Chapter 10: Optical Properties

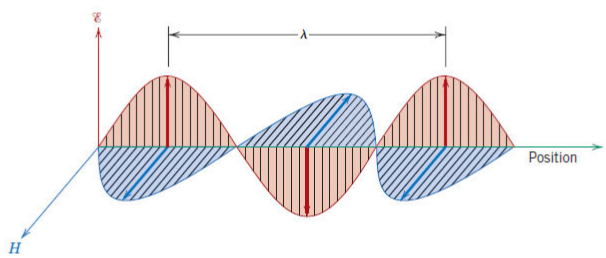
ISSUES TO ADDRESS...

- What phenomena occur when light is shined on a material?
- What determines the characteristic colors of materials?
- Why are some materials transparent and others are translucent or opaque?
- How does a laser operate?

1

Electromagnetic radiation

•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.



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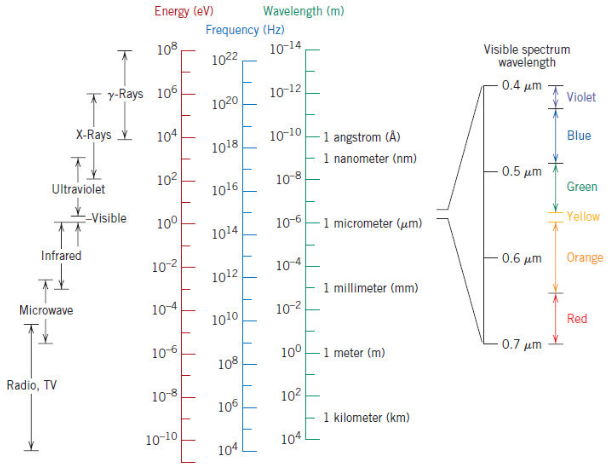
Optical Properties

•Light, heat, radar, radio waves, and x-rays are all forms of electromagnetic radiation.
•Each is characterized primarily by a specific range of wavelengths, and also according to the technique by which it is generated.



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Optical Properties

•All electromagnetic radiation traverses a vacuum at the same velocity, that of light—namely, $3x10^8$m/s.

•This velocity, *c, is related to the "***electric permittivity**" of a vacuum and the "**magnetic permeability**" of a vacuum through

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

•There is an association between the electromagnetic constant *c and these electrical* and magnetic constants

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Optical Properties

Light has both particulate and wavelike characteristics

– Photon - a quantum unit of light

$$E = h\nu = \frac{hc}{\lambda}$$

E = energy of a photon

λ = wavelength of radiation

ν = frequency of radiation

h = Planck's constant (6.62×10^{-34} J·s)

c = speed of light in a vacuum (3.00×10^{8} m/s)

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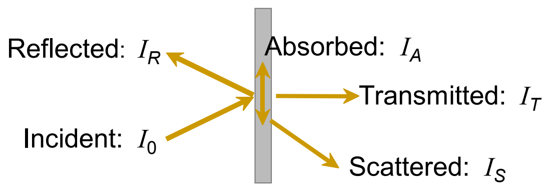
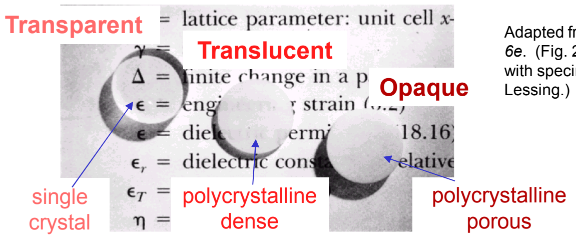
Light Interactions with Solids

- Incident light is reflected, absorbed, scattered, and/or transmitted: $I_0 = I_T + I_A + I_R + I_S$



- Optical classification of materials:



Adapted from Fig. 21.10, *Callister 6e*. (Fig. 21.10 is by J. Telford, with specimen preparation by P.A. Lessing.)

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Atomic and Electronic Interactions

Two of the most important interactions are
- •Electronic polarization
- •Electron energy transitions

-Electronic polarization:

For the visible range of frequencies, electric field component of electro-magnetic wave (light) 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.

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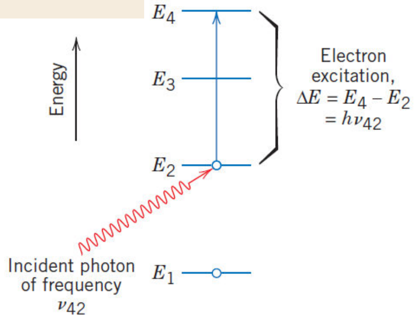
-Electron transitions:

•The absorption and emission of electromagnetic radiation may involve electron transitions from one energy state to another.
•Consider an isolated atom, the electron energy diagram. An electron may be excited from an occupied state at energy E_2 to a vacant and higher-lying one, denoted E_4 by the absorption of a photon of energy.
•The change in energy experienced by the electron, depends on the radiation frequency:

$$\Delta E = h\nu$$



•Only photons of frequencies corresponding to the possible ΔE's for the atom can be absorbed by electron transitions,

•All of a photon's energy is absorbed in each excitation event

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•A second important concept is that a stimulated electron cannot remain in an excited state,

•After a short time, it falls or decays back into its ground state, or unexcited level, with a reemission of electromagnetic radiation,

•Several decay paths are possible. In any case, there must be a conservation of energy for absorption and emission electron transitions.

The optical characteristics of solid materials that relate to absorption and emission of electromagnetic radiation are explained in terms of the electron band structure of the material and the principles relating to electron transitions.

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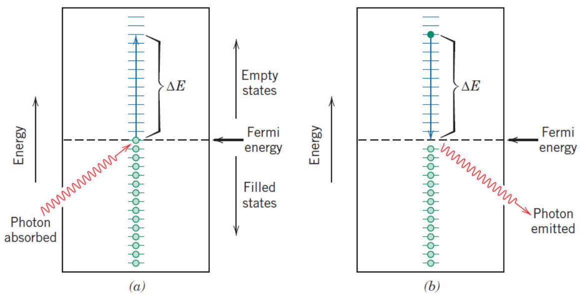
Optical Properties of Metals: Absorption



•In both cases a high-energy band is only partially filled with electrons.

•Metals are opaque because the incident radiation having frequencies within the visible range excites electrons into unoccupied energy states above the Fermi energy.

•As a consequence, the incident radiation is absorbed,

•Total absorption is within a very thin outer layer, usually less than 0.1μ thus only metallic films thinner than 0.1μ are capable of transmitting visible light.

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Light Absorption

The amount of light absorbed by a material is calculated using Beer's Law

$$I'_T = I'_0 e^{-\beta\ell}$$

β = absorption coefficient, cm^{-1}
ℓ = sample thickness, cm
I'_0 = incident light intensity
I'_T = transmitted light intensity

Rearranging and taking the natural log of both sides of the equation leads to

$$\ln\left[\frac{I'_T}{I'_0}\right] = -\beta\ell$$

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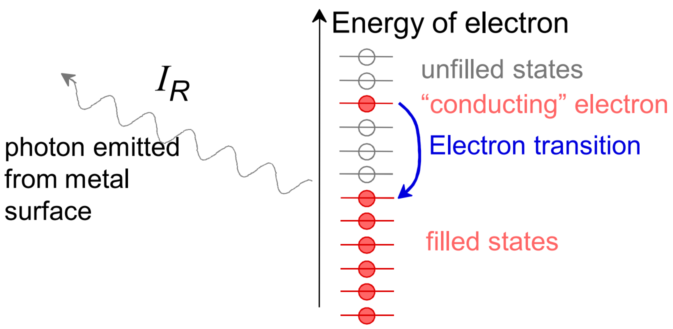
Reflection of Light for Metals

- 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.
- Electron transition from an excited state produces a photon.



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Reflection of Light for Metals (cont.)

- Reflectivity = I_R/I_0 is between 0.90 and 0.95.
- Metal surfaces appear shiny
- Most of absorbed light is reflected at the same wavelength
- Small fraction of light may be absorbed
- Color of reflected light depends on wavelength distribution
  - Example: The metals copper and gold absorb light in blue and green => reflected light has gold color

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Optical Properties of Nonmetals:

•By virtue of their electron energy band structures, **nonmetallic materials may be transparent to visible light**.

•Therefore, in addition to "**reflection**" and "**absorption**", "**refraction**" and "**transmission**" phenomena also need to be considered.

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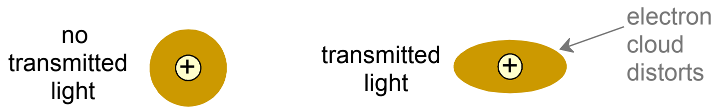
Refraction

- Transmitted light distorts electron clouds.



- The velocity of light in a material is lower than in a vacuum (Decrease in velocity).

$$n = \text{index of refraction} \equiv \frac{c\ (\text{velocity of light in vacuum})}{v\ (\text{velocity of light in medium})}$$

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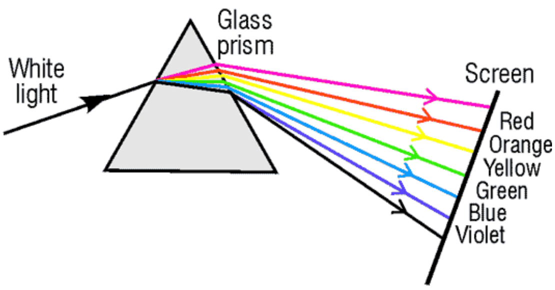
•The magnitude of “**n**” (or the degree of bending) will depend on the wavelength of the light.

•This effect is graphically demonstrated by dispersion or separation of a beam of white light into its component colors by a glass prism.



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

•Not only does the index of refraction affect the optical path of light, but also it influences the fraction of incident light that is reflected at the surface.

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•For transparent materials, there is a relation between the index of refraction and the dielectric constant:

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

Dielectric Constant

Relative Magnetic Permeability

most substances are only slightly magnetic: $\mu_r=1$

$$n \cong \sqrt{\epsilon_r}$$

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•Since the retardation of electromagnetic radiation in a medium results from electronic polarization, the size of the constituent atoms or ions has a considerable influence on the magnitude of this effect.

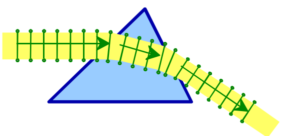
•The larger an atom or ion, the greater will be the electronic polarization, the slower the velocity, and the greater the index of refraction.

•For crystalline ceramics that have cubic crystal structures, and for glasses, the index of refraction is independent of crystallographic direction.

•Noncubic crystals, on the other hand, have an anisotropic ***n***; the index is greatest along the directions that have the highest density of ions.

-- Adding large ions (e.g., lead) to glass decreases the speed of light in the glass.

-- Light can be "bent" as it passes through a transparent prism



Material	n
Typical glasses ca.	1.5 -1.7
Plastics	1.3 -1.6
PbO (Litharge)	2.67
Diamond	2.41

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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.

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

Intensity of reflected beam (I_R)

Intensity of Incident beam (I_0)

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

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Reflection

•When light is transmitted from a vacuum or air into a solid *s,*

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

•The higher the index of refraction of the solid, the greater is the reflectivity.

•Just as the "index of refraction" of a solid depends on the wavelength of the incident light, so also does the reflectivity vary with wavelength.

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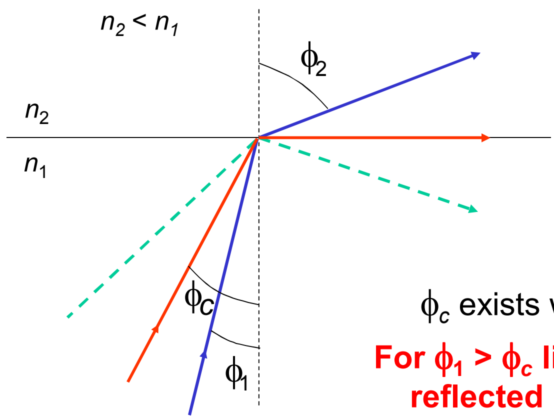
Total Internal Reflectance



$$\frac{n_1}{n_2} = \frac{\sin \phi_2}{\sin \phi_1}$$

ϕ_1 = incident angle

ϕ_2 = refracted angle

ϕ_c = critical angle

ϕ_c exists when $\phi_2 = 90°$

For $\phi_1 > \phi_c$ light is internally reflected

- Fiber optic cables are clad in low *n* material so that light will experience total internal reflectance and not escape from the optical fiber.

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Absorption

•In principle, light radiation is absorbed in **nonmetalic 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: Band structures for semiconductors and insulators.

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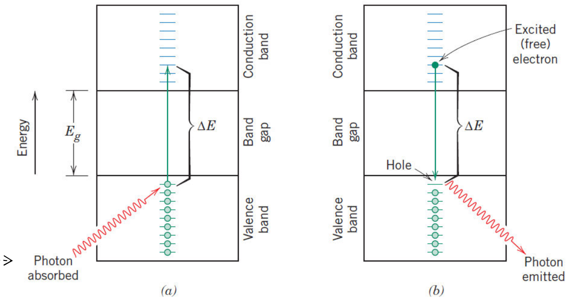
•Absorption of a photon of light may occur by the promotion or excitation of an electron from the nearly filled valence band, across the band gap, and into an empty state within the conduction band.

$$h\nu > E_g$$



•These excitations with the accompanying absorption can take place only if the photon energy is greater than that of the band gap.

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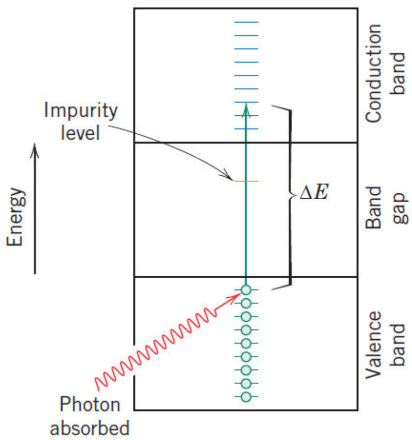
•All visible light is absorbed by “valence band to conduction band electron transitions” for those semiconducting materials that have band gap energies less than about 1.8 eV; thus, these materials are **opaque.**

•Interactions with light radiation can also occur in dielectric solids having wide band gaps, involving other than valence band-conduction band electron transitions.

•If impurities or other electrically active defects are present, electron levels within the band gap may be introduced (such as the donor and acceptor levels, **except that they lie closer to the center of the band gap**).



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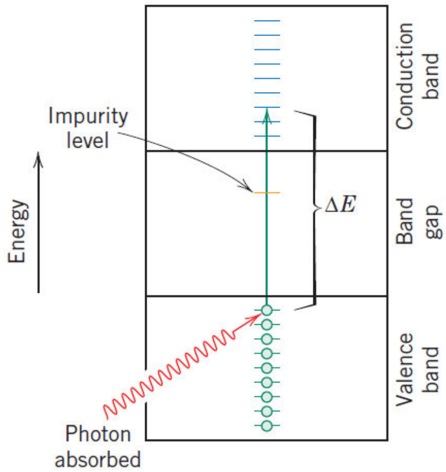
•Light radiation of specific wavelengths may be emitted as a result of electron transitions involving these levels within the band gap.

•For example, according to figure, which shows the valence band - conduction band electron excitation for a material that has one such impurity level.

•The electromagnetic energy that was absorbed by this electron excitation must be dissipated in some manner; several mechanisms are possible:



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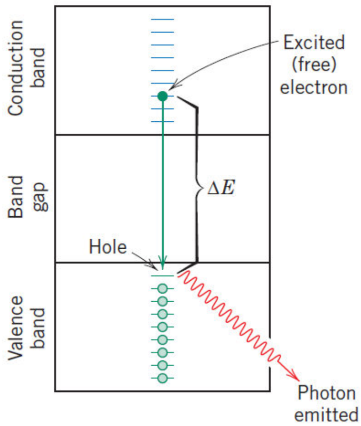
(**1**): Dissipation may occur via direct electron and hole recombination according to the reaction:

$$\text{electron} + \text{hole} \longrightarrow \text{energy}\ (\Delta E)$$



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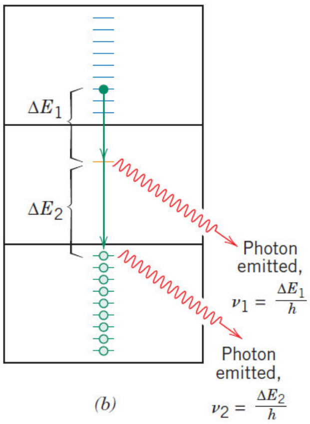
(**2-1**): Multiple-step electron transitions:

- The emission of two photons;
  - one is emitted as the electron drops from a state in the conduction band to the impurity level,
  - the other as it decays back into the valence band.



(b)

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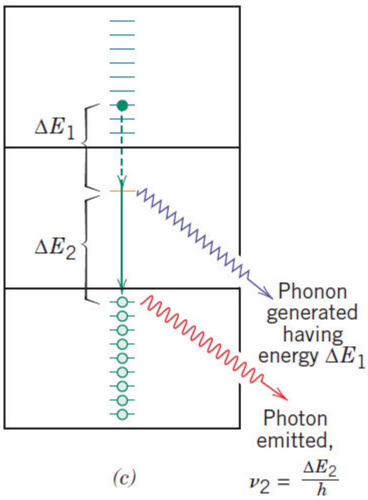
(**2-2**): Multiple-step electron transitions:



(c)

- One of the transitions may involve the generation of a **phonon**, wherein the associated energy is dissipated in the form of "**heat**".

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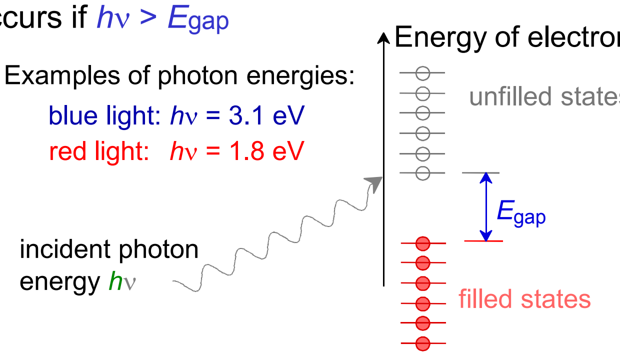
Selected Light Absorption in Semiconductors

Absorption of light of frequency ν by electron transition occurs if $h\nu > E_{gap}$

Examples of photon energies:

blue light: $h\nu$ = 3.1 eV

red light: $h\nu$ = 1.8 eV



Adapted from Fig. 21.5(a), *Callister & Rethwisch 8e.*

- If E_{gap} < 1.8 eV, all light absorbed; material is **opaque** (e.g., Si, GaAs)
- If E_{gap} > 3.1 eV, no light absorption; material is **transparent** and **colorless** (e.g., diamond)
- If 1.8 eV < E_{gap} < 3.1 eV, partial light absorption; material is **colored**

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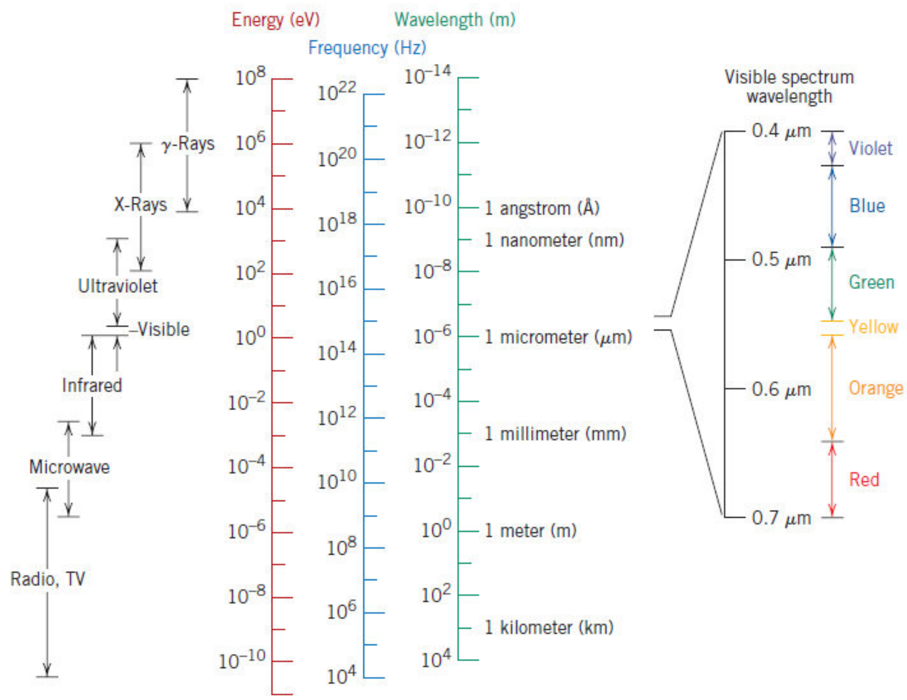
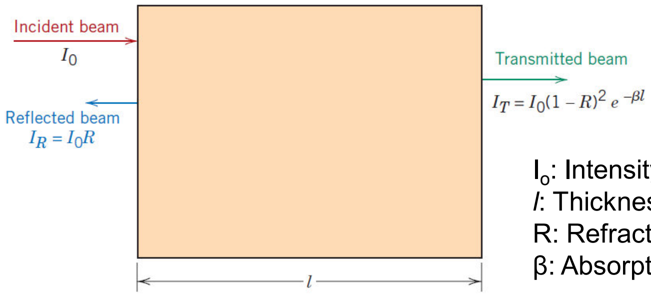


Transmission:

•The phenomena of absorption, reflection, and transmission may be applied to the passage of light through a transparent solid.
•The fraction of incident light that is transmitted through a transparent material depends on the losses that are incurred by absorption and reflection.



I_o: Intensity of beam
l: Thickness
R: Refraction
β: Absorption coefficient

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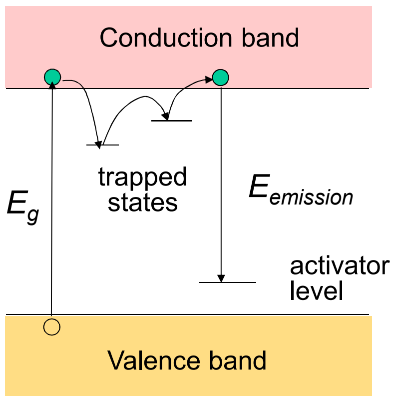
Luminescence

- Luminescence – reemission of light by a material
  - Material absorbs light at one frequency and reemits it at another (lower) frequency.
  - Trapped (donor/acceptor) states introduced by impurities/defects



- If residence time in trapped state is relatively long (> 10^{-8} s) -- phosphorescence
- For short residence times (< 10^{-8} s) -- fluorescence

Example: Toys that glow in the dark. Charge toys by exposing them to light. Reemission of light over time— phosphorescence

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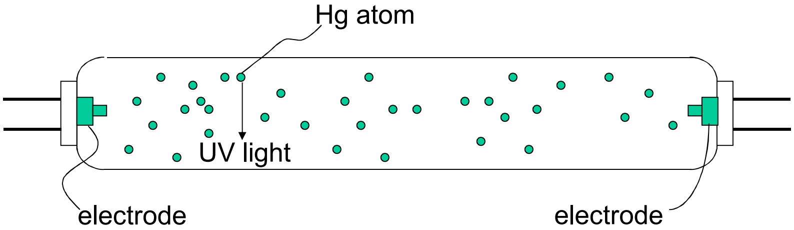
Photoluminescence



- Arc between electrodes excites electrons in mercury atoms in the lamp to higher energy levels.
- As electron falls back into their ground states, UV light is emitted (e.g., suntan lamp).
- Inside surface of tube lined with material that absorbs UV and reemits visible light
  - For example, $Ca_{10}F_2P_6O_{24}$ with 20% of F^- replaced by Cl^-

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The LASER

- The laser generates light waves that are in phase (coherent) and that travel parallel to one another
  - LASER
    - Light
    - Amplification by
    - Stimulated
    - Emission of
    - Radiation
- Operation of laser involves a population inversion of energy states process

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•All the radiative electron transitions heretofore discussed are spontaneous; that is an electron falls from a high energy state to a lower one without any external provacation.
•These transition events occur independently of one another and at random times, producing radiaton that is incoherent (*uyumsuz*); that is, the light waves are out of phase with one another.
•With laser's, however, coherent light is generated by electron transitions initiated by an **external stimulus**.

Light **A**mplification by **S**timulated **E**mission of **R**adiation

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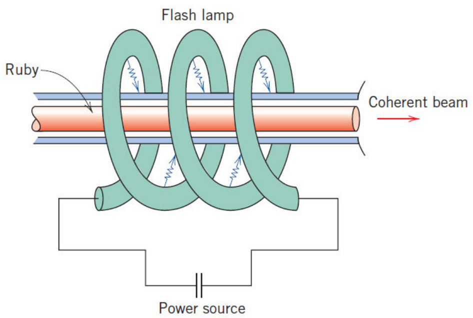
Ruby Laser



•**Ruby**: A single crystal of Al_2O_3 (Sapphire) to which has been added on the order of 0.05% Cr^{+3}

•The ruby laser is in the form of a rod, the ends of which are flat, parallel, and highly polished. Both ends are silvered such that one is totaly reflecting and the other partially transmitting.

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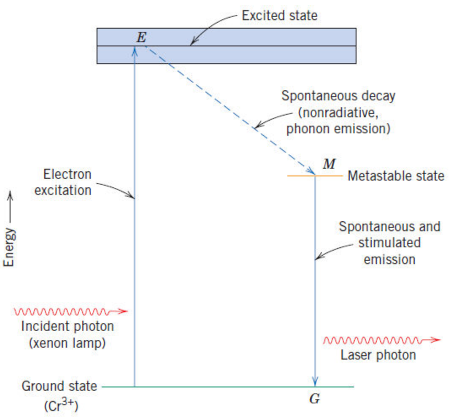

- The ruby is iluminated with light from xenon flash lamb. Before this exposure, virtually all the Cr^{3+} ions are in their ground states; that is electrons fill the lowest energy levels.
- However, photons of wavelength 0.56µm from the xenon lamb excite electrons from the Cr^{3+} ions into higher energy states.
- These electrons can decay back into their ground state by 2 different paths:
  - Some fall back directly; associated photon emission are not part of the laser beam.
  - Other electrons decay into a metastable intermediate state (EM) where they may reside for up to 3 milliseconds before spontaneous emission (MG).

In terms of electronic processes , 3ms is a relatively long time which means that a large number of these metastable states may become occupied.

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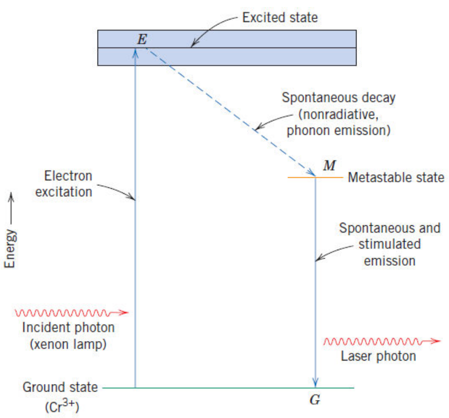

- The initial spontaneous photon emmision by a few of these electrons is the stimulus that trigger an avalanche of emission from the remaining electrons in the metastable state.
- Of the photons directed parallel to the long axix of the ruby rod, some are transmitted through the partially silvered end; others, incident to the totally silvered end, are reflected.
- Photons that are not emitted in this axial direction are lost.
- The light beam repeatedly travels back and forth along the rod length, and intensity increases as more emission are stimulated.

Ultimately, a high intensity and coherent laser light beam of short duration is transmitted through the partially silvered end of the rod.

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Other Applications - Optical Fibers

Schematic diagram showing components of a fiber optic communications system

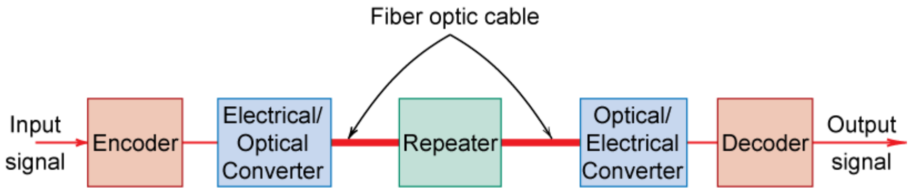

Fig. 21.18, *Callister & Rethwisch 8e.*

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Optical Fibers (cont.)

- fibers have diameters of 125 μm or less
- plastic cladding 60 μm thick is applied to fibers

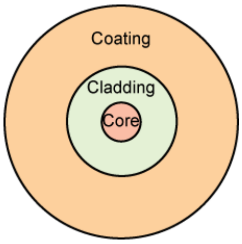

Fig. 21.20, *Callister & Rethwisch 8e.*

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Optical Fiber Designs

Step-index Optical Fiber

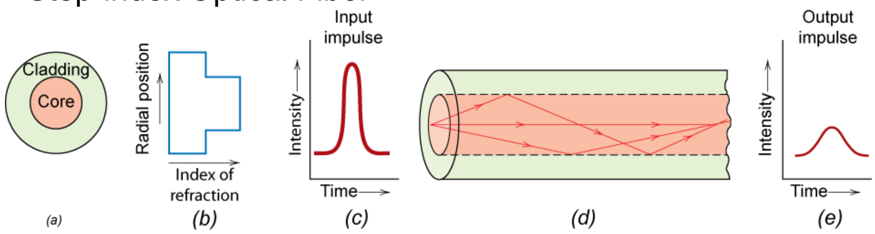

Fig. 21.21, *Callister & Rethwisch 8e.*

Graded-index Optical Fiber

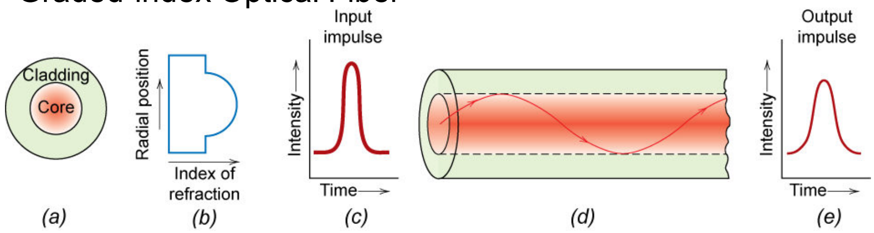

Fig. 21.22, *Callister & Rethwisch 8e.*

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SUMMARY

- Light radiation impinging on a material may be reflected from, absorbed within, and/or transmitted through
- Light transmission characteristics:
  -- transparent, translucent, opaque
- Optical properties of **metals**:
  -- opaque and highly reflective due to electron energy band structure.
- Optical properties of **non-Metals**:
  -- for E_{gap} < 1.8 eV, absorption of all wavelengths of light radiation
  -- for E_{gap} > 3.1 eV, no absorption of visible light radiation
  -- for 1.8 eV < E_{gap} < 3.1 eV, absorption of some range of light radiation wavelengths
  -- color determined by wavelength distribution of transmitted light
- Other important optical applications/devices:
  -- luminescence, **photoconductivity**, **light-emitting diodes**, **solar cells**, lasers, and optical fibers

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