Optical Properties

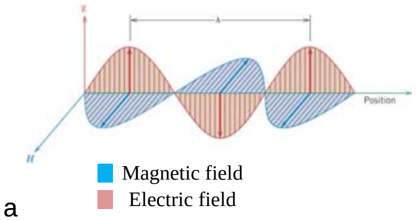
Outline

- Introduction
- Basic Concepts
  - **absorption**
  - **reflection**
  - **transmission**
  - **refraction**
- Applications
  - **luminescence and fluorescence**
  - **Laser and fiber optics**

Introduction

The study of the optical properties of materials is a huge field and we will only be able to scratch the surface of this science.

- Light is an ………………… wave:
- with a velocity given by $c = 1/\sqrt{(\varepsilon_0 \mu_0)} = 3 \times 10^8$ m/s
  - ε_0 is the electric permittivity of a vacuum
  - μ_0 is the magnetic permeability of a vacuum
- **c =** $\lambda\nu$ = wavelength*frequency



In view of this, it is not surprising that the electric field component of the light waves interact with electrons.

Optical properties: are the materials responses to exposure to electromagnetic radiation especially to ***visible*** light.

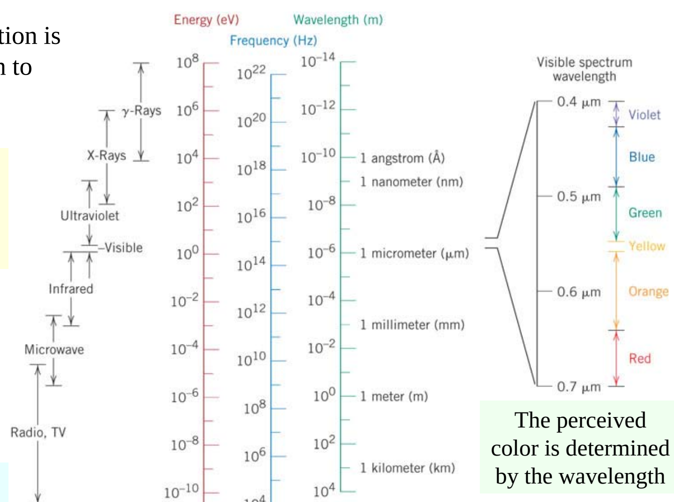
Introduction

The visible radiation is the only radiation to which the eye is sensitive

Frequency, Energy and wavelength are different for each radiation.

From Quantum-mechanical perspective, radiations are packets of energy called …………

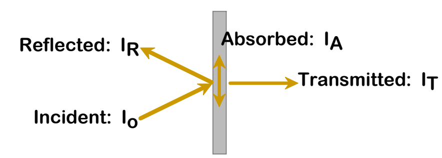
$E = h\nu = hc/\lambda$
h is Planck's constant 6.63×10^{-34} J-s



The spectrum of electromagnetic radiation, including wavelength ranges for the various colors in the visible spectrum.

Light Interactions with Solids

- Because of conservation of energy, we can say that: $\mathbf{I_0 = I_T + I_A + I_R}$
  - I_o is the intensity (W/m²) of incident light and subscripts refer to transmitted, absorbed or reflected
- Alternatively **T + A + R = 1** where T, A, and R are fractions of the amount of incident light.
  - $T = I_T/I_0$, etc.



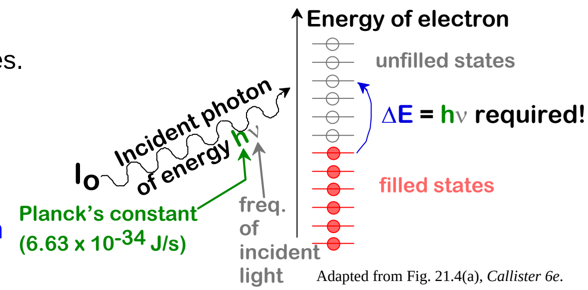
- So materials are broadly classified as
  - transparent: relatively little absorption and reflection
  - translucent: light scatters **within** the material
  - opaque: relatively little transmission

Fig. 21.10, *Callister 8e*

Generally, metals are opaque, electrical insulators can be made transparent and some semiconductors are transparent.

OPTICAL PROPERTIES OF METALS: *ABSORPTION*

- Absorption of photons by electron transition:



Adapted from Fig. 21.4(a), *Callister 6e*.

- Metals have a fine succession of energy states.
- This structure for metals means that almost any frequency of light can be absorbed.
- Since there is a very high concentration of electrons, practically all the light is absorbed within about 0.1µm of the surface.
- Metal films thinner than this will transmit light - *e.g. gold coatings on space suit helmets*

Depending on the material and the wavelength, light can be absorbed by:

- nuclei – all materials
- electrons – metals and small band-gap materials

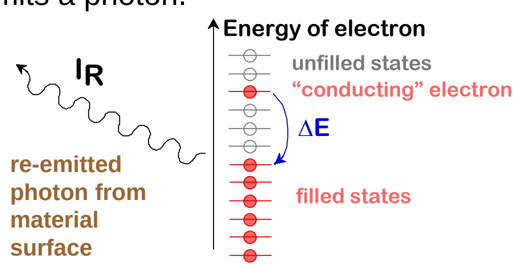
OPTICAL PROPERTIES OF METALS: *ABSORPTION*

- Penetration depths for some materials are:
  - water: 32 cm
  - glass: 29 cm
  - graphite: 0.6 µm
  - gold: 0.15µm
- So what happens to the excited atoms in the surface layers of metal atoms?
  - they relax again, ………… a photon
- The energy lost by the descending electron is the same as the one originally incident
- So the metal reflects the light very well – about ……. for most metals
  - metals are both opaque and reflective
  - the remaining energy is usually lost as heat

Optical Properties Of Metals: *Reflection*

- Electron transition emits a photon.

- Reflectivity = I_R/I_o is between 0.90 and 0.95.
- Reflected light is same frequency as incident.
- Metals appear reflective (shiny)!

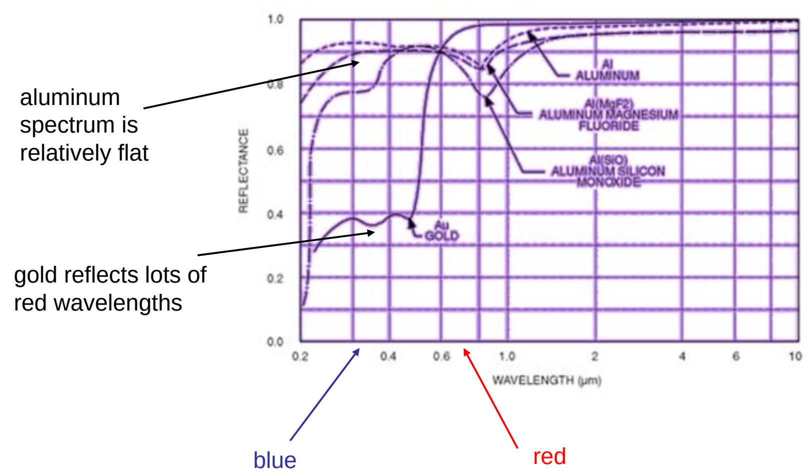


Adapted from Fig. 21.4(b), *Callister 6e*.

- The metal appears "silvery" since it acts as a perfect mirror
- OK then, why are gold and copper not silvery?
  - because the band structure of a real metal is not always as simple as we have assumed; there can be some empty levels below E_F and the energy re-emitted from these absorptions is not in the visible spectrum
- Metals are more transparent to very high energy radiation (x-ray & γ-ray).

OPTICAL PROPERTIES OF METALS: *REFLECTION*

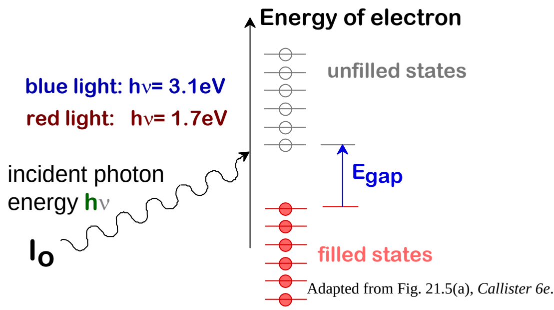
- Reflection spectra for gold and aluminum are:



Selected Absorption: *Nonmetals*

- Absorption by electron transition occurs if $h\nu > E_{gap}$

Semiconductors and insulators behave essentially the same way, the only difference being in the size of the ………..



Adapted from Fig. 21.5(a), *Callister 6e.*

- 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.

Optical Properties of Semiconductors


Germanium


CdS

- Cadmium Sulfide (CdS)
- E_{gap} = 2.4eV,
- absorbs higher energy visible light (blue, violet),
- Red/yellow/orange is transmitted and gives it color.

- Semiconductors can appear "metallic" if visible photons are all reflected (like Ge) but those with smaller E_g, such as CdS look coloured
  - yellow for CdS which absorbs 540nm and above
- This is applicable for pure materials but impurities can cause extra absorption.
- Impurities divide up the band gap to allow transitions with energies less than E_g

Color of Nonmetals

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

- Example: Ruby = Sapphire (Al_2O_3) + (0.5 to 2) at% Cr_2O_3
  - Sapphire is colorless (i.e., E_{gap} > 3.1eV)
  - adding Cr_2O_3 :
    - alters the band gap
    - blue light is absorbed
    - yellow/green is absorbed
    - red is transmitted
    - → Ruby has deep red color.

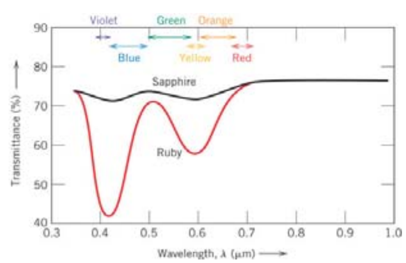
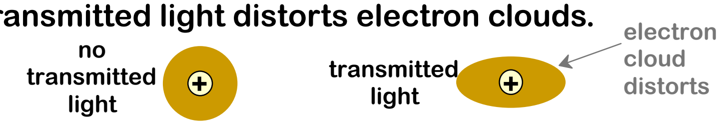


Fig. 21.9, *Callister 8e.*

Transmitted Light: *Refraction*

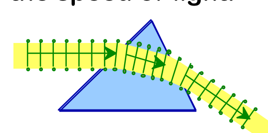
- **Transmitted light distorts electron clouds.**



- **Result 1: Light is slower in a material vs vacuum.**

Index of refraction (n) = speed of light in a vacuum / speed of light in a material

- **Adding large, heavy ions (e.g., lead can decrease the speed of light.**
- **Light can be "bent"**



Material	n
Lead glass	2.1
Silica glass	1.46
Soda-lime glass	1.51
Quartz	1.55
Plexiglas	1.49
Polypropylene	1.49

Selected values from Table 21.1, *Callister 6e.*

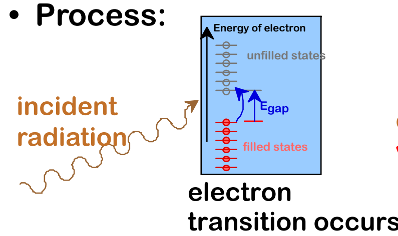
- **Result 2: Intensity of transmitted light decreases with distance traveled (thick pieces less transparent!)**

Translucency

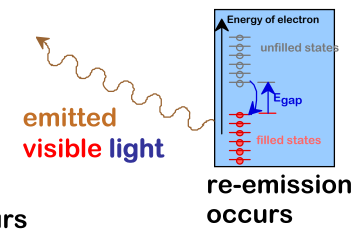
- **Even after the light has entered the material, it might yet be reflected out again due to scattering *inside* the material**
- **Even the transmitted light can lose information by being scattered internally**
  - so a beam of light will spread out or an image will become blurred
- **In extreme cases, the material could become opaque due to excessive internal scattering**
- **Scattering can come from obvious causes:**
  - …………………. in poly-crystalline materials
  - fine pores in ceramics
  - different phases of materials

Application 1: *Luminescence*

- **Process:**

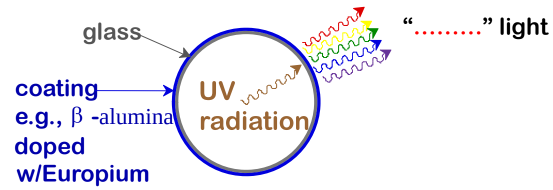


Adapted from Fig. 21.5(a), *Callister 6e.*



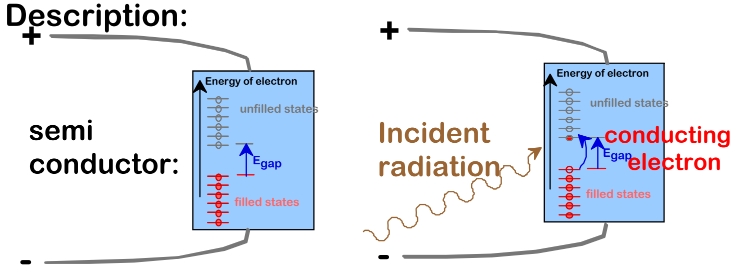
Adapted from Fig. 21.5(a), *Callister 6e.*

- **Example: fluorescent lamps**



Application 2: *Photoconductivity*

- **Description:**



A. No incident radiation: little current flow

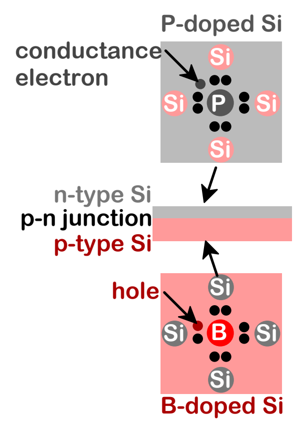
B. Incident radiation: increased current flow

- **Example: Photodetector (Cadmium sulfide)**

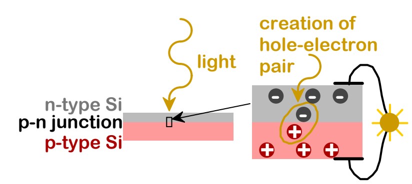
This phenomenon is utilized in photographic light meters. A photo-induced current is measured and its magnitude is a direct function of the intensity of the incident light radiation.

Application 3: *Solar Cell*

- **p-n junction:**



- **Operation:**
  - **- incident photon produces hole-elec. pair.**
  - **- typically 0.5V potential.**
  - **- current increases with light intensity.**



Can be thought of as the reverse operation of the light-emitting diode.

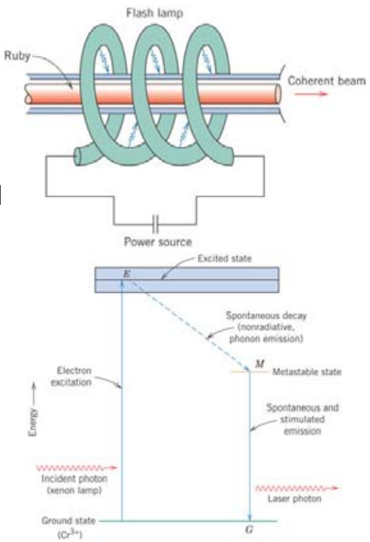
Application 4: *Laser*

- LASER stands for Light Amplification by the Stimulated Emission of Radiation.
- The key word here is "……………"
- All of the light emission we have mentioned so far is *spontaneous.*
  - *It happened just due to randomly occurring "natural" effects.*

- The emitted light has the same energy and phase as the incident light (= …………)
- Under normal circumstances, there are few excited electrons and many in the ground-state,
  - *so we get predominantly absorption*
- If we could arrange for ……… excited than non-excited electrons, then we would get mostly stimulated emission.
- Clearly, random spontaneous emission "wastes" electron transitions by giving incoherent output.

Application 4: *Laser*

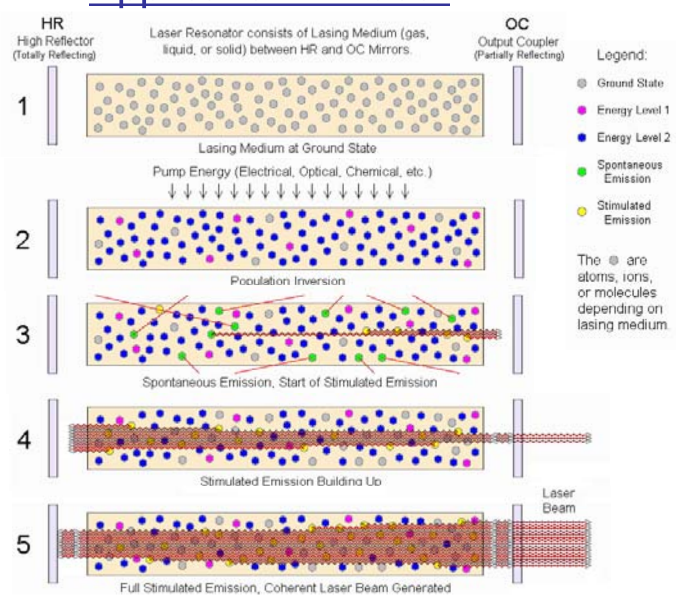
- The first is achieved by filling the metastable states with electrons generated by light from a xenon flash lamp.
- The second condition is achieved by confining the photons to travel back and forth along the rod of ruby using mirrored ends.
- Ruby is a common laser material, which we saw was Al_2O_3 (sapphire) with Cr^{3+} impurities.
- When the electrons decay to the metastable state they may reside up to …… before stimulated emission→ long time → large number of these metastable states become occupied → avalanche of stimulated electrons.



The energy levels of a laser material.

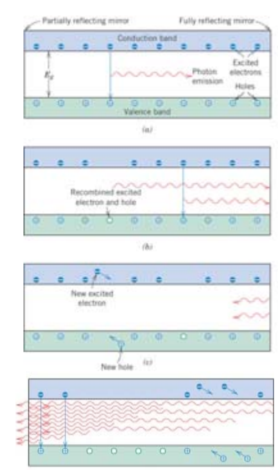
Application 4: *Laser*

- The rod's ends are flat, parallel and highly polished.
- Both ends are silvered such that one is totally reflecting and the other partially transmitting.



Application 4: *Laser*

- In order to keep the coherent emission, we must ensure that the light which completes the round trip between the mirrors returns ………… with itself.
- Hence the distance between the mirrors should obey 2L = Nλ – *where N is an integer, λ is the laser wavelength and L is the cavity length.*
- Semiconductor lasers work in just the same way except that they achieve the population inversion electrically using a carefully designed band structure.



Semiconductor laser (Callister Fig. 21.14)

Application 4: *Laser*

- Some laser characteristics are given in the following table:

Table 21.2 Characteristics and Applications of Several Types of Lasers Callister 6 edition

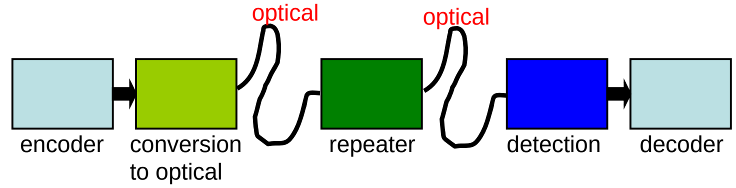
Laser	*Type*	*Common Wavelengths (μm)*	*Max. Output Power (W)*[a]	*Applications*
He–Ne	Gas	0.6328, 1.15, 3.39	0.0005–0.05 (CW)	Line-of-sight communications, recording/playback of holograms
CO_2	Gas	9.6, 10.6	500–15,000 (CW)	Heat treating, welding, cutting, scribing, marking
Argon	Gas ion	0.488, 0.5145	0.005–20 (CW)	Surgery, distance measurements, holography
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.

Application 5: *Fiber Optics*

- Fibre-optic technology has revolutionised telecommunications owing to the speed of data transmission:
  - equivalent to >3 hrs of TV per second
  - 24,000 simultaneous phone calls
  - 0.1kg of fibre carries same information as …………. of copper cable

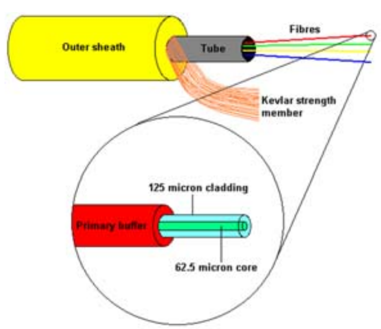
- Owing to attenuation in the cable, transmission is usually digital and the system requires several sections:



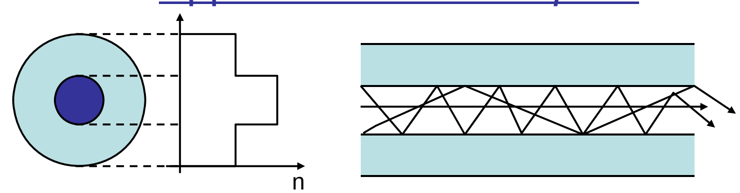
Application 5: *Fiber Optics*

- Obviously, the loss in the cable is important because is determines the maximum uninterrupted length of the fibre.
- We know that losses depend on the wavelength of the light and the purity of the material
  - recall the penetration depth for glass was ~30cm
- In 1970, 1km of fibre attenuated 850nm light by a factor of 100
- By 1979, 1km of fibre attenuated 1.2μm light (*infrared*) by a factor of only …….
- Now, over 10 km of optical fibre silica glass, the loss is the same as 25mm of ordinary window glass!

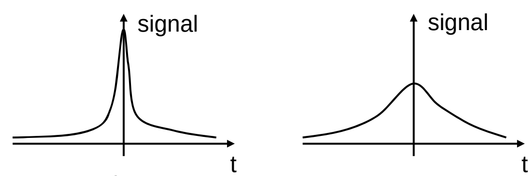
Thus, the cross section of the fibre is designed as follows:



Application 5: *Fiber Optics*



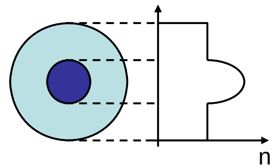
- The light is transmitted in the core and total internal reflection is made possible by the difference in the index of refraction between the cladding and the core.
- A simple approach is the "step-index" design.
- The main problem with this design is that different light rays follow slightly different trajectories and will reach at different times.
- Hence the input pulse is found to broaden during transmission:



This limits the data rate of digital communication

Application 5: *Fiber Optics*

Such broadening is largely eliminated by using a "graded-index" design.



- This is achieved by doping the silica with B_2O_3 or GeO_2 parabolically as shown above.
- Now, waves which travel in the outer regions that have lower refractive index material and hence the velocity is higher (v = c/n)
- Therefore, they travel both *further* and *faster*
  - as a result, they arrive at the output at almost ……….. time as the waves with shorter trajectories
- Anything that might cause scattering in the core must be minimised
  - Cu, Fe, V are all reduced to parts per billion
  - H_2O and OH concentrations also need to be very low
  - Variations in the diameter of the fibre also cause scattering; this variation is now ……… over a length of 1km

Summary

- When light (radiation) shines on a material, it may be:
  - reflected, absorbed and/or transmitted.
- Optical classification:
  - transparent, translucent, opaque
- Metals:
  - fine succession of energy states causes absorption and reflection.
- Non-Metals:
  - may have *full no* or *partial* absorption (depends on the E_{gap}).
  - color is determined by light wavelengths that are transmitted or re-emitted from electron transitions.
  - color may be changed by adding impurities which change the band gap magnitude (e.g., Ruby)
- Refraction:
  - speed of transmitted light varies among materials.
- Applications of this knowledge include:
  - anti-reflective coatings for lenses
  - fibre-optic communications
  - lasers

Next Time:

Review for the Final Exam