Optical behavior

Topic 10
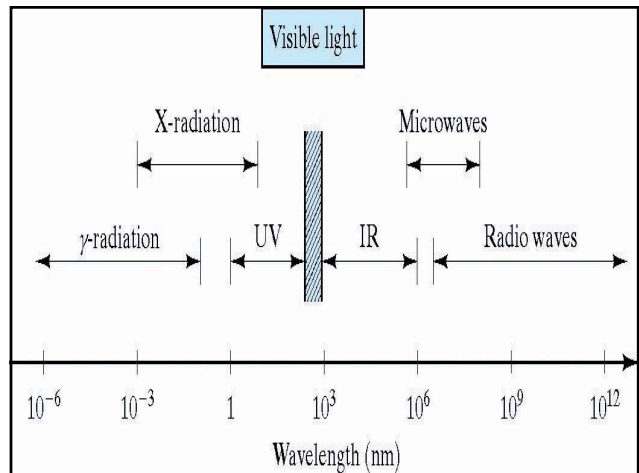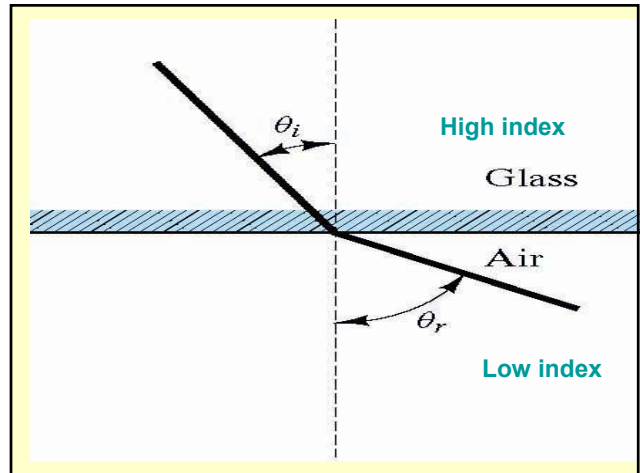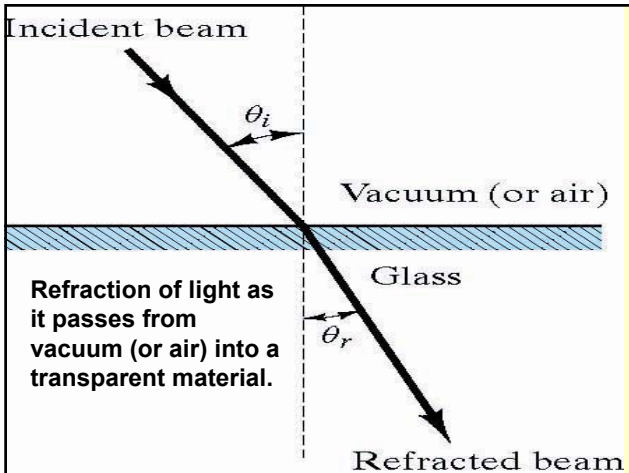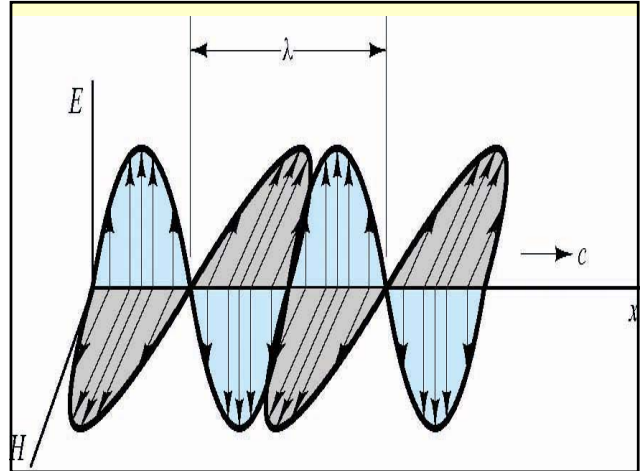
Reading assignment

- Askeland and Phule, The Science and Engineering of Materials, 4th Ed. ,Ch. 20.
- Shackelford, Materials Science for Engineers, 6th Ed., Ch. 16.
- Chung, Composite Materials, Ch. 8.

The Electromagnetic Spectrum

- **Light is energy, or radiation, in the form of waves or particles called photons that can be emitted from a material.**
- **The important characteristics of the photons—their energy E, wavelength λ, and frequency ν—are related by the equation**

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

Figure 20.1 The electromagnetic spectrum of radiation; the bandgaps and cutoff frequencies for some optical materials are also shown. (*Source: From* Optoelectronics: An Introduction to Materials and Devices, *by J. Singh. Copyright © 1996 The McGraw-Hill Companies. Reprinted by permission of The McGraw-Hill Companies.*)

Refraction of light as it passes from vacuum (or air) into a transparent material.

High index

Low index
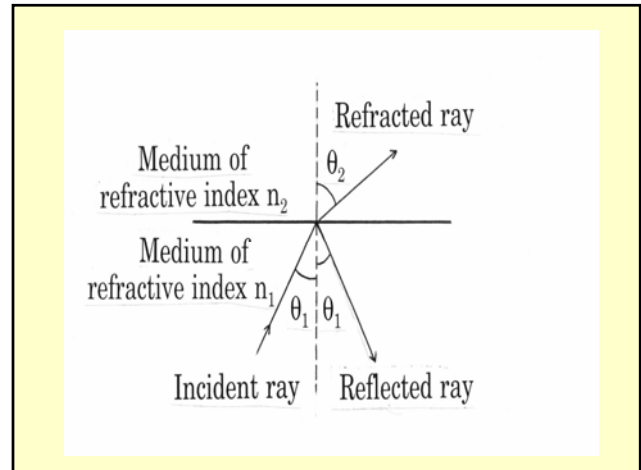
2

Refractive index n

n = Speed of light in vacuum (essentially the same as that in air), divided by the speed of light in a transparent material.

$$n_1 \sin \theta_1 = n_2 \sin \theta_2 \qquad \text{Snell's Law}$$

If $n_1 > n_2$, then $\theta_2 > \theta_1$

Since a larger refractive index means lower speed, $n_1 > n_2$ means $v_2 > v_1$. Thus, the medium with the larger speed is associated with a larger angle between the ray in it and the normal.

TABLE 20-1 ■ Index of refraction of selected materials for photons of wavelength 5890 Å

Material	Index of Refraction (n)
Air	1.00
Ice	1.309
Water	1.333
Teflon™	1.35
SiO_2 (glass)	1.46
Polymethyl methacrylate	1.49
Typical silicate glasses	~1.50
Polyethylene	1.52
Sodium chloride (NaCl)	1.54
SiO_2 (quartz)	1.55
Epoxy	1.58
Polystyrene	1.60
TiO_2	1.74
Sapphire (Al_2O_3)	1.8
Leaded glasses (crystal)	2.50
Rutile (TiO_2)	2.6
Diamond	2.417
Silicon	3.49
Gallium arsenide	3.35
Indium phosphide	3.21
Germanium	4.0

3

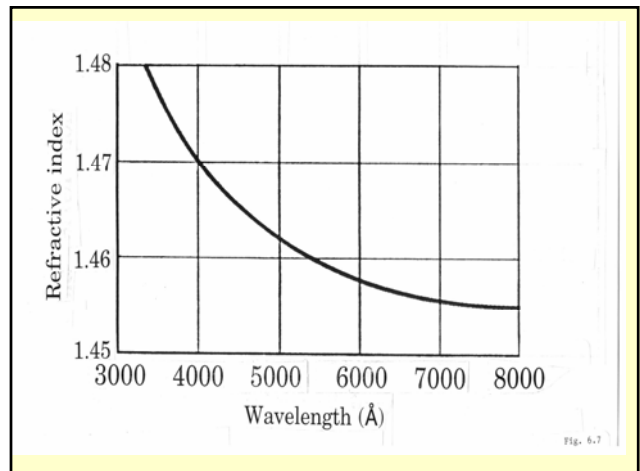| Material	Average refractive index
Quartz (SiO_2)	1.55
Mullite ($3Al_2O_3 \cdot 2SiO_2$)	1.64
Orthoclase ($KAlSi_3O_8$)	1.525
Albite ($NaAlSi_3O_8$)	1.529
Corundum (Al_2O_3)	1.76
Periclase (MgO)	1.74
Spinel ($MgO \cdot Al_2O_3$)	1.72
Silica glass (SiO_2)	1.458
Borosilicate glass	1.47
Soda–lime–silica glass	1.51–1.52
Glass from orthoclase	1.51
Glass from albite	1.49

Source: W. D. Kingery, H. K. Bowen, and D. R. Uhlmann, *Introduction to Ceramics*, 2nd ed., John Wiley & Sons, Inc., NY, 1976.
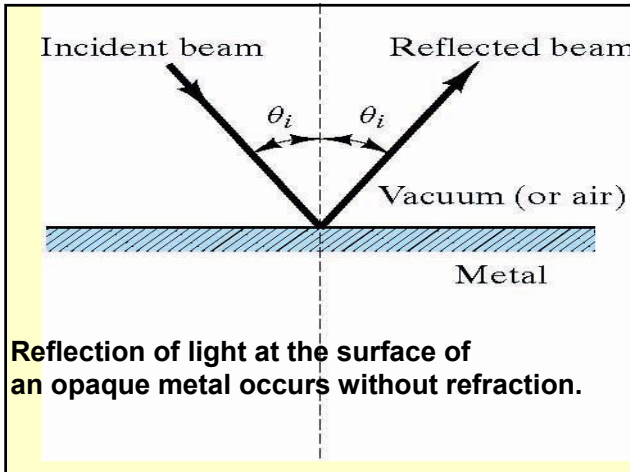
Polymer	Average refractive index
Thermoplastic polymers	
Polyethylene	
High-density	1.545
Low-density	1.51
Polyvinyl chloride	1.54–1.55
Polypropylene	1.47
Polystyrene	1.59
Cellulosics	1.46–1.50
Polyamides (nylon 66)	1.53
Polytetrafluoroethylene (Teflon)	1.35–1.38
Thermosetting polymers	
Phenolics (phenol-formaldehyde)	1.47–1.50
Urethanes	1.5–1.6
Epoxies	1.55–1.60
Elastomers	
Polybutadiene/polystyrene copolymer	1.53
Polyisoprene (natural rubber)	1.52
Polychloroprene	1.55–1.56

Source: Data from J. Brandrup and E. H. Immergut, eds., *Polymer Handbook*, 2nd ed., John Wiley & Sons, Inc., NY, 1975.

Dispersion
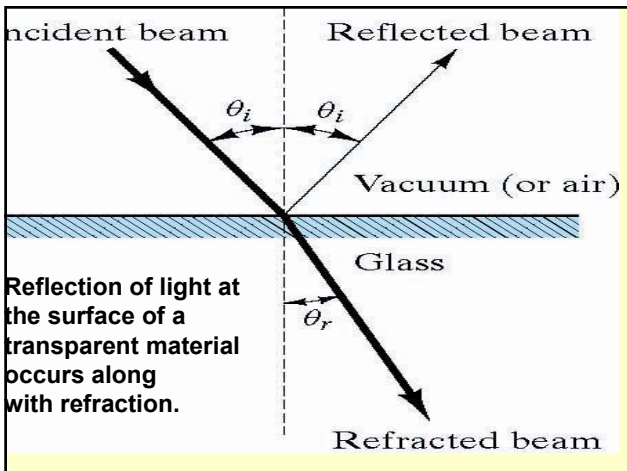
**Frequency dependence
of the index of refraction**

Fig. 6.7

Incident beam   Reflected beam

θ_i θ_i

Vacuum (or air)

Metal

Reflection of light at the surface of an opaque metal occurs without refraction.

Reflectance (reflectivity) R

• **R = Fraction of light reflected**

• **Fresnel's formula**

$$R = [(n-1)/(n+1)]^2$$
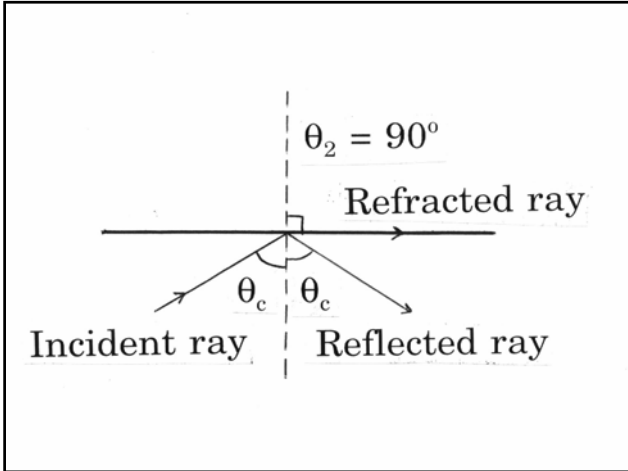
Strictly valid for θ_i = 0 (normal incidence)

High n results in high R
(i.e., R approaches 1)

Incident beam   Reflected beam

θ_i θ_i

Vacuum (or air)

Glass

θ_r

Reflection of light at the surface of a transparent material occurs along with refraction.

Refracted beam

• When θ_2 = 90°, the refracted ray is along the interface

$$\sin \theta_1 = \frac{n_2}{n_1}.$$

The value of θ_1 corresponding to θ_2 = 90° is called θ_c (the critical angle).

$\theta_2 = 90°$

Refracted ray

θ_c θ_c

Incident ray | Reflected ray

When $\theta_1 > \theta_c$, there is no refracted ray and all the incident ray is reflected.

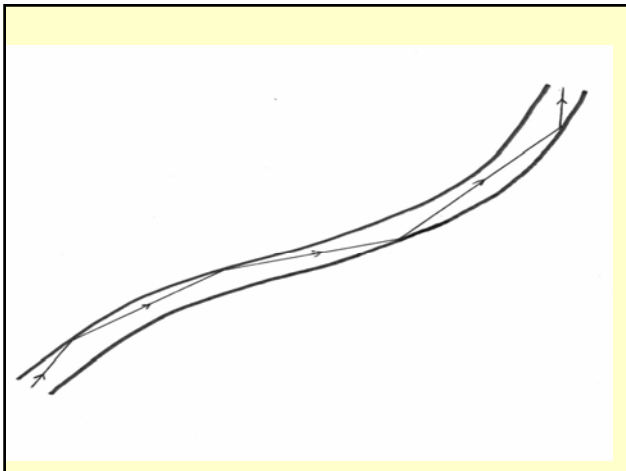**Total internal reflection when θ_1 exceeds θ_c**

θ_1 θ_1

Incident ray   Reflected ray

Cable with 144 glass fibers (right)

Copper-wire cable (left)
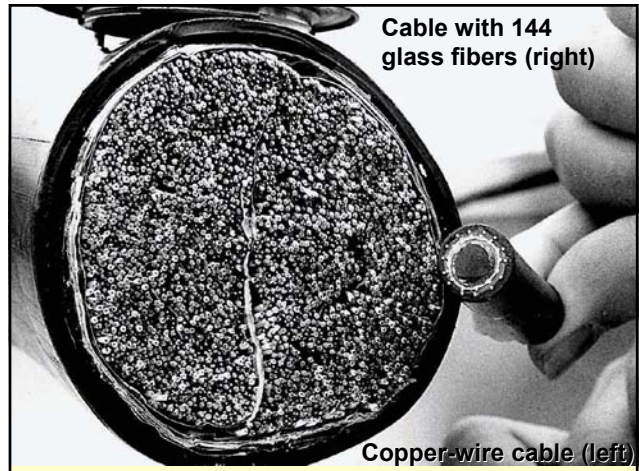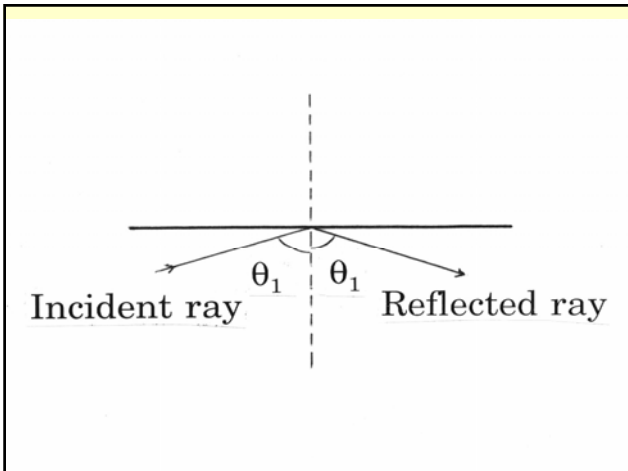
Applications of optical fiber

- **Communication**
- **Digital processing**
- **Sensing (extrinsic smartness)**

Optical fiber

An optical fiber guides the light in it so that the light stays inside even when the fiber is bent.

Optical fiber

- This is because the fiber has a cladding of refractive index n_2 and a core of refractive index n_1, such that $n_1 > n_2$ and total internal reflection takes place when $\theta_1 > \theta_c$.
- This means that the incident ray should have an angle of incidence more than θ_c in order to have the light not leak out of the core. Hence, incoming rays that are at too large an angle (exceeding θ_{NA}) from the axis of the fiber leak.
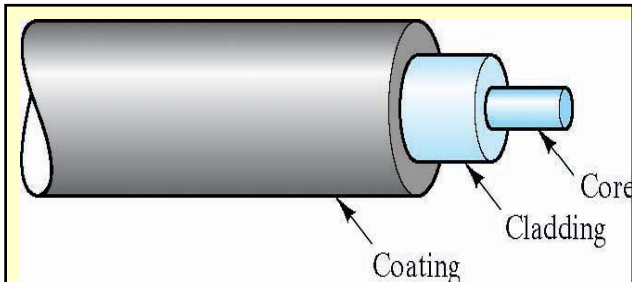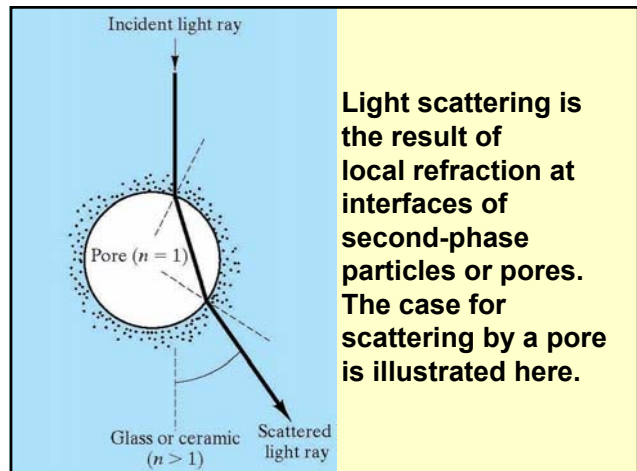
The coaxial design of commercial optical fibers

Core diameter: 5-100 microns

Core material

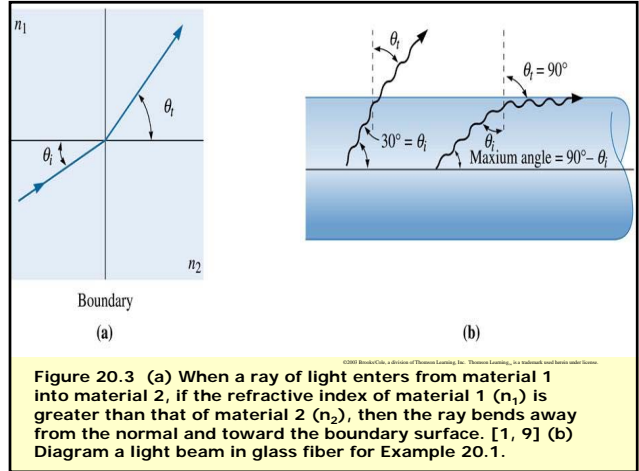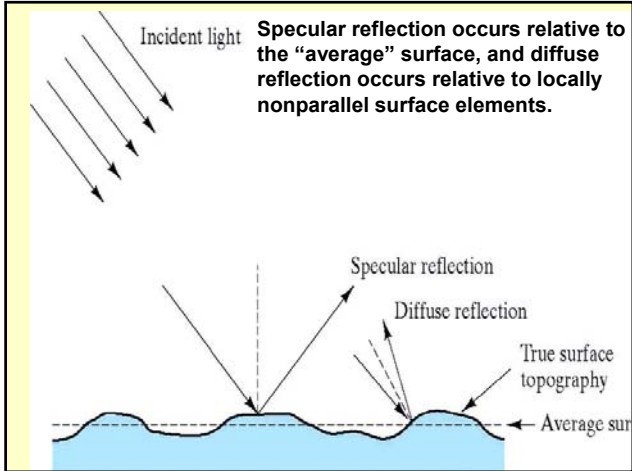**High-purity silica glass**

Attenuation of light

Power loss through a 16-kilometer (19-mile) thickness of optical fiber glass is equivalent to the power loss through a 25-millimeter (1-inch) thickness of ordinary window glass.

Light scattering is the result of local refraction at interfaces of second-phase particles or pores. The case for scattering by a pore is illustrated here.

Specular reflection occurs relative to the "average" surface, and diffuse reflection occurs relative to locally nonparallel surface elements.

Figure 20.3 (a) When a ray of light enters from material 1 into material 2, if the refractive index of material 1 (n_1) is greater than that of material 2 (n_2), then the ray bends away from the normal and toward the boundary surface. [1, 9] (b) Diagram a light beam in glass fiber for Example 20.1.

- The <u>acceptance angle</u> of the fiber is defined as twice θ_{NA}. Rays within the acceptance angle do not leak.
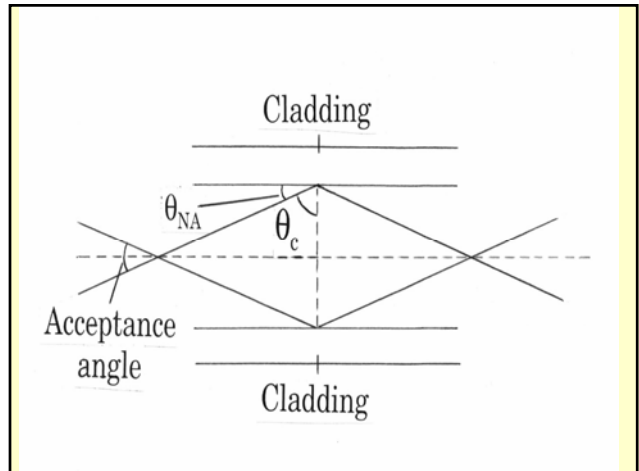
- The <u>numerical aperture</u> (NA) of the fiber is defined as $n_1 \sin \theta_{NA}$. Since $\theta_{NA} = 90° - \theta_c$,
  $n_1 \sin \theta_{NA} = n_1 \sin (90° - \theta_c)$
  $\qquad = n_1 \cos \theta_c$

$$\sin \theta_c = \frac{n_2}{n_1}.$$

$$\cos \theta_c = \sqrt{1 - \left(\frac{n_2}{n_1}\right)^2} = \sqrt{\frac{n_1^2 - n_2^2}{n_1^2}}$$

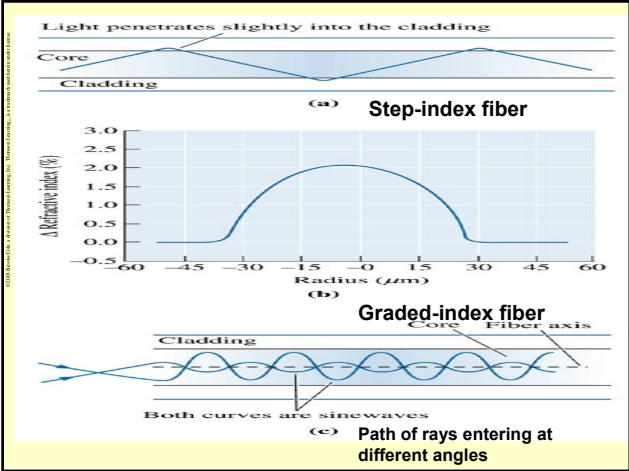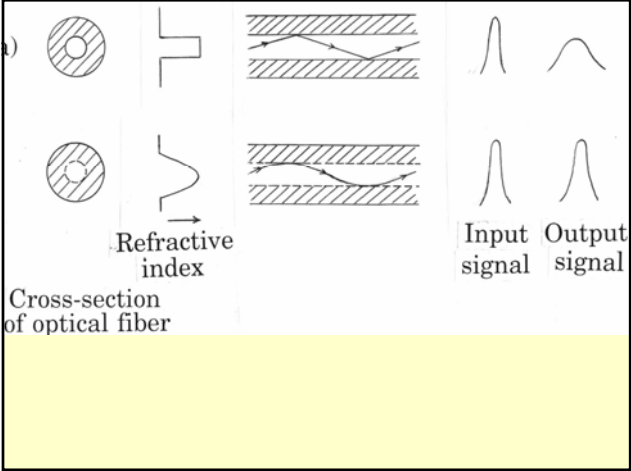$$= \frac{\sqrt{n_1^2 - n_2^2}}{n_1}$$

Numerical aperture
$$= n_1 \left(\frac{\sqrt{n_1^2 - n_2^2}}{n_1}\right)$$

$$\mathbf{=} \sqrt{n_1^2 - n_2^2}$$

- An optical fiber (or optical wave guide) has a low-index glass cladding and a normal-index glass core.
- The refractive index may decrease sharply or gradually from core to cladding, depending on how the fiber is made.
- A sharp decrease in index is obtained in a composite glass fiber; a gradual decrease is obtained in a glass fiber that is doped at the surface to lower the index.
- A gradual decrease is akin to having a diffuse interface between core and cladding. As a consequence, a ray does not change direction sharply as it is reflected by the interface

- A sharp decrease in index corresponds to a sharp interface and a ray changes direction sharply upon reflection by the interface.

Cross-section of optical fiber / Refractive index / Input signal / Output signal

Light penetrates slightly into the cladding
Core
Cladding
(a) **Step-index fiber**
(b)
Graded-index fiber
Core   Fiber axis
Cladding
Both curves are sinewaves
(c) **Path of rays entering at different angles**

- A fiber with a sharp change in index is called a stepped index fiber.
- A fiber with a gradual change in index is called a graded index fiber.
- A graded index fiber gives a sharper output pulse (i.e., less pulse distortion) in response to an input pulse, compared to a stepped index fiber.

An optical fiber may have different diameters of the core.

- A small core (e.g., 3 μm diameter) means that only rays that are essentially parallel to the fiber axis can go all the way through the fiber, as off-axis rays need to be reflected too many times as they travel through the fiber and, as a result, tend to leak.
- A large core (e.g., 50-200 μm) means that both on-axis and off-axis rays make their way through the fiber.
- A fiber with a large core is called a <u>multimode fiber</u>, whereas one with a small core is called <u>single-mode fiber.</u>

(a)

(b)

Cross-section of optical fiber

Input signal Output signal
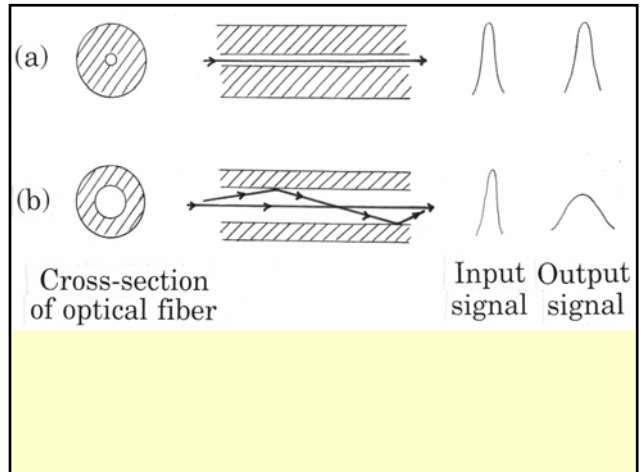
- A single-mode fiber gives less pulse distortion than a multimode fiber, so it is preferred for long-distance optical communication. However, the intensity of light that can go through a single-mode fiber is smaller than that for a multimode fiber.
- The NA tends to be around 0.1 for a single-mode glass fiber and around 0.2 for a multimode glass fiber.

- A single-mode fiber tends to have the cladding thicker than the core, so that the overall fiber diameter is not too small. For example, the cladding may be 70-150 μm thick, while the core diameter is 3 μm.
- A multimode fiber tends to have the cladding thinner than the core, as the core is already large. For example, the cladding may be 1-50 μm thick, while the core diameter is 50-200 μm.
- A single-mode fiber is stepped index, whereas a multimode fiber may be either stepped index or graded index.

3 types of optical fiber

- **Single-mode stepped index**
- **Multimode stepped index**
- **Multimode graded index**

Pulse distortion increases in the order: single-mode stepped index, multimode graded index and multimode stepped index.

Index of refraction, n

(a) **Step-index fiber**

(b) **Graded-index fiber**

Single-mode fiber

Input pulse / Output pulse
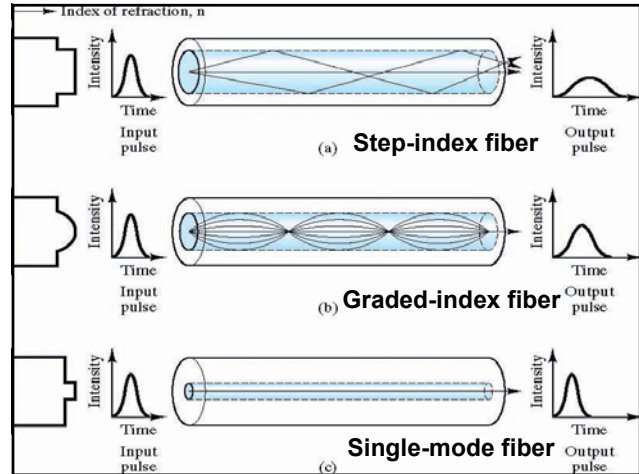
Design of a Fiber Optic System

Optical fibers are commonly made from high-purity silicate glasses. They consist of a core that has refractive index (~ 1.48) that is higher than a region called cladding (refractive index ~ 1.46). This is why even a simple glass fiber in air (refractive index 1.0) can serve as an optical fiber. In designing a fiber optic transmission system, we plan to introduce a beam of photons from a laser into a glass fiber whose index of refraction of is 1.5. Design a system to introduce the beam with a minimum of leakage of the beam from the fiber.
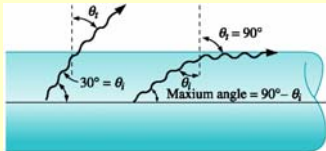

Figure 20.3 (b) Diagram a light beam in glass fiber for Example 20.1.

Example 20.1 SOLUTION

To prevent leakage of the beam, we need the total internal reflection and thus the angle θ_t must be at least 90°. Suppose that the photons enter at a 60° angle to the axis of the fiber. From Figure 20.3(b), we find that θ_i = 90 - 60 = 30°. If we let the glass be Material 1 and if the glass fiber is in air (n = 1.0), then

$$\frac{n_2}{n_1} = \frac{\sin \theta_i}{\sin \theta_t} \quad \text{or} \quad \frac{1}{1.5} = \frac{\sin 30}{\sin \theta_t}$$

$$\sin \theta_t = 1.5 \sin 30 = 1.5(0.50) = 0.75 \quad \text{or} \quad \theta_t = 48.6°$$

Because θ_t is less than 90°, photons escape from the fiber. To prevent transmission, we must introduce the photons at a shallower angle, giving θ_t = 90°.

$$\frac{1}{1.5} = \frac{\sin \theta_i}{\sin \theta_t} = \frac{\sin \theta_i}{\sin 90°} = \sin \theta_i$$

$$\sin \theta_i = 0.6667 \quad \text{or} \quad \theta_i = 41.8°$$

Example 20.1 SOLUTION (Continued)

If the angle between the beam and the axis of the fiber is 90 - 41.8 = 48.2 or less, the beam is reflected.
If the fiber were immersed in water (*n* = 1.333), then:

$$\frac{1.333}{1.5} = \frac{\sin \theta_i}{\sin \theta_t} = \frac{\sin \theta_i}{\sin 90°} = \sin \theta_i$$

$$\sin \theta_i = 0.8887 \quad \text{or} \quad \theta_i = 62.7°$$

In water, the photons would have to be introduced at an angle of less than 90 – 62.7 = 27.3 in order to prevent transmission.

Light is absorbed as it travels through any medium (whether solid, liquid or gas), such that the intensity I at distance x is related to the intensity Io at x = 0 by

$$I = I_o e^{-\alpha x} \quad \text{Beer-Lambert law}$$

where α is the <u>absorption coefficient</u>, which varies from one medium to another and has the unit m^{-1}.

The greater is α, the more severe is the absorption.

The intensity decreases exponentially as light travels through the medium.
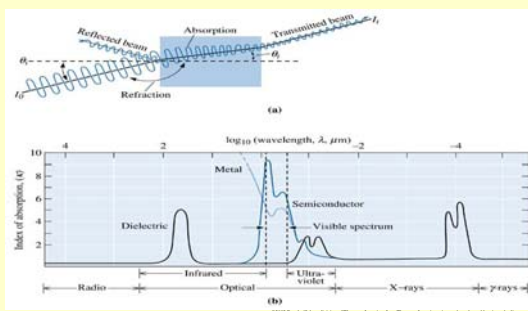

Figure 20.2 (a) Interaction of photons with a material. In addition to reflection, absorption, and transmission, the bream changes direction, or is refracted. The change in direction is given by the index of refraction *n*. (b) The absorption index (*k*) as a function of wavelength.

$$\ln \frac{I}{I_o} = -\alpha x$$

Converting natural logarithm to logarithm to the base 10 gives

$$2.3 \log \frac{I}{I_o} = -\alpha x$$

Attenuation loss (in dB) =

$$-10 \; \log \; \frac{I}{I_o}.$$

When I/Io = 0.1, the attenuation loss is 10 dB.

When I/I$_o$ = 0.01, the attenuation loss is 20 dB

Attenuation loss (in dB) =

$$\frac{10 \quad \alpha \quad x}{2.3}$$

Hence, the attenuation loss is proportional to x.

A typical loss for glass fibers is around 1 dB/km. Polymers are not as attractive as glass for use as optical fibers because of their relatively high attenuation loss.

The imperfect coupling between the light source and an optical fiber is another source of loss, called coupling loss, which is typically 10-12 dB.

This loss is because the light from the source has rays that are at angles greater than the acceptance angle of the optical fiber.
Even if the light source (a light emitting diode with rays exiting it within an angle of 100°) is butt directly with the optical fiber, coupling loss still occurs. Less coupling loss occurs if the light source is a laser, since laser light diverges negligibly as it travels.

- The intensity of light (related to the amplitude) that goes through an optical fiber is called the light throughput, which decreases as the fiber decreases in diameter, as the fiber bends (causing leakage through the cladding) and as the fiber is damaged.

An optical fiber may contain partially reflecting (partially transmitting) mirrors at certain points along its length within the fiber. In this way, a part of the light is reflected and a part is transmitted. By measuring the time it takes for the reflected light to reach the start of the fiber, information can be obtained concerning the location of the strain or damage. This technique is called <u>time domain reflectometry</u>.

3 types of optical fiber sensor

- **Transmission-gap sensor**
- **Evanescent-wave sensor**
- **Internal-sensing sensor**

Transmission-gap sensor

A transmission-gap sensor has a gap between the input fiber and the output fiber (which are end to end except for the gap) and the disturbance at the gap affects the output. The disturbance may be pressure, temperature, etc. In case that the ends of the fibers delineating the gap are polished to enhance light reflection, a slight change in the gap distance causes a change in phase difference between the light rays reflected from the adjacent ends of the two fibers and travelling in the same direction back toward the light source.

Evanescent-wave sensor

An evanescent-wave sensor has a part of the length of an optical fiber stripped of its cladding. The stripped part is the sensor, since the light loss from the stripped part is affected by the refractive index of the medium around the stripped part. Hence, a change in medium is detected by this sensor.

Internal-sensing sensor

An internal-sensing sensor is just an unmodified optical fiber; the amplitude and phase of light going through the fiber is affected by the disturbance encountered by the fiber.
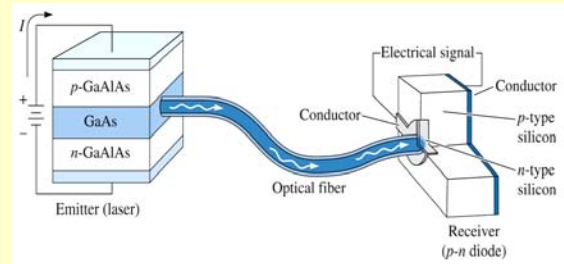

Figure 20.8 Elements of a photonic system for transmitting information involves a laser or LED to generate photons from an electrical signal, optical fibers to transmit the beam of photons efficiently, and an LED receiver to convert the photons back into an electrical signal.

Example 20.3
Determining Critical Energy Gaps

Determine the critical energy gaps that provide complete transmission and complete absorption of photons in the visible spectrum.

Example 20.3 SOLUTION

The visible light spectrum varies from 4×10^{-5} cm to 7×10^{-5} cm. The minimum E_g required to assure that no photons in the visible spectrum are absorbed is:
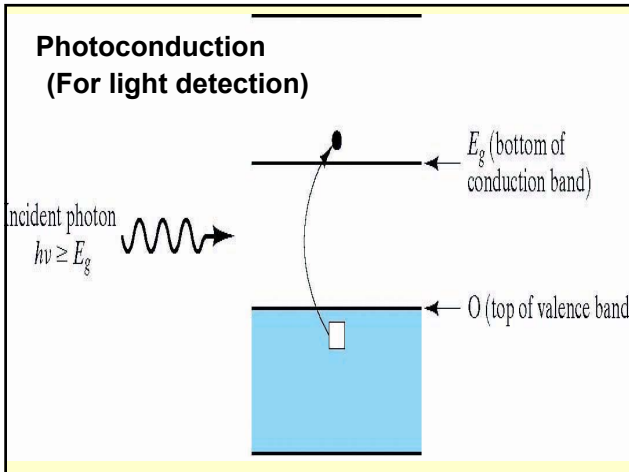
$$E_g = \frac{hc}{\lambda} = \frac{(6.62 \times 10^{-34} \text{ J} \cdot \text{s})(3 \times 10^{10} \text{ cm/s})}{(4 \times 10^{-5} \text{ cm})(1.6 \times 10^{-19} \text{ J/eV})}$$

$$= 3.1 \text{ eV}$$

Example 20.3 SOLUTION (Continued)

The maximum E_g below which all of the photons in the visible spectrum are absorbed is:

$$E_g = \frac{hc}{\lambda} = \frac{(6.62 \times 10^{-34} \text{ J} \cdot \text{s})(3 \times 10^{10} \text{ cm/s})}{(7 \times 10^{-5} \text{ cm})(1.6 \times 10^{-19} \text{ J/eV})}$$

$$= 1.8 \text{ eV}$$

For materials with an intermediate E_g, a portion of the photons in the visible spectrum will be absorbed.

Photoconduction
 (For light detection)

E_g (bottom of conduction band)

Incident photon
$hv \geq E_g$

O (top of valence band)

Photoresponse

• **Ratio of the light conductivity to dark conductivity**

• **Describes the effectiveness of a light detector**

Luminescence

• **Photon absorption is accompanied by the reemission of some photons of visible light.**

• **May be accompanied by the absorption of other forms of energy (thermal, mechanical and chemical) or particles (e.g., high-energy electrons).**

• **Any emission of light from a substance for any reason other than a rise in its temperature.**

Luminescence

Atoms of a material emit photons of electromagnetic energy when they return to the ground state after having been in an excited state due to the absorption of energy.
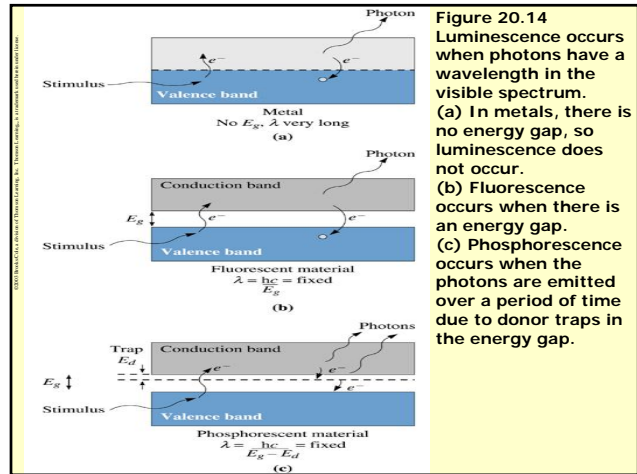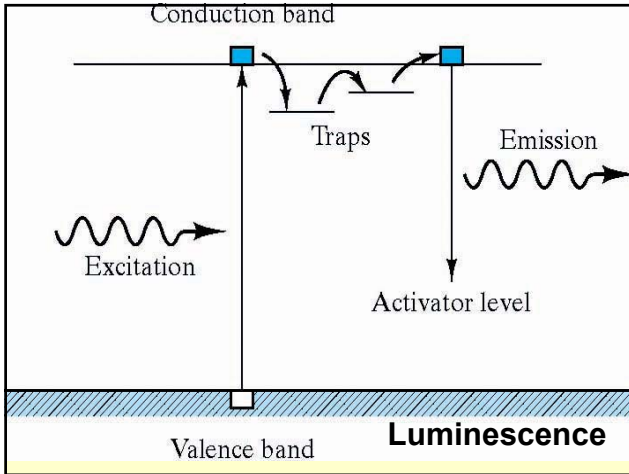
Conduction band

Traps

Emission

Excitation

Activator level

Luminescence

Valence band

Figure 20.14 Luminescence occurs when photons have a wavelength in the visible spectrum.
(a) In metals, there is no energy gap, so luminescence does not occur.
(b) Fluorescence occurs when there is an energy gap.
(c) Phosphorescence occurs when the photons are emitted over a period of time due to donor traps in the energy gap.

Metal
No E_g, λ very long
(a)

Conduction band
E_g
Valence band
Fluorescent material
$\lambda = \dfrac{hc}{E_g} = $ fixed
(b)

Trap E_d
E_g
Conduction band
Valence band
Phosphorescent material
$\lambda = \dfrac{hc}{E_g - E_d} = $ fixed
(c)

- **Luminescence** - Conversion of radiation to visible light.
- **Fluorescence** - Emission of light obtained typically within ~ 10^{-8} seconds.
- **Phosphorescence** - Emission of radiation from a material after the stimulus is removed.

X-ray fluoresence

Copper
K_α $\lambda = 1.54$ Å $\Delta E = 1.29 \times 10^{-15}$ J
K_β $\lambda = 1.39$ Å $\Delta E = 1.43 \times 10^{-15}$ J
L_α $\lambda = 13.36$ Å $\Delta E = 0.15 \times 10^{-15}$ J

where $K = 1s^2$ level
$L = 2s^2p^6$ level
$M = 3s^2p^6d^{10}$ level

$\Delta E = 1.29 \times 10^{-15}$ J
$\Delta E = 0.15 \ 10^{-15}$ J
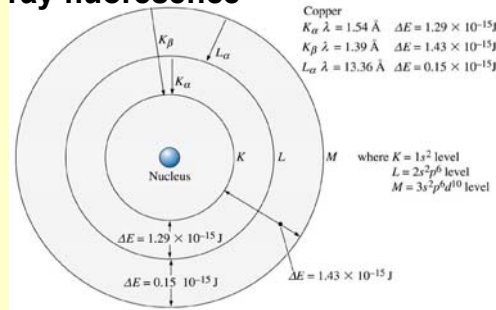$\Delta E = 1.43 \times 10^{-15}$ J

Figure 20.11 Characteristic x-rays are produced when electrons change from one energy level to a lower energy level, as illustrated here for copper. The energy and wavelength of the x-rays are fixed by the energy differences between the energy levels.
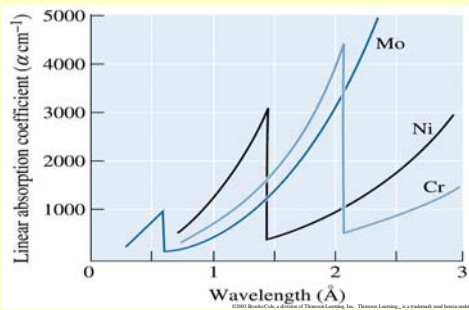
Figure 20.4 The linear absorption coefficient relative to wavelength for several metals. Note the sudden decrease in the absorption coefficient for wavelengths greater than the absorption edge.

TABLE 20-2 ■ Characteristic emission lines and absorption edges for selected elements

Metal	K_α (Å)	K_β (Å)	L_α (Å)	Absorption Edge (Å)
Al	8.337	7.981	—	7.951
Si	7.125	6.768	—	6.745
S	5.372	5.032	—	5.018
Cr	2.291	2.084	—	2.070
Mn	2.104	1.910	—	1.896
Fe	1.937	1.757	—	1.743
Co	1.790	1.621	—	1.608
Ni	1.660	1.500	—	1.488
Cu	1.542	1.392	13.357	1.380
Mo	0.711	0.632	5.724	0.620
W	0.211	0.184	1.476	0.178
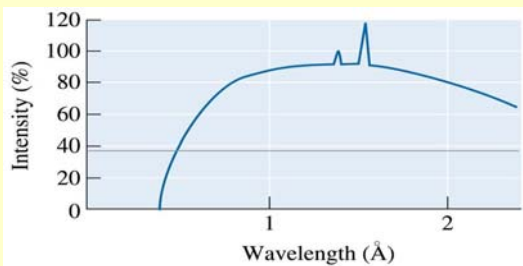
Figure 20.24 Intensity of the initial spectrum from a copper x-ray source before filtering (for Problem 20.43).
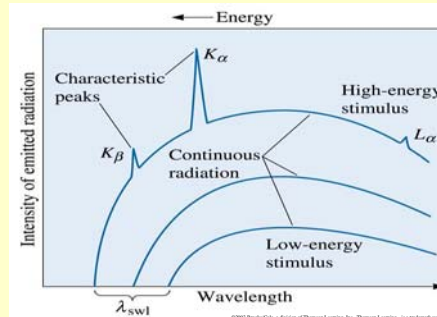

Figure 20.10 The continuous and characteristic spectra of radiation emitted from a material. Low-energy stimuli produce a continuous spectrum of low-energy, long-wavelength photons. A more intense, higher energy spectrum is emitted when the stimulus is more powerful until, eventually, characteristic radiation is observed.

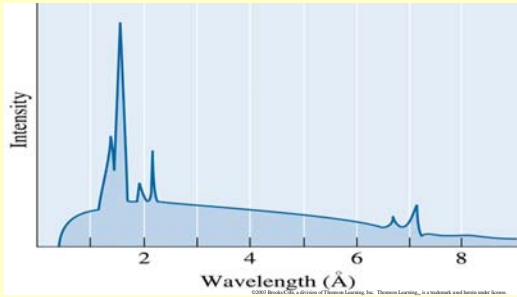## X-ray fluorescence for elemental analysis

Figure 20.22 Results from an x-ray fluorescence analysis of an unknown metal sample (for Problem 20.41).
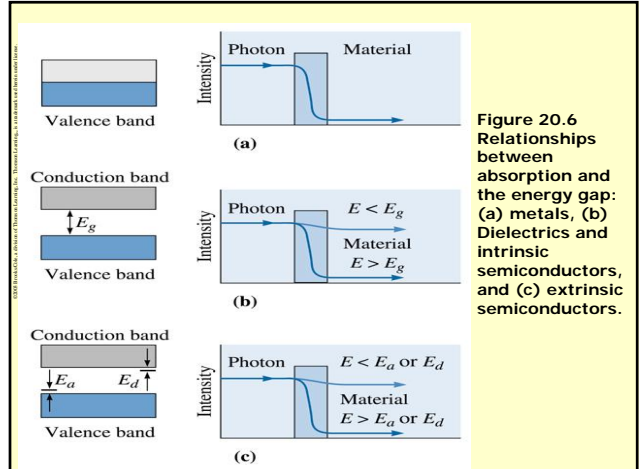

Figure 20.6 Relationships between absorption and the energy gap: (a) metals, (b) Dielectrics and intrinsic semiconductors, and (c) extrinsic semiconductors.
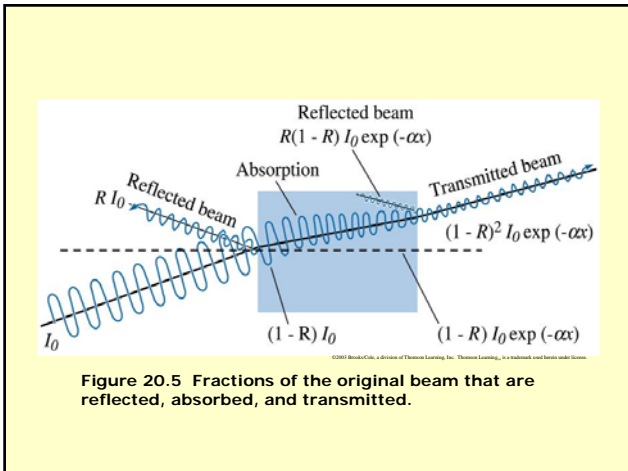

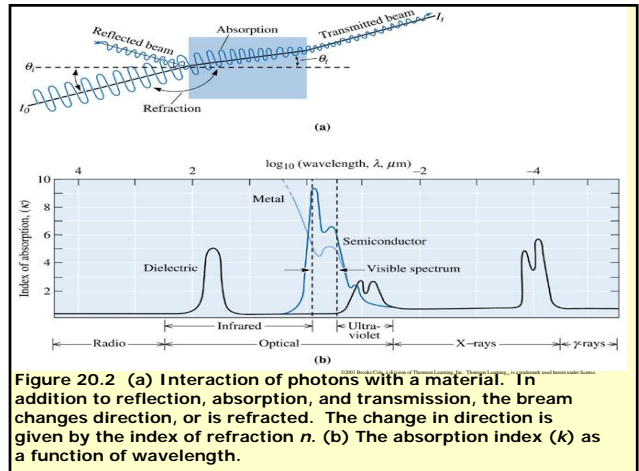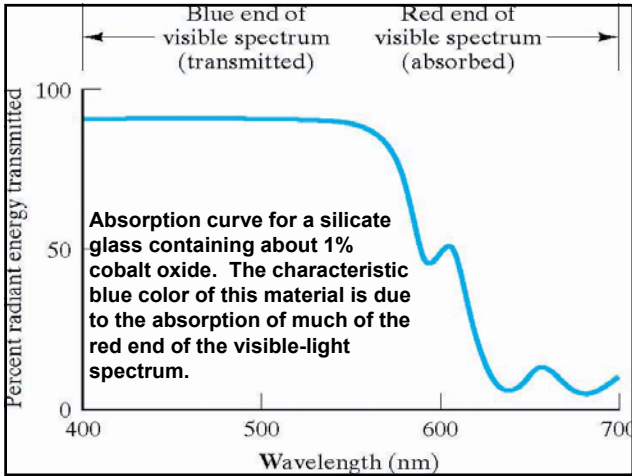Figure 20.5 Fractions of the original beam that are reflected, absorbed, and transmitted.

Figure 20.2 (a) Interaction of photons with a material. In addition to reflection, absorption, and transmission, the bream changes direction, or is refracted. The change in direction is given by the index of refraction n. (b) The absorption index (k) as a function of wavelength.
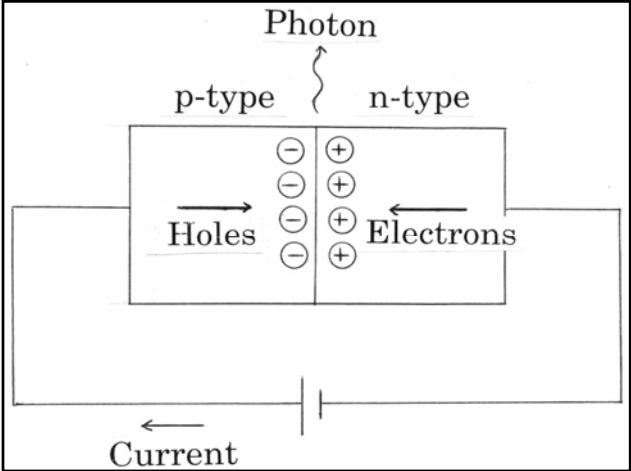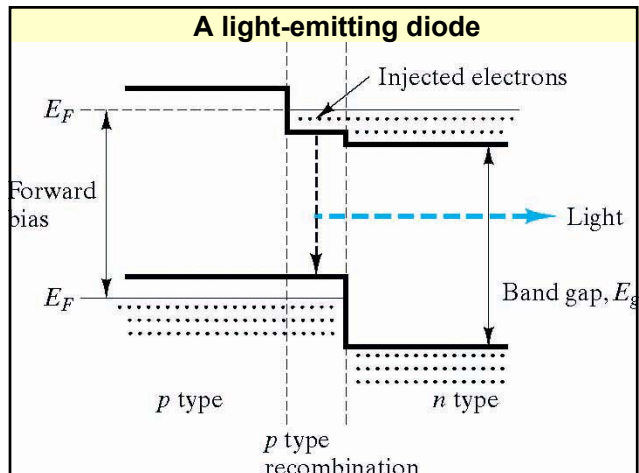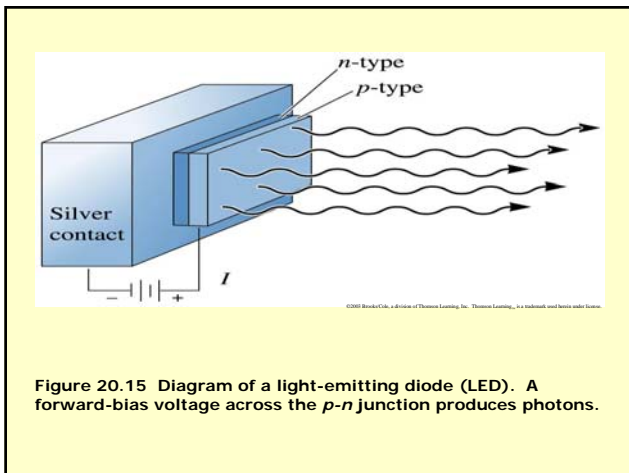
Absorption curve for a silicate glass containing about 1% cobalt oxide. The characteristic blue color of this material is due to the absorption of much of the red end of the visible-light spectrum.
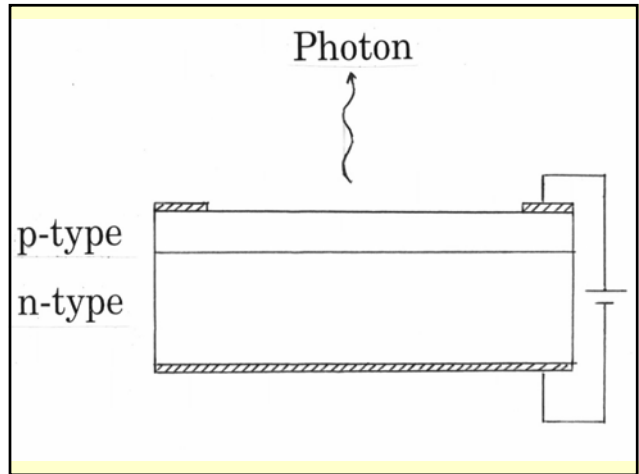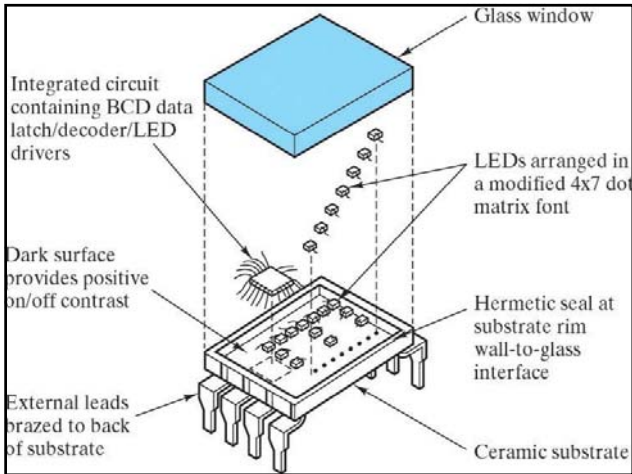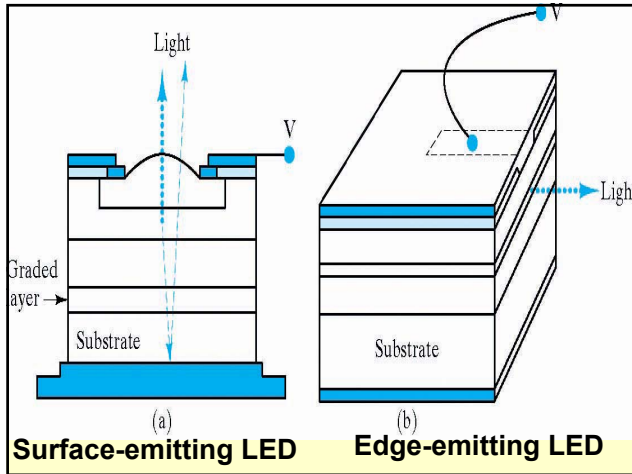
Electroluminescence

Use of an applied electrical signal to stimulate photons from a material.

Light-emitting diode (LED)

**pn-junction
under forward bias**

Glass window

Integrated circuit containing BCD data latch/decoder/LED drivers

LEDs arranged in a modified 4x7 dot matrix font

Dark surface provides positive on/off contrast

Hermetic seal at substrate rim wall-to-glass interface

External leads brazed to back of substrate

Ceramic substrate

Photon

p-type

n-type

Figure 20.15 Diagram of a light-emitting diode (LED). A forward-bias voltage across the *p-n* junction produces photons.

n-type
p-type
Silver contact
I

A light-emitting diode

E_F

Injected electrons

Forward bias

E_F

Light

Band gap, E_g

p type

n type

p type recombination

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Surface-emitting LED (a) **Edge-emitting LED** (b)

Compound	Wavelength (nm)	Color
GaP	565	Green
GaAsP	590	Yellow
GaAsP	632	Orange
GaAsP	649	Red
GaAlAs	850	Near IR
GaAs	940	Near IR
InGaAs	1,060	Near IR
InGaAsP	1,300	Near IR
InGaAsP	1,550	Near IR

[a] From R. C. Dorf, *Engineering Handbook*, CRC Press, Boca Raton, FL, 1993, p. 751.

Table 20.8
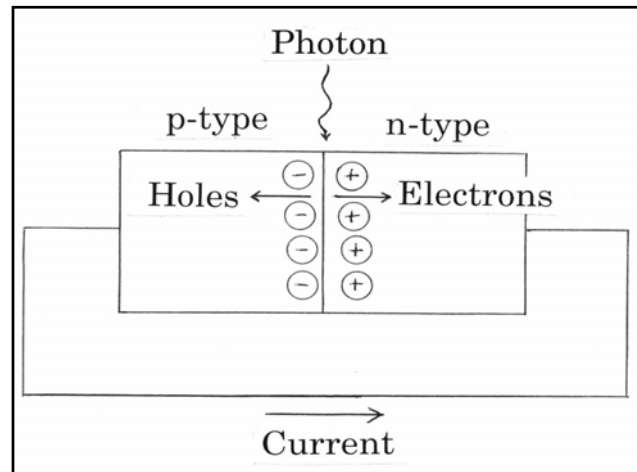*Common Light-Emitting Diode Compounds and Wavelengths*[a].
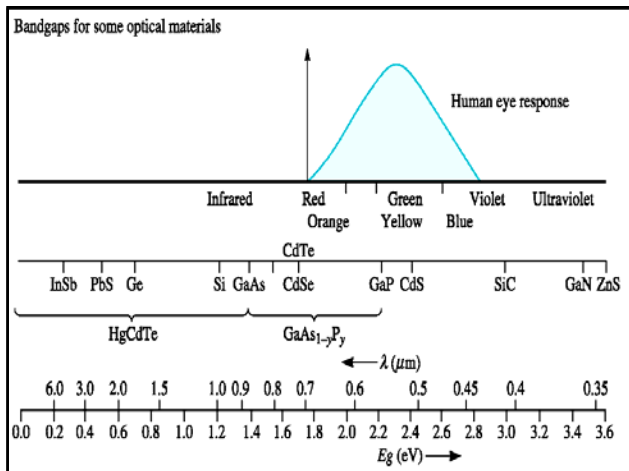
Photonic bandgap materials

These are structures produced using micromachined silicon or colloidal particles, such that there is a range of frequencies that cannot be transmitted through the structure.

Solar cell

**Short-circuited
pn-junction**

Photon

p-type   n-type

Holes ← ⊖ ⊕ → Electrons
      ⊖ ⊕
      ⊖ ⊕
      ⊖ ⊕

→
Current

Laser

**The acronym stands for light
amplification by stimulated
emission of radiation. A beam of
monochromatic coherent radiation
produced by the controlled
emission of photons.**

Characteristics of
a laser beam

- **Parallel (not diverging)**
- **Nearly monochromatic**
- **Coherent**

Nearly monochromatic

- Of nearly one wavelength
- Frequency bandwidth (range of frequencies) is narrow.
- He-Ne laser: bandwidth 10^4 Hz
- Gas discharge tubes: bandwidth 10^9 Hz
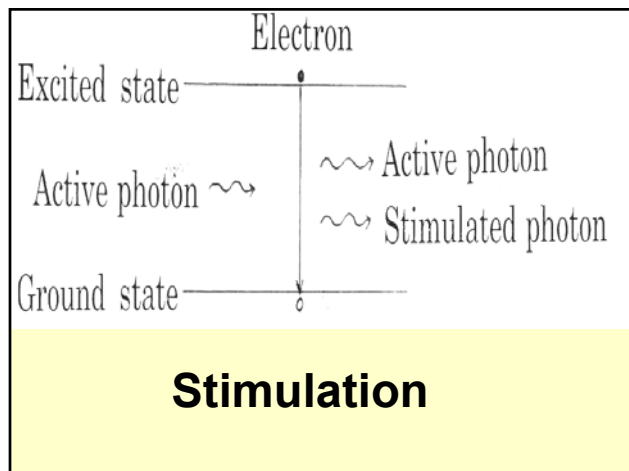- White light: bandwidth 3×10^{14} Hz

Coherence

Any two points in the laser beam having a predictable phase relationship

Condition for coherence

$$\Delta\upsilon \, \Delta t \ll 1$$

$$\Delta x = c\Delta t$$
$$\Delta x \ll c/\Delta\upsilon = \text{coherence length}$$

Stimulation

He-Ne laser

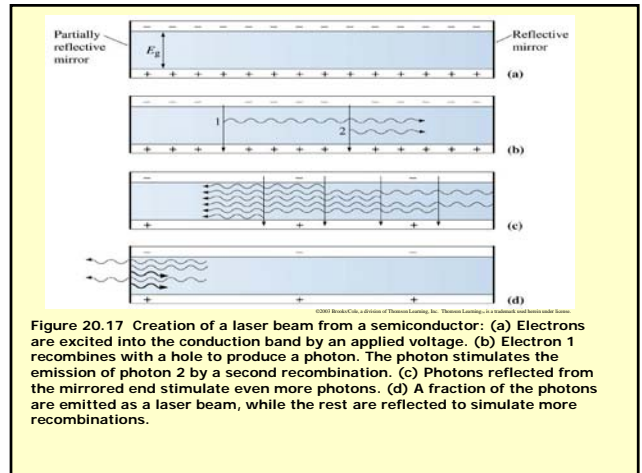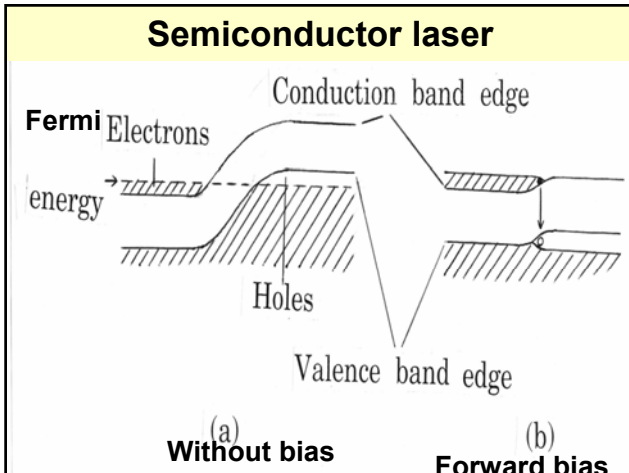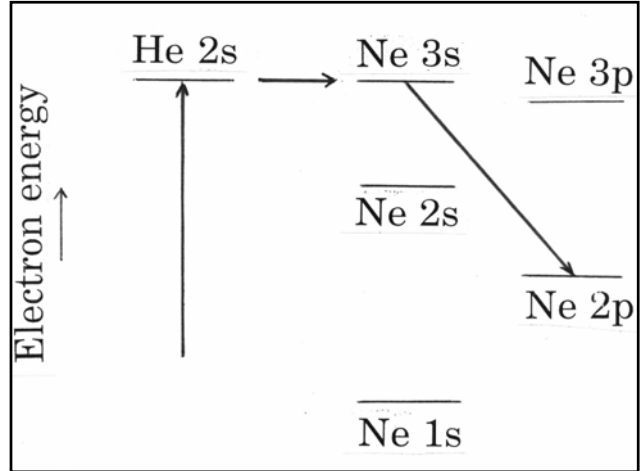**Semiconductor laser**

Without bias

Forward bias
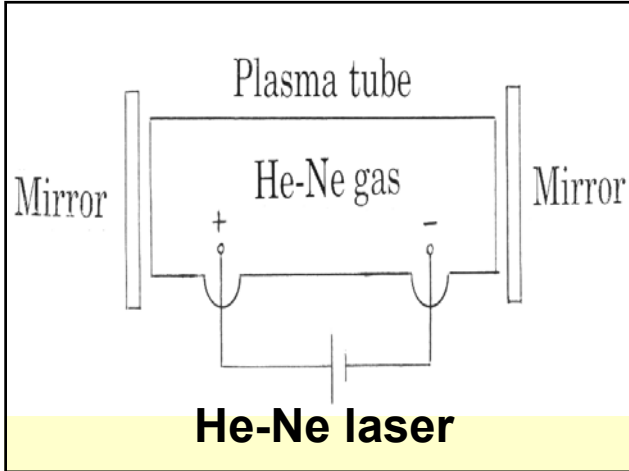
Figure 20.17 Creation of a laser beam from a semiconductor: (a) Electrons are excited into the conduction band by an applied voltage. (b) Electron 1 recombines with a hole to produce a photon. The photon stimulates the emission of photon 2 by a second recombination. (c) Photons reflected from the mirrored end stimulate even more photons. (d) A fraction of the photons are emitted as a laser beam, while the rest are reflected to simulate more recombinations.
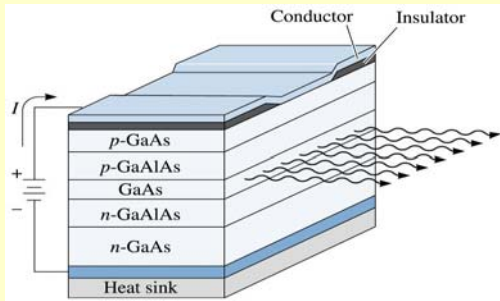
Figure 20.18 Schematic cross-section of a GaAs laser. Because the surrounding *p*- and n-type GaAlAs layers have a higher energy gap and a lower index of refraction than GaAs, the photons are trapped in the active GaAs layer.

Solid-state lasers

- **Ruby laser (single crystal Al_2O_3 doped with a small amount of Cr_2O_3) –emits at 6943 Å**
- **Yttrium aluminium garnet ($Y_3Al_5O_{12}$ YAG) doped with neodymium (Nd) – emits at 1.06 µm**
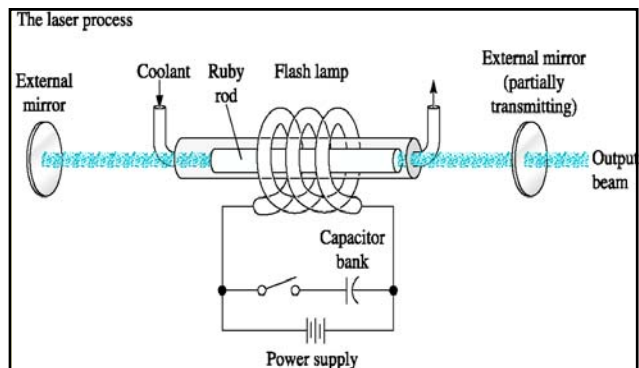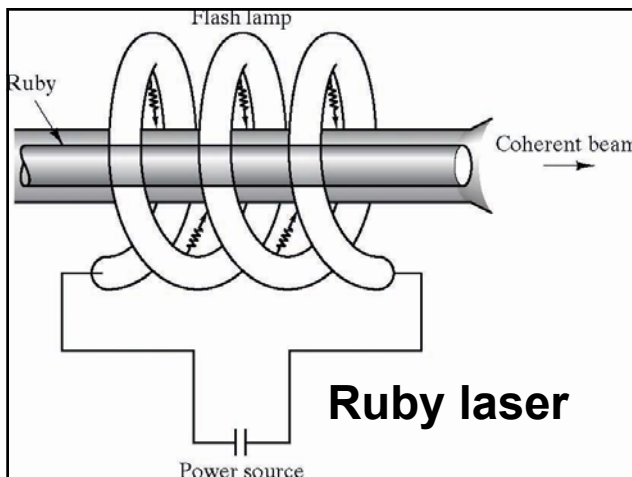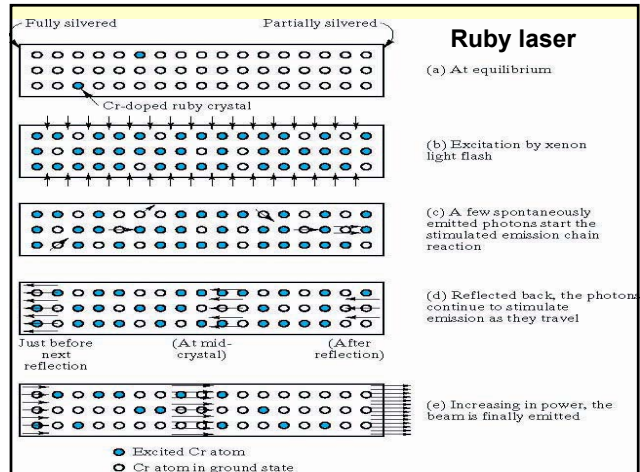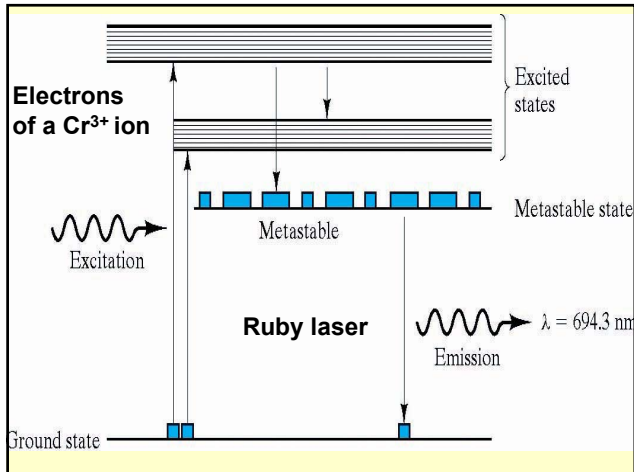

Ruby laser

Figure 20.16 The laser converts a stimulus into a beam of coherent photons. The mirror on one side is 100% reflecting, the mirror on the right transmits partially. (*Source: From* Optical Materials: An Introduction to Selection and Application, *by S. Musikant, p. 201, Fig. 10-1. Copyright © 1985 Marcel Dekker, Inc.*)

Electrons of a Cr³⁺ ion

Excited states

Metastable state

Metastable

Excitation

Ruby laser

Emission

$\lambda = 694.3$ nm

Ground state

Ruby laser

Fully silvered — Partially silvered

(a) At equilibrium

Cr-doped ruby crystal

(b) Excitation by xenon light flash

(c) A few spontaneously emitted photons start the stimulated emission chain reaction

(d) Reflected back, the photons continue to stimulate emission as they travel

Just before next reflection | (At mid-crystal) | (After reflection)

(e) Increasing in power, the beam is finally emitted

● Excited Cr atom
○ Cr atom in ground state

Laser	Wavelengths (μm)	Output Type and Power
Gas		
He–Ne	0.5435–3.39	CW,[a] 1–50 mW
Liquid		
Dye	0.37–1.0	CW,[a] to a few watts
Dye	0.32–1.0	Pulsed, to tens of watts
Glass		
Nd–silicate	1.061	Pulsed, to 100 W
Solid-state		
Ruby	0.694	Pulsed, to a few watts
Semiconductor		
InGaAsP	1.2–1.6	CW,[a] to 100 mW

Source: Data from J. Hecht, in *Electrical Engineering Handbook*, R. Dorf, Ed., CRC Press, Boca Raton, FL, 1993.

[a] CW = continuous wave

Thermal emission

Emission of photons from a material due to excitation of the material by heat.

Figure 20.19 Intensity in relation to wavelengths of photons emitted thermally from a material. As the temperature increases, more photons are emitted from the visible spectrum.

Unique structural configuration of liquid crystal polymers

Use of a "one-quarter-wavelength" thick coating minimizes surface reflectivity. The coating has an intermediate index of refraction, and the primary reflected wave is just cancelled by the secondary reflected wave of equal magnitude and opposite phase. Such coatings are commonly used on microscope lenses.