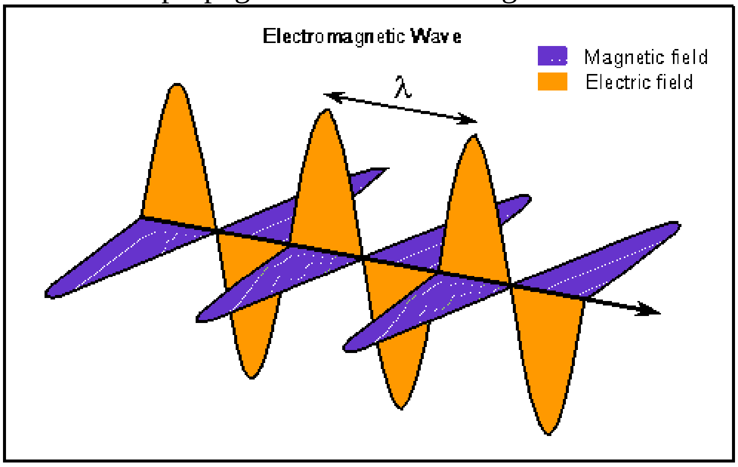
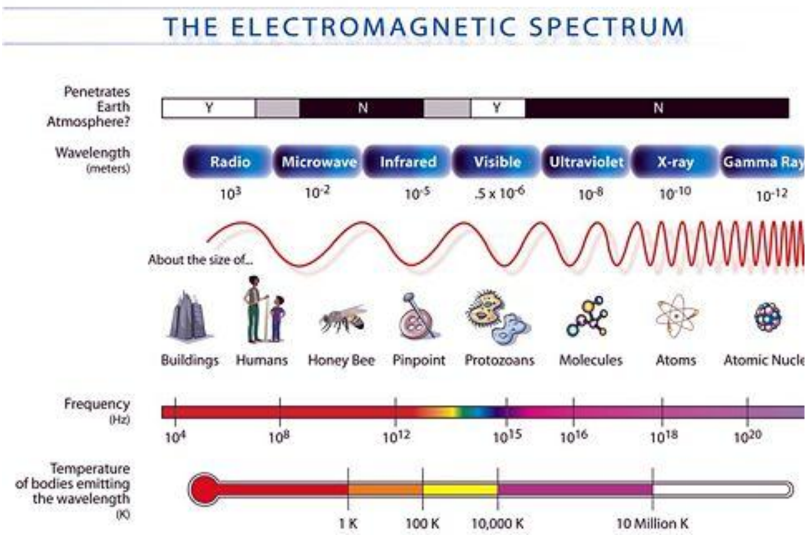
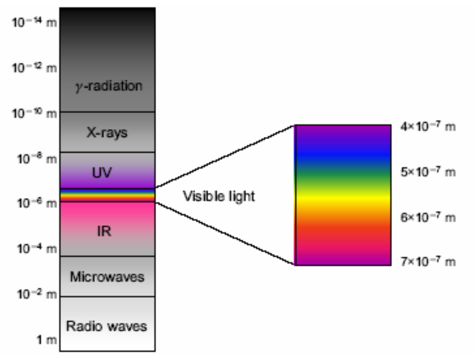
Electromagnetic Radiation:

Light is an electromagnetic wave or **photon.** In the classical sense, electromagnetic radiation is considered to be wave-like, consisting of electric and magnetic field components that are perpendicular to each other and also to the direction of propagation as shown in figure below. The velocity of light is **c =** ***3 x 10^8 m/s***c



The spectrum consists of radiation such as gamma rays, x-rays, ultraviolet, visible, infrared and radio. Visible light lies within a very narrow region of the spectrum, with wavelengths ranging between about 0.4µm ($4x10^{-7}$ m) for violet and 0.7µm for red color.





All electromagnetic radiation traverses a vacuum at the same velocity, that of light—namely, 3×10^8 m/s (186,000 miles/s). This velocity, *c*, is related to the electric permittivity of a vacuum and the magnetic permeability of a vacuum through

$$c = \frac{1}{\sqrt{\epsilon_0 \mu_0}}$$

Energy of photon is $E = hf = h\nu = h\frac{c}{\lambda}$

h: Planck's constant = 6.63x10^-34 J-s (6.63×10^{-34} J-s)

$f = \nu$ is a frequency (Hz)
c is the speed of light = $3x10^8$ m/s
λ is a wave length (m)

Example: Visible light having a wavelength of **$5 x10^{-7}$ m** appears green. Compute the frequency and energy of a photon of this light.

We must compute the frequency of a photon of green light,
$\boldsymbol{\nu} = \boldsymbol{c\lambda} = 3x10^8$m/s . $5x10^{-7}$m= 6×10^{14} s^{-1} (Hz)
The energy a photon of green light
$\boldsymbol{E = hc / \lambda} = (6.63x10^{-34}$J-s$)(3x10^8m/s)$ / $5x10^{-7}$m
= 3.98×10^{-19} J = (2.48 eV)

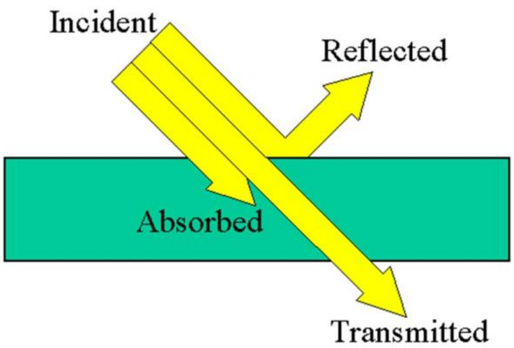
Light Interactions With Solids:

When light proceeds from one medium into another (e.g., from air into a solid substance), several things happen. Some of the light radiation may be transmitted through the medium, some will be absorbed, and some will be reflected at the interface between the two media. The intensity I_O of the beam incident to the surface of the solid medium must equal the sum of the intensities of the transmitted, absorbed, and reflected beams, denoted as I_T, I_A, and I_R respectively, or

$I_O = I_T + I_A + I_R$

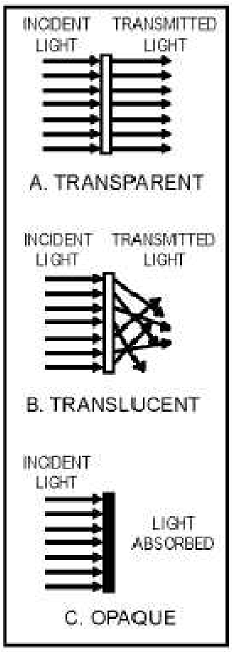
$T = I_T / I_0$ Transmissivity
$A = I_A / I_0$ Absorptivity
$R = I_R / I_0$ Reflectivity
T~1 : Transparent
T~0 : Opaque

T + A + R = 1



Example: Distinguish between materials that are opaque, translucent, and transparent in terms of their appearance and light transmittance

.
Opaque materials are impervious to light transmission; it is not possible to see through them.
Light is transmitted diffusely through translucent materials (there is some internal light scattering). Objects are not clearly distinguishable when viewed through a translucent material.
Virtually all of the incident light is transmitted through transparent materials, and one can see clearly through them.



In figure above three (3) things can happen.

- Light *passes through easily* (if the object is **transparent**) –Material is capable of transmitting light with little absorption or reflection – One can see through them
- Light is *blurred* (if the object is **translucent**) –Materials through which light is transmitted diffusely –Light is scattered within the material –Objects are not clearly visible through the material
- Light is *blocked* (if the object is **opaque**) –Materials which are impervious to the transmission of visiblelight

Atomic And Electronic Interactions:

- The optical phenomena that occur within solid materials involve interactions between the electromagnetic radiation and atoms, ions, and/or electrons.
- Two of the most important of these interactions are electronic polarization and electron energy transitions.

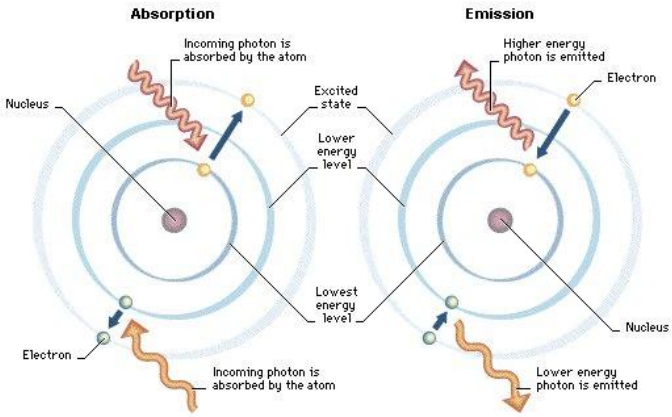
Electronic Polarization:

- One component of an electromagnetic wave is simply a rapidly fluctuating electric field.
- For the visible range of frequencies, this electric field interacts with the electron cloud surrounding each atom within its path in such a way as to induce electronic polarization, or to shift the electron cloud relative to the nucleus of the atom with each change in direction of electric field component.
- Two consequences of this polarization are: (1) some of the radiation energy may be absorbed, and (2) light waves are retarded in velocity as they pass through the medium.

Electron Transitions:

The absorption and emission of electromagnetic radiation may involve electron transitions from one energy state to another.
When a photon, or packet of light energy, is absorbed by an atom, the atom gains the energy of the photon, and one of the atom's electrons may jump to a higher energy level. The atom is then said to be **excited**. When an electron of an excited atom falls to a lower energy level, the atom may emit the electron's excess energy in the form of a photon. The energy levels, or orbitals, of the atoms shown here have been greatly simplified to illustrate these absorption and emission processes. For a more accurate depiction of electron orbitals, see Atom and Atomic Theory.

$$\Delta E = hv$$



Optical Properties of Metals:

- Metals are opaque because the incident radiation having frequencies within the visible range excites electrons into unoccupied energy states above the Fermi energy, as demonstrated in Figure (a) below.
- Total absorption is within a very thin outer layer, usually less than 0.1 μm thus only metallic films thinner than 0.1 μm are capable of transmitting visible light.
- In fact, metals are opaque to all electromagnetic radiation on the low end of the frequency spectrum, from radio waves, through infrared, the visible, and into about the middle of the ultraviolet radiation.
- Metals are transparent to high-frequency (x- and γ-ray) radiation.
- All frequencies of visible light are absorbed by metals because of the continuously available empty electron states, which permit electron transitions.
- Most of the absorbed radiation is reemitted from the surface in the form of visible light of the same wavelength, which appears as reflected light.
- Aluminum and silver are two metals that exhibit this reflective behavior.
- Copper and gold appear red-orange and yellow, respectively, because some of the energy associated with light photons having short wavelengths is not reemitted as visible light.

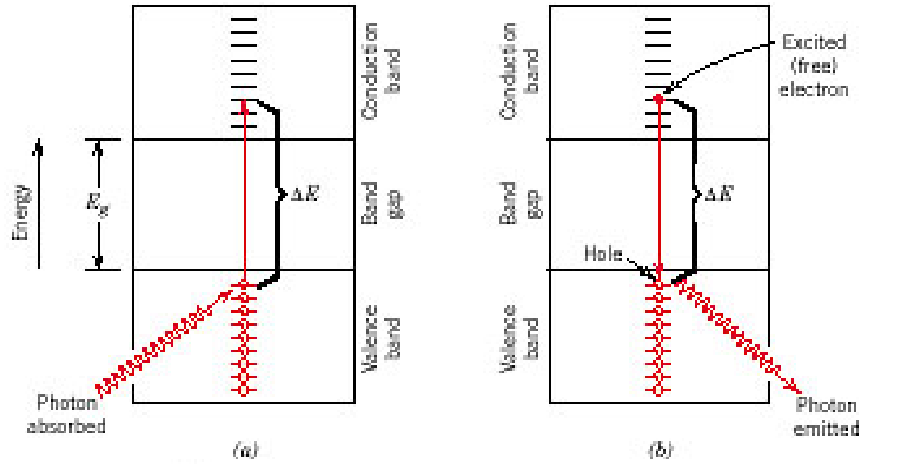
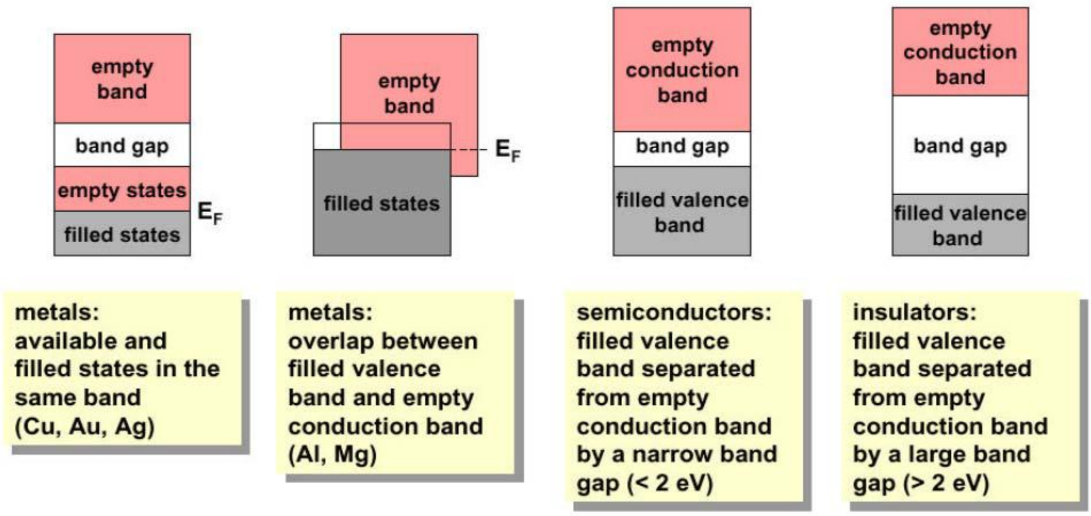


FIGURE (*a*) Mechanism of photon absorption for nonmetallic materials in which an electron is excited across the band gap, leaving behind a hole in the valence band. The energy of the photon absorbed is ΔE, which is necessarily greater than the band gap energy E_g. (*b*) Emission of a photon of light by a direct electron transition across the band gap.

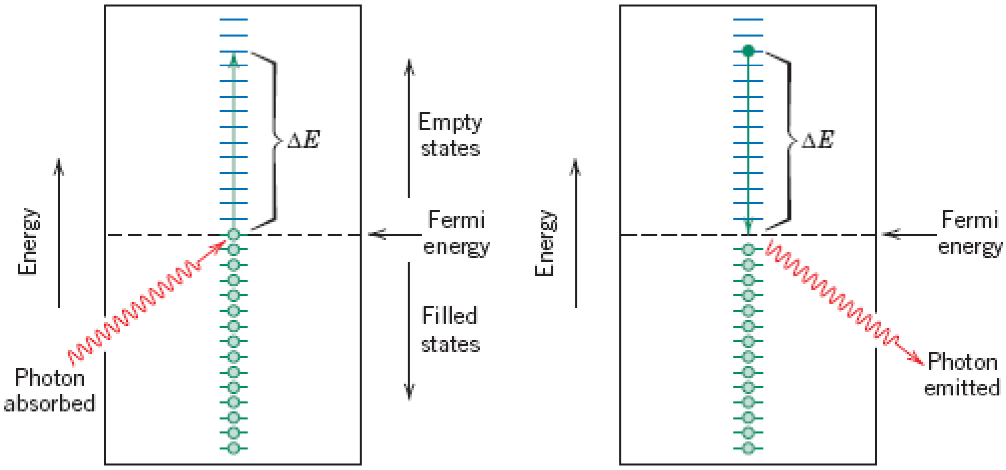
Typical band structures:



Example: Briefly explain why metals are opaque to electromagnetic radiation having photon energies within the visible region of the spectrum.

The electron band structures of metals are such that empty and available electron states are adjacent to filled states. Electron excitations from filled to empty states are possible with the absorption of electromagnetic radiation having frequencies within the visible spectrum. The light energy is totally absorbed or reflected, and, since none is transmitted, the material is opaque.

Optical Properties of metals:



- All frequencies of visible light are absorbed by metals because of the continuously available empty electron states, which permit electron transitions.
- Metals are opaque to all electromagnetic radiation on the low end of the frequency spectrum, from radio waves, through infrared, the visible, and into about the middle of the ultraviolet radiation. Metals are transparent to high-frequency (x- and -ray) radiation.
- Most of the absorbed radiation is reemitted from the surface in the form of visible light of the same wavelength, which appears as reflected light; an electron transition accompanying reradiation.

Refraction :

Light that is transmitted into the interior of transparent materials experiences decrease in velocity and as result is bent at the interface; this phenomenon is termed refraction. The index of refraction n of a material is defined as the ratio of the velocity in vacuum c to the velocity in the medium v , or

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

The magnitude of n (or the degree of bending) will depend on the wavelength of the light. This effect is graphically demonstrated by the familiar dispersion or separation of a beam of white light into its component colors by a glass prism.

Table 21.1 Refractive Indices for Some Transparent Materials

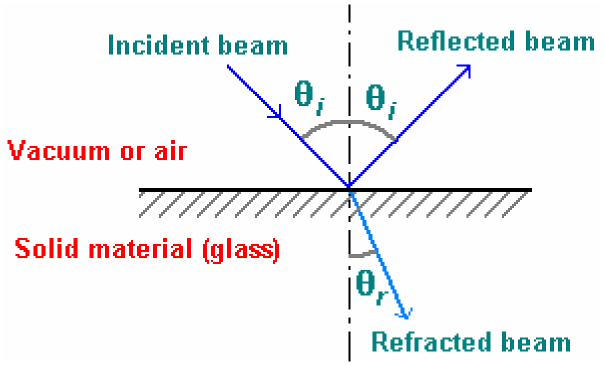
Material	*Average Index of Refraction*
Ceramics	
Silica glass	1.458
Borosilicate (Pyrex) glass	1.47
Soda–lime glass	1.51
Quartz (SiO_2)	1.55
Dense optical flint glass	1.65
Spinel ($MgAl_2O_4$)	1.72
Periclase (MgO)	1.74
Corundum (Al_2O_3)	1.76
Polymers	
Polytetrafluoroethylene	1.35
Poly(methyl methacrylate)	1.49
Polypropylene	1.49
Polyethylene	1.51
Polystyrene	1.60

Each color is deflected by a different amount as it passes into and out of the glass, which results in the separation of colors.

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

$$v = \frac{1}{\sqrt{\epsilon\mu}}$$



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

$$n = \frac{c}{v} = \frac{\sqrt{\epsilon\mu}}{\sqrt{\epsilon_0\mu_0}} = \sqrt{\epsilon_r\mu_r}$$

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

$$n = \sqrt{\epsilon_r}$$

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

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

Example: Compute the velocity of light in diamond, which has a dielectric constant ϵ_r of 5.5 (at frequencies within the visible range) and a magnetic susceptibility of -2.17×10^{-5}.

$\varepsilon = \varepsilon_r\varepsilon_0 = (5.5)(8.85 \times 10^{-12}$ F/m$) = 4.87 \times 10^{-11}$ F/m
$\mu = \mu_0\mu_r = \mu_0(\chi_m + 1) = (1.257 \times 10^{-6}$ H/m$)(1 - 2.17 \times 10^{-5}) = 1.257 \times 10^{-6}$ H/m
$v = \frac{1}{\sqrt{\epsilon\mu}} = 1 / \{(4.87\times10^{-11}\text{F/m})(1.257\times10^{-6}\text{H/m})\}^{0.5}$
$= 1.28 \times 10^{8}$ m/s

Reflection :

When light radiation passes from one medium into another having a different index of refraction, some of the light is scattered at the interface between the two media even if both are transparent. The reflectivity R represents the fraction of the incident light that is reflected at the interface, or

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

where I_0 and I_R are the incident and reflected beams intensities respectively. If the light is normal (or perpendicular) to the interface, then

$$R = \left(\frac{n_2 - n_1}{n_2 + n_1}\right)^2$$

where and are the indices of refraction of the two media. If the incident light is not normal to the interface, R will depend on the angle of incidence. When light is transmitted from a vacuum or air into a solid s, then

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

Example: It is desired that the reflectivity of light at normal incidence to the surface of a transparent medium be less than 5.0%.Which of the following materials: soda–lime glass, Pyrex glass, periclase, spinel, polystyrene, and polypropylene? Justify your selections.

$0.050 = (n_s-1)^2 / (n_s+1)^2 = (n_s^2-2n_s+1) / (n_s^2+2n_s+1)$
or, upon rearrangement $0.95n_s^2 - 2.10n_s + 0.95 = 0$
The value of n_s is determined by using the quadratic equation solution as follows:
$n_s = -(-2.10) \pm \{(-2.10)^2 - (4)(0.95)(0.95)\}^{0.5} / (2)(0.95) = (2.10 \pm 0.894) / 1.90$
The two solutions are: $n_s(+) = 1.576$ and $ns(–) = 0.634$.
The $n_s(+)$ solution is the one that is physically reasonable. Thus, of the materials listed in tables, soda-lime glass, Pyrex glass, and polypropylene have indices of refraction less than 1.576, and would be suitable for this application.

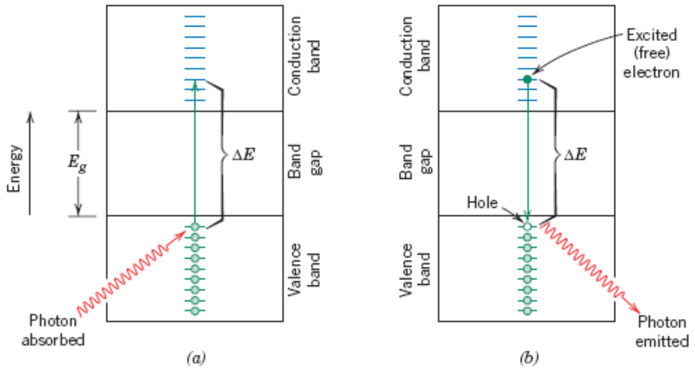
Example: The index of refraction of quartz is anisotropic. Suppose that visible light is passing from one grain to another of different crystallographic orientation and at normal incidence to the grain boundary. Calculate the reflectivity at the boundary if the indices of refraction for the two grains are 1.544 and 1.553 in the direction of light propagation.

$R = (n_2-n_1)^2 / (n_2+n_1)^2$
$= (1.553-1.544)^2 / (1.553+1.544)^2 = 8.45 \times 10^{-6}$

Absorption :

- Nonmetallic materials may be opaque or transparent to visible light; and, if transparent they often appear colored. In principle, light radiation is absorbed in this group of materials by two basic mechanisms, which also influence the transmission characteristics of these nonmetals.
- One of these is electronic polarization. Absorption by electronic polarization is important only at light frequencies in the vicinity of the relaxation frequency of the constituent atoms.
- The other mechanism involves valence band-conduction band electron transitions, which depend on the electron energy band structure of the material.
- Absorption of a photon of light may occur by the promotion or excitation of an electron from the nearly filled valence band, across the band gap, and into an empty state within the conduction band.

- Every nonmetallic material becomes opaque at some wavelength, which depends on the magnitude of its E_g. For example, diamond, having a band gap of 5.6 eV, is opaque to radiation having wavelengths less than about 0.22 μm.



$$h\nu > E_g$$

$$\frac{hc}{\lambda} > E_g$$

$$E_g(\max) = \frac{hc}{\lambda(\min)}$$

$$= \frac{(4.13 \times 10^{-15}\ \text{eV-s})(3 \times 10^{8}\ \text{m/s})}{4 \times 10^{-7}\ \text{m}}$$

$$= 3.1\ \text{eV}$$

Eg (min)=hc/λ(max)=1.8 eV (λ=700 nm)
Eg< 1.8 eV, *all visible light is absorbed*
1.8 eV< Eg< 3.1 eV, *Colored*
Eg>3.1 eV, *transparent to visible light*

- 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.
- $\boldsymbol{I_T' = I_0' \, e^{-\beta x}}$
- 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
- $\boldsymbol{\beta}$– linear absorption coefficient in (mm^{-1}), 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.

Example: Zinc selenide (ZnSe) has a band gap of 2.58 eV. Over what range of wavelengths of visible light is it transparent?

Only photons having energies of 2.58 eV or greater are absorbed by valence-band-to-conduction-band electron transitions. The minimum photon energy for visible light is 1.8 eV, which corresponds to a wavelength of 0.7 µm.

$\lambda = hc / E = (4.13\text{x}10^{-15}\text{eV-s})(3\text{x}10^{8}\text{m/s}) / 2.58\text{eV} = 4.80 \text{ x } 10^{-7}\text{ m} = 0.48\ \mu\text{m}$
Thus, pure ZnSe is transparent to visible light having wavelengths between 0.48 and 0.7 µm.

Example: The fraction of nonreflected radiation that is transmitted through a 5-mm thickness of a transparent material is 0.95. If the thickness is increased to 12 mm, what fraction of light will be transmitted?

$$\boldsymbol{I'_T = I'_0\, e^{-\beta x}}\ ,$$

$$\ln (I_T' / I_{0'}) = -\beta x$$

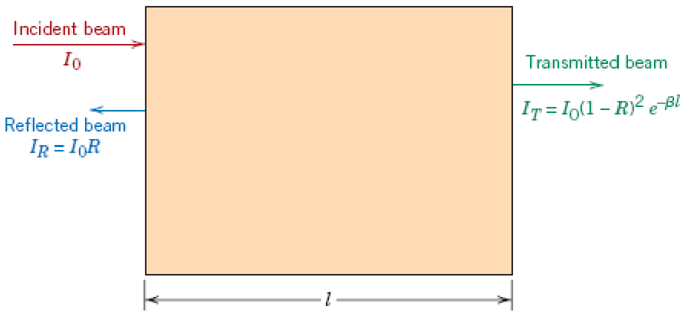
$\beta = (-1 / x) \ln I_T' / I_0' = -(15\text{mm}) \ln(0.95) = 1.026 \text{ x } 10^{-2}\text{ mm}^{-1}$
And computation of I_T'/I_0' when $x = 12$ mm , $I_T' / I_0' = \exp(-\beta x)$
$=\exp[-(1.026\text{x}10^{-2}\text{mm}^{-1})(12\text{mm})] = 0.884$

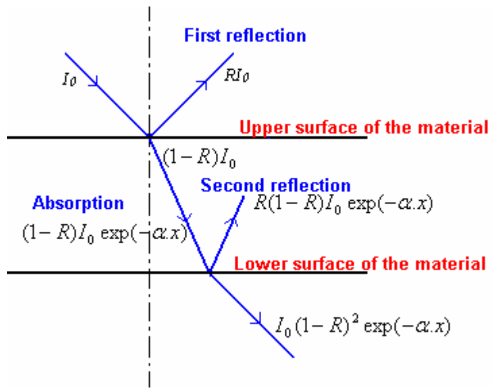
Transmission :

The phenomena of absorption, reflection, and transmission may be applied to the passage of light through a transparent solid.

$$I_T = I_0(1 - R)^2 e^{-\beta l}$$

For an incident beam of intensity I_0 that impinges on the front surface of a specimen of thickness l and absorption coefficient *ß* the transmitted intensity at the back face I_T is where R is the reflectance.





Transparent materials appear colored as a consequence of specific wavelength ranges of light that are selectively absorbed; the **color** discerned is a result of the combination of wavelengths that are transmitted.

If absorption is uniform for all visible wavelengths, the material appears colorless; examples include high-purity inorganic glasses and high-purity and single-crystal diamonds and sapphire.

Usually, any selective absorption is by electron excitation

the fraction of the visible light having energies greater than E_g = (1.8 to 3.1 eV) is selectively absorbed by valence band–conduction band electron transitions.

Of course, some of this absorbed radiation is reemitted as the excited electrons drop back into their original, lower-lying energy states. It is not necessary that this reemission occur at the same frequency as that of the absorption. As a result, the color depends on the frequency distribution of both transmitted and reemitted light beams.

Example: The transmissivity T of a transparent material 15 mm thick to normally incident light is 0.80. If the index of refraction of this material is 1.5, compute the thickness of material that will yield a transmissivity of 0.70. All reflection losses should be considered.

$R = (n_s-1)^2 / (n_s+1)^2$
$= (1.5-1)^2 / (1.5+1)^2 = 4.0 \times 10^{-2}$
since: $I_T = I_0(1-R)^2 e^{-\beta l}$

$I_T / I_0(1-R)^2 = e^{-\beta l}$
And taking the natural logarithms of both sides of this expression gives
$\ln[I_T / I_0(1-R)^2] = -\beta l$
$\beta = -1 / l \ln [I_T / I_0(1-R)^2]$
Since the transmissivity is T is equal to I_T/I_0, then the above equation takes the form
$\beta = -(1/l) \ln [T / (1-R)^2]$
$\beta = -(1 / 15\text{mm}) \ln [0.80 / (1-4.0\times10^{-2})^2] = 9.43 \times 10^{-3}\ \text{mm}^{-1}$

Colors:

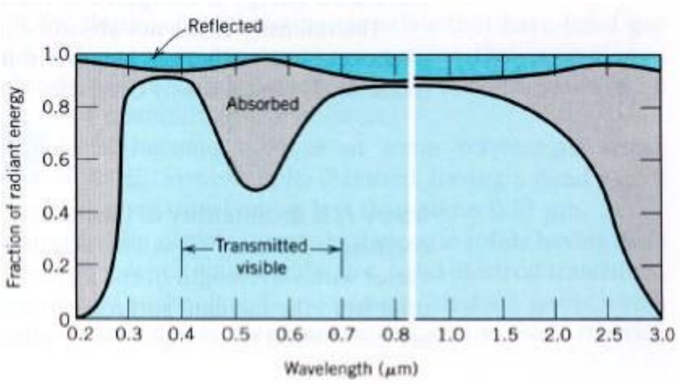
•Color determined by sum of frequencies of, transmitted light, and -re-emitted light from electron transitions.

- Small differences in composition can lead to large differences in appearance
- •Ex: Cadmium Sulfide (CdS)--E_{gap}= 2.4eV,--absorbs higher energy visible light (blue, violet),--Red/yellow/orange is transmitted and gives it color.
- For example, high-purity single-crystal Al_2O_3(sapphire) is colourless
- If only 0.5 - 2.0% of Cr_2O_3 add, the material looks red(ruby)
- The Cr substitutes for the Al and introduces impurity levels in the bandgap of the sapphire
- These levels give strong absorptions at: 400nm (green) and 600nm (blue) leaving only red to be transmitted.

A similar technique is used to color glasses or pottery glaze by adding impurities into the molten state:
Cu^{2+}: blue-green, Cr^{3+}: green
Co^{2+}: blue-violet, Mn^{2+}: yellow

• If E_{gap} < 1.8eV, full absorption; color is black (Si, GaAs)
• If E_{gap} > 3.1eV, no absorption; colorless (diamond)
• If E_{gap} in between, partial absorption; material has a color.

- reflection and absorption are dependent on wavelength and transmission is what's left over!
- Thus the three components for a green glass are:



Example: Briefly explain why some transparent materials appear colored while others are colorless.

For a transparent material that appears colorless, any absorption within its interior is the same for all visible wavelengths. On the other hand, if there is any selective absorption of visible light (usually by electron excitations), the material will appear colored, its color being dependent on the frequency distribution of the transmitted light beam.

Example: Briefly explain what determines the characteristic color of **(a)** a metal and **(b)** a transparent nonmetal.

(a) The characteristic color of a metal is determined by the distribution of wavelengths of the nonabsorbed light radiation that is reflected.
(b) The characteristic color of a transparent nonmetal is determined by the distribution of wavelengths of the nonabsorbed light radiation that is transmitted through the material.

Translucency:

- Even after the light has entered the material, it might yet be reflected out again due to scattering inside the material.
- Even the transmitted light can lose information by being scattered internally. So a beam of light will spread out or an image will become blurred.
- In extreme cases, the material could become opaque due to excessive internal scattering.
- Scattering can come from obvious causes:
    - grain boundaries in poly-crystalline materials
    - fine pores in ceramics
    - different phases of materials
- In highly pure materials, scattering still occurs and an important contribution comes from Rayleigh scattering
- This is due to small, random differences in refractive index from place to place.
- In amorphous materials such as glass this is typically due to density or compositional differences in the random structure.

- In crystals, lattice defects, thermal motion of atoms etc. also give rise to Rayleigh scattering.
- Rayleigh scattering also causes the sky to be blue. The reason for this is the wavelength-dependence of Rayleigh scattering:
    - scattering goes as λ^{-4}.
    - so since λ red~ 2 λ blue light is scattered ~16 times more than red light
- This mechanism is of great technological importance because it governs losses in optical fibers for communication.
- But before we get onto fibers, we will mention a couple more basic effects

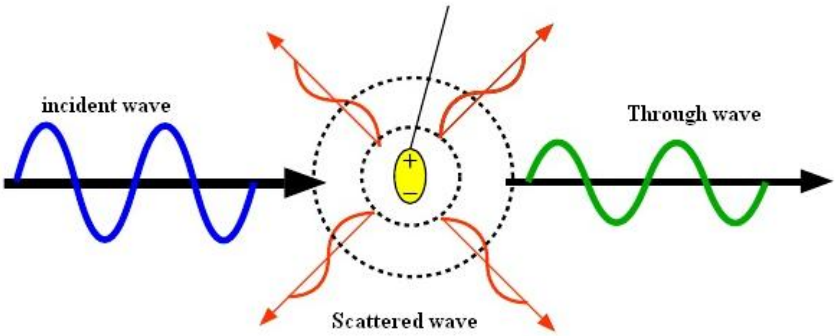


Figure: Rayleigh scattering involves the polarization of a small dielectric particle or a region that is much smaller than the light wavelength. The field forces dipole oscillations in the particle (by polarizing it) which leads to the emission of EM waves in "many" directions so that a portion of the light energy is directed away from the incident beam.

Figure : Photograph showing the light transmittance of three aluminum oxide specimens. From left to right; single-crystal material (sapphire), which is transparent; a polycrystalline and fully dense (nonporous) material, which is translucent; and a polycrystalline material that contains approximately 5% porosity, which is opaque.

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 phenomena occurs, which are known as optical phenomena. These include:

o luminescence

o lasers

o thermal emission

o photo-conductivity

o optical fibers

• All these find quite many applications in technology for everyday 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. Visible light is emitted when it falls back to a lower energy state if 1.8 eV < $h\upsilon$ < 3.1 eV.

• If the reemission 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.**

• 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. Ordinarily, pure materials do not display these phenomena, and to induce them, impurities in controlled concentrations must be added.

• The intensity of luminescence is given as: $I = I_0 \exp\left(-\frac{t}{\tau}\right)$

• 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. Arc between electrodes excites mercury in lamp to higher energy level. Electron falls back emitting UV light . Fluorescent lamps consist of a glass housing, coated on the inside with specially prepared tungstates or silicates. Ultraviolet light is generated within the tube from a mercury glow discharge, which causes the coating to fluoresce and emit white light.

• 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.

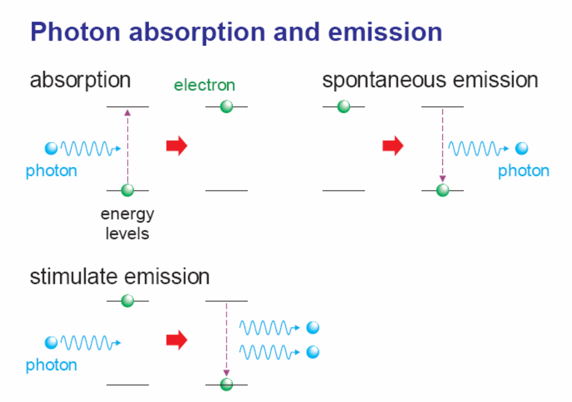
• Commercial phosphors for different colors are: red – yttrium oxy-sulfide (Y_2O_2S) with 3% europium (Eu); green – (Zn,Cd)S with a Cu^+ acceptor and Al^{3+} donor; blue – zinc sulfide (ZnS) with Ag^+ acceptor and Cl^- donor.

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	GaP0.85As0.15
556	Green	GaP (GaP1.00As0.00)
-	Blue	Ga0.94NIn0.06

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.
- All of the light emission we have mentioned so far is spontaneous. It happened just due to randomly occurring "natural" effects
- Stimulated emission refers to electron transitions that are "encouraged" by the presence of other photons
- Einstein showed that an incident photon with $E \geq E_g$ was equally likely to cause stimulated emission of light as to be absorbed
- The emitted light has the same energy and phase as the incident light (= coherent)

• Under normal circumstances, there are few excited electrons and many in the ground-state, so we get predominantly absorption.
• If we could arrange for more excited than non-excited electrons, then we would get mostly stimulated emission.

• 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, as shown in figure below.

• 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.

Presented in this figure is an illustration of the gain, or amplification, that occurs with increased path length in the resonant cavity due to the mirrors at each end. Figure (a) shows the beginning of stimulated emission, which is amplified in figure (b) through Figure (g) as the light is reflected from the mirrors positioned at the cavity ends. A portion of light passes through the partially reflected mirror on the right-hand side of the cavity (figures (b,d, and f)) during each pass. Finally, at the equilibrium state (figure (h)), the cavity is saturated with stimulated emission.

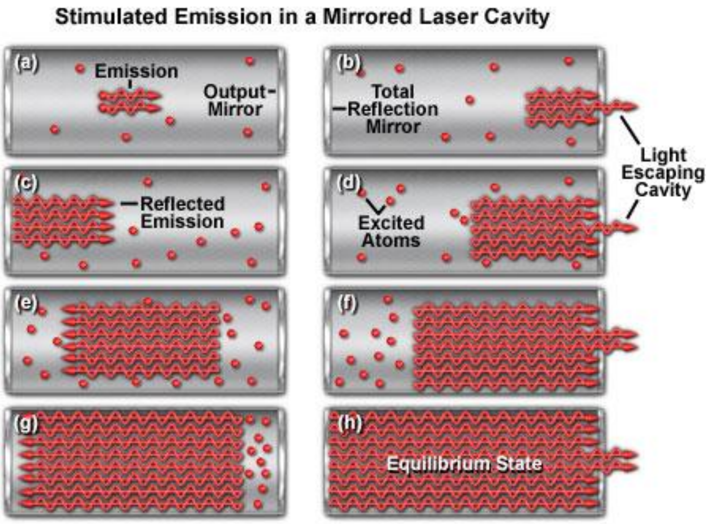


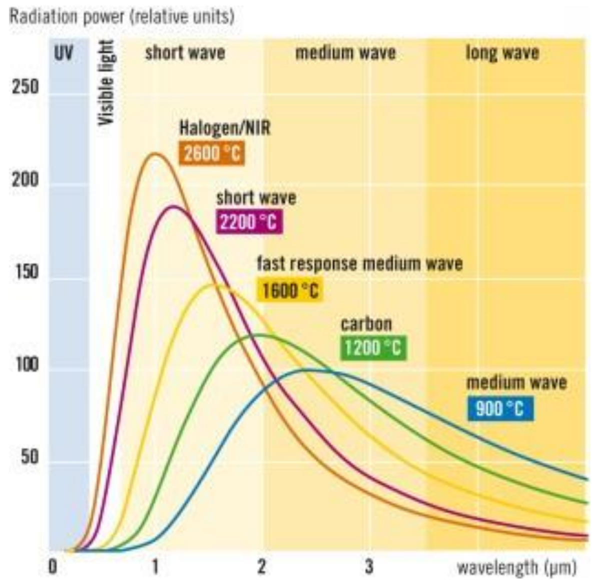
Figure 1

Table 21.2 Characteristics and Applications of Several Types of Lasers

Laser	*Type*	*Common Wavelengths (μm)*	*Max. Output Power (W)*[a]	*Applications*
He–Ne	Gas	0.6328, 1.15, 3.39	0.0005–0.05 (CW)	Line-of sight communications, recording/ playback of holograms
CO_2	Gas	9.6, 10.6	500–15,000 (CW)	Heat treating, welding, cutting, scribing, marking
Argon	Gas ion	0.488, 0.5145	0.005–20 (CW)	Surgery, distance measurements, holog-raphy
HeCd	Metal vapor	0.441, 0.325	0.05–0.1	Light shows, spectroscopy
Dye	Liquid	0.38–1.0	0.01 (CW) 1×10^6 (P)	Spectroscopy, pollution detection
Ruby	Solid state	0.694	(P)	Pulsed holography, hole piercing
Nd–YAG	Solid state	1.06	1000 (CW) 2×10^8 (P)	Welding, hole piercing, cutting
Nd–Glass	Solid state	1.06	5×10^{14} (P)	Pulse welding, hole piercing
Diode	Semiconductor	0.33–40	0.6 (CW) 100 (P)	Bar-code reading, CDs and DVDs, optical communications

[a] "CW" denotes continuous; "P" denotes pulsed.

Thermal emission

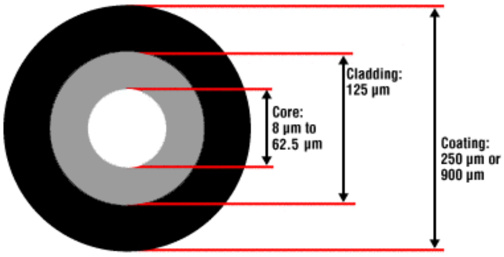


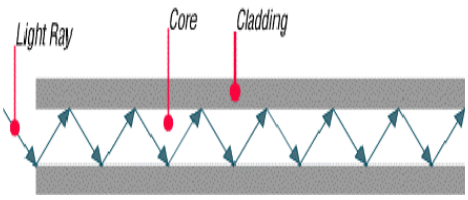
- When a material is heated, electrons are excited to higher energy levels, particularly in the outer energy levels where the electrons are less strongly bound to the nucleus.
- These excited electrons, upon dropping back to the ground state, release photons in process what is called **thermal emission.**
- During thermal emission a continuous spectrum of radiation is emitted with a minimum wavelength and the intensity distribution is dependent on the temperature as shown in figure beside.
- 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.

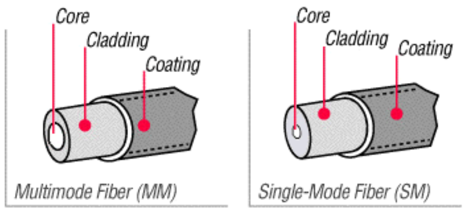
Photo-conductivity

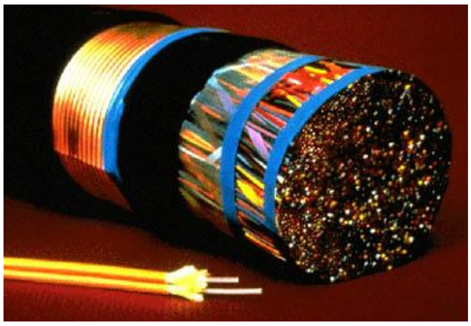
- The conductivity of semiconducting materials depends on the number of free electrons in the conduction band and also the number of holes in the valence band
- Bombardment of semiconductors by photons, with energy equal to greater than the band gap, may result in creation of electron-hole pairs that 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 (sunlight) 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

$n_{claddind} < n_{cor}$

- 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.

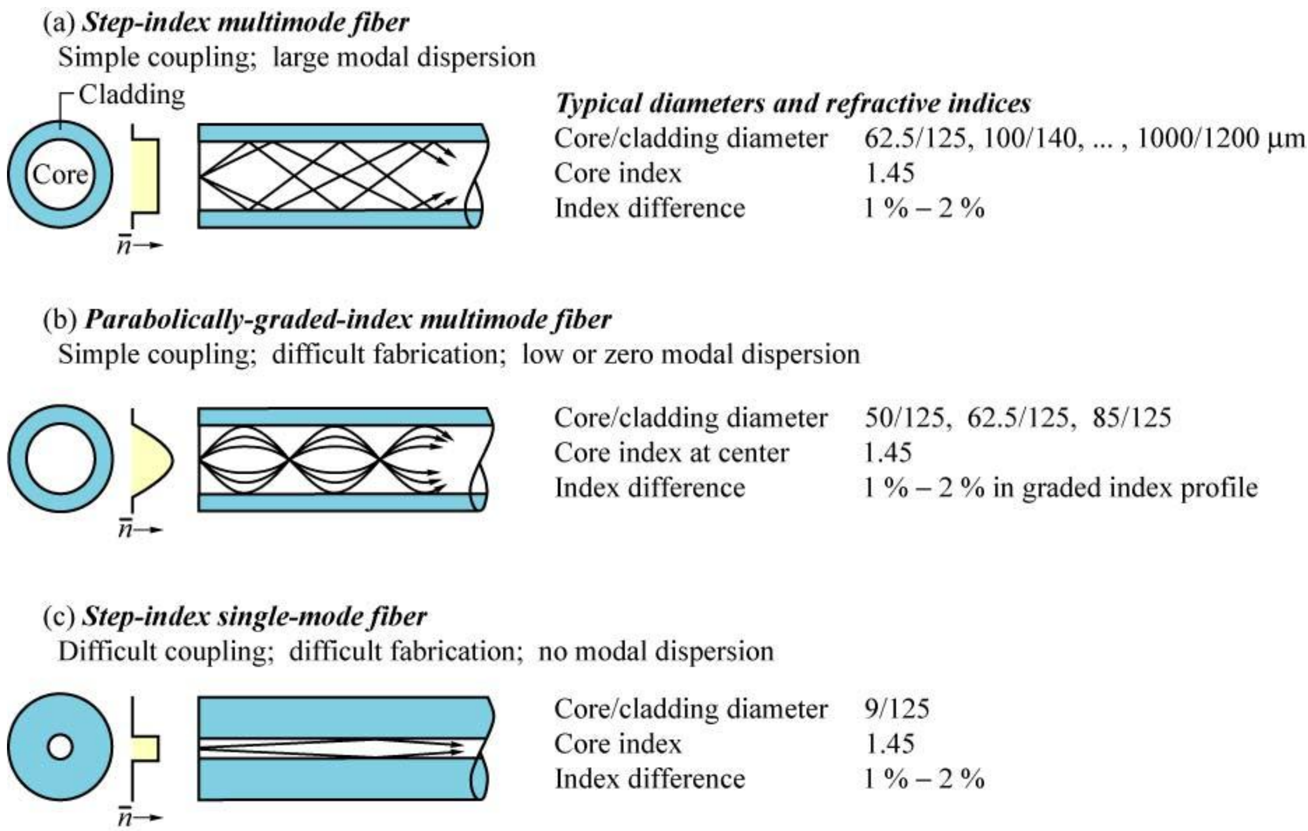


Fig. 22.1. (a) Step-index multimode fibers allow for the propagation of several optical modes. (b) Parabolically graded-index multimode fibers allow for the propagation of several modes with similar propagation constant. Graded-index multimode fibers have a lower modal dispersion than step-index multimode fibers. (c) Step-index single-mode fibers have a small core diameter and no modal dispersion.

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

Example: The intensity of light absorbed while passing through a 16-kilometer length of optical fiber glass is equivalent to the light intensity absorbed through for a 25-mm thickness of ordinary window glass. Calculate the absorption coefficient β of the optical fiber glass if the value of b for the window glass is 10^{-4} mm^{-1}.

$$I'_T = I'_0\, e^{-\beta x} \quad , \quad \frac{I'_T}{I'_0} = e^{-\left(10^{-4} mm^{-1}\right)(25.4 mm)} = 0.9975$$

$\beta = (-1 / x) \ln (I_T' / I_0')$
Now, solving for β leads to
$\beta = -(1 / x) \ln (I_T' I_0')$
For x = 16 km = 16 x 10^3 m = 16 x 10^6 mm
$\beta = -(1 / 16 \times 10^6 mm) \ln(0.9975) = 1.56 \times 10^{-10} mm^{-1}$