet radiation from low-pressure mercury arc is converted to visible light by calcium halo-phosphate phosphor ($Ca_{10}F_2P_6O_{24}$).
- In commercial lamps, about 20% of F^- ions are replaced with Cl^- ions.
- Antimony, Sb^{3+}, ions provide a blue emission while manganese, Mn^{2+}, ions provide an orange-red emission band.

Cathode-luminescence

- *Cathode-luminescence* is produced by an energized cathode which generates a beam of high-energy bombarding electrons.
- Applications of this include electron microscope; cathode-ray oscilloscope; color television screens.
- The modern televisions have very narrow, about 0.25 mm wide, vertical stripes of red-, green-, and blue- emitting phosphors deposited on the inner surface of the screens.
- Commercial phosphors for different colors are: red – yttrium oxy-sulfide (Y_2O_2S) with 3% europium (Eu); green – (Zn,Cd)S with a Cu^+ acceptor and Al^{3+} donor; blue – zinc sulfide (ZnS) with Ag^+ acceptor and Cl^- donor.

Electro-luminescence

- *Electro-luminescence* occurs in devices with p-n rectifying junctions which are stimulated by an externally applied voltage.
- When a forward biased voltage is applied across the device, electrons and holes recombine at the junction and emit photons in the visible range (mono-chromatic light i.e. singe color). These diodes are called *light emitting diodes* (LEDs).
- LEDs emit light of many colors, from red to violet, depending on the composition of the semiconductor material used.
- Ex.: GaAs, GaP, GaAlAs, and GaAsP are typical materials for LEDs.
- Materials for colored LEDs are

Wave length (nm)	Color	Material
-	Infra-red	GaAs
660	Red	$GaP_{0.40}As_{0.60}$ *or* $Al_{0.25}Ga_{0.75}As$
635	Orange	$GaP_{0.65}As_{0.35}$

578	Yellow	$GaP_{0.85}As_{0.15}$
556	Green	GaP ($GaP_{1.00}As_{0.00}$)
-	Blue	$Ga_{0.94}NIn_{0.06}$

Lasers

- Laser is an acronym for *light amplification by stimulated emission of radiation*. It is in fact special application of luminescence.
- Unlike most radiation processes, such as luminescence, which produce incoherent light, the light produced by laser emission is coherent.
- This is based on the fact that in certain materials, electrons excited by a stimulus produce photons which in turn excite additional photons of identical wavelength. Thus a large amplification of the photons emitted in the material occurs.
- Lasers are useful in many applications such as welding, metal cutting, heat treatment, surgery, mapping, reading compact disks, etc. Ex.: Ruby, single crystal of Al_2O_3 doped with little amount of Cr_2O_3; yttrium aluminium garnet ($Y_3Al_5O_{12}$ − YAG) doped with neodymium, Nd; CO_2 gas; He-Ne gas; some semi-conductors like GaAs and InGaAsP.

Thermal emission

- When a material is heated, electrons are excited to higher energy levels, particularly in the outer energy levels where the electrons are less strongly bound to the nucleus.
- These excited electrons, upon dropping back to the ground state, release photons in process what is called *thermal emission*.
- During thermal emission a continuous spectrum of radiation is emitted with a minimum wavelength and the intensity distribution is dependent on the temperature.
- Higher the temperature, wider will be the range of wavelengths emitted. By measuring the intensity of a narrow band of the emitted wavelengths with a pyrometer, material's temperature can be estimated.

Photo-conductivity

- Bombardment of semiconductors by photons, with energy equal to greater than the band gap, may result in creation of electron-hole pairs that can be used to generate current. This process is called *photo-conductivity*.
- It is different from photo-electric effect in the sense that an electron-hole pair is generated whose energy is related to the band gap energy instead of free electron alone whose energy is related to the Fermi level.
- The current produced in photo-conductivity is directly related to the incident light intensity.
- This phenomenon is utilized in photographic light meters. Cadmium sulfide (CdS) is commonly used for the detection of visible light, as in light meters.
- Photo-conductivity is also the underlying principle of the photo-voltaic cell, known to common man as *solar cell*, used for conversion of solar energy into electricity.

Optical fibers

- Optical fibers have revolutionized the communication industry.
- These systems consists of transmitter (a semiconductor laser) to convert electrical signals to light signals, optical fiber to transmit the light signals, and a photodiode to convert light signals back to electrical signals.
- It primarily consists of core, cladding and coating. The core transmits the signals, while the cladding constrains the light beam to the core; outer coating protects the core and cladding from the external environment.
- Typically both the core and cladding are made of special types of glass with carefully controlled indices of refraction.
- The indices of refraction are selected such that

$$n_{cladding} < n_{core}$$

- Once the light enters the core from the source, it is reflected internally and propagates along the length of the fiber.
- Internal reflection is accomplished by varying the index of refraction of the core and cladding glass materials. Usually two designs are employed in this regard.

Types of optical fibers

- In *step-index optical fiber*, there is a sharp change in refractive index between the core and cladding. In this design output pulse will be broader than the input one. It is because light rays traveling in different trajectories have a variety of path lengths.
- It is possible to avoid pulse broadening by using *graded-index fiber*. This results in a helical path for the light rays, as opposed to zig-zag path in a step-index fiber.
- Here impurities such as boron oxide (B_2O_3) or germanium dioxide (GeO_2) are added to the silica glass such that the index of refraction varied gradually in parabolic manner across the cross section. This enables light to travel faster while close to the periphery than at the center. This avoids pulse broadening.
- Both step- and graded- index fibers are termed as multi-mode fibers.
- Third type optical fiber is called *single-mode fiber* in which light travels largely parallel to the fiber axis with little distortion of the digital light pulse. These are used for long transmission lines.

Optical fiber properties

- Core and cladding materials are selected not only on the basis of their refractive indices, but also on basis of ease of manufacturability, light loss, mechanical strength properties and dispersion properties.
- However, density (ρ) and refractive index (n) are critical. These two parameters are related approximately as

$$n = \frac{\rho + 10.4}{8.6}$$

- High-purity silica-based glasses are used as fiber material, with fiber diameter ranging from 5 to 100 µm.
- The fibers are carefully fabricated to be virtually free from flaws.

Multiple Choice Questions' Bank:

1. Visible light's wavelength range _____.

(a) 0.39 – 0.77 mm   (b) 0.39 – 0.77 µm
(c) 0.39 – 0.77 nm   (d) 0.39 – 0.77 cm

2. Planck's constant

(a) 6.62×10^{-34} J.sec   (b) 6.62×10^{-34} J.min   (c) 6.62×10^{-34} Cal.sec (d) 6.62×10^{-34} Cal.min

3. Sum of these is unity

(a) Reflectivity   (b) Reflectivity + Refractivity
(c) Reflectivity + Refractivity + Transmitivity   (d) Any

4. Metals can _____ the light beams.

(a) Reflect   (b) Refract   (c) Transmit   (d) Any

5. Metals are _____.

(a) Transparent   (b) Opaque   (c) Translucent   (d) None

6. Metals can transmit these _____.

(a) Radio ways   (b) Visible light   (c) Microwaves   (d) x-rays

7. Reflectivity of metals

(a) 0.05   (b) 0.50   (c) 0.95   (d) None

8. Refractive index of materials is approximately equal to square root of

(a) electrical permittivity   (b) magnetic permeability
(c) electrical permittivity x magnetic permeability   (d) None

9. Snell's law relates _____.

(a) Light relfection   (b) Light refraction   (c) Light transmission (d) Light Absorption

10. Bouguer's law relates _____.

(a) Light relfection   (b) Light refraction   (c) Light transmission (d) Light Absorption

11. Sky looks blue because the sun light is subjected to _____.

(a) Rayleigh scattering   (b) Compton scattering   (c) Both   (d) None

12. Luminescence is because of

(a) Photons emitted while excited electrons drops down
(b) Knocking out of electrons by photons
(c) Photons stimulated by photons
(d) All

13. Fluorescence occurs within _____.

(a) 10^{-5} s.   (b) 10^{-5} ms.   (c) 10^{-5} µs.   (d) 10^{-5} ns.

14. Electro-luminescence occurs in _____.

(a) Electrical conductors   (b) Electrical insulators   (c) p-n junctions   (d) all

15. Pyrometer works based on

(a) Laser technology   (b) Photo-conduction   (c) Thermal emission   (c) Tyndall effect

16. Solar cell works based on

(a) Laser technology   (b) Photo-conduction (c) Thermal emission (c) Tyndall effect

17. Optical fiber operates on the principle of

(a) Total internal reflectance (b) Tyndall effect   (c) Photo-electric effect   (d) Laser technology

Answers:

1. b
2. a
3. c
4. a
5. b
6. d
7. c
8. a
9. b
10. d
11. a
12. a
13. b
14. c
15. c
16. b
17. a