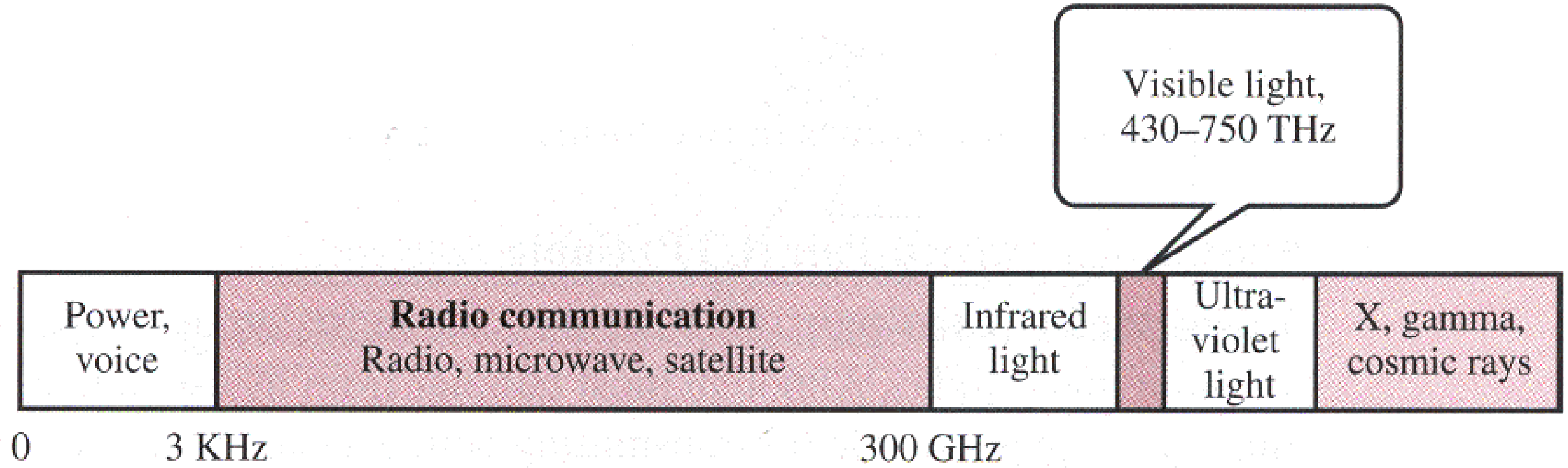
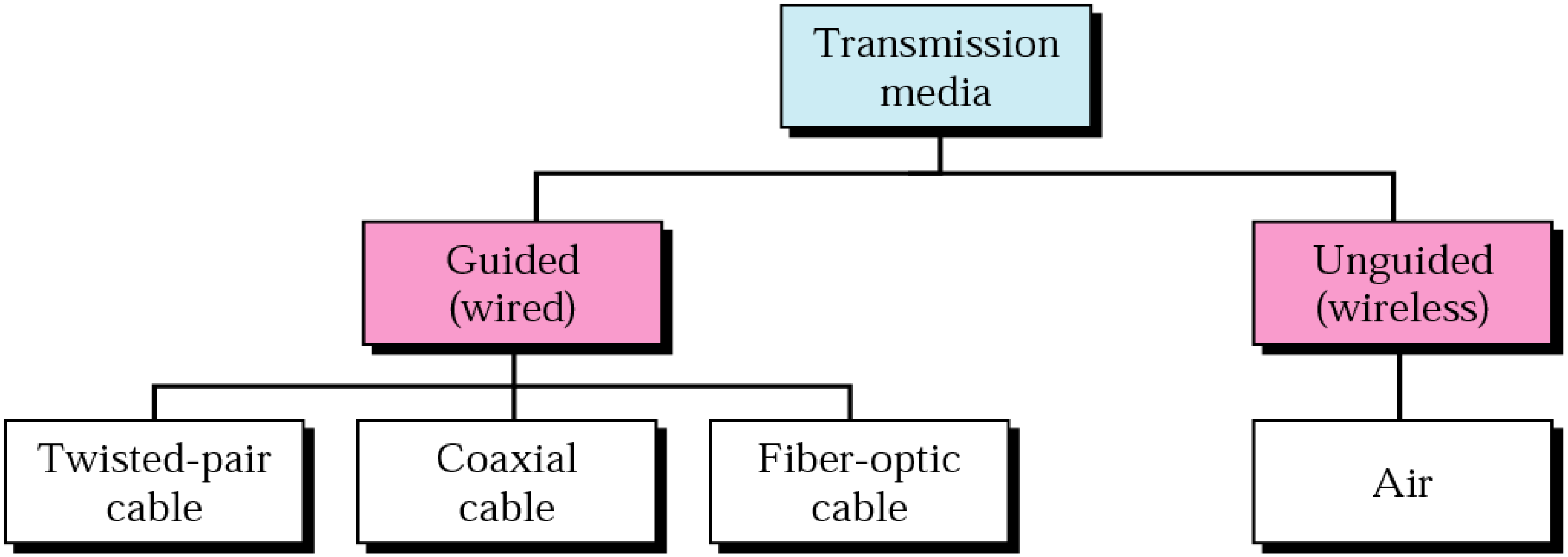
Transmission Media



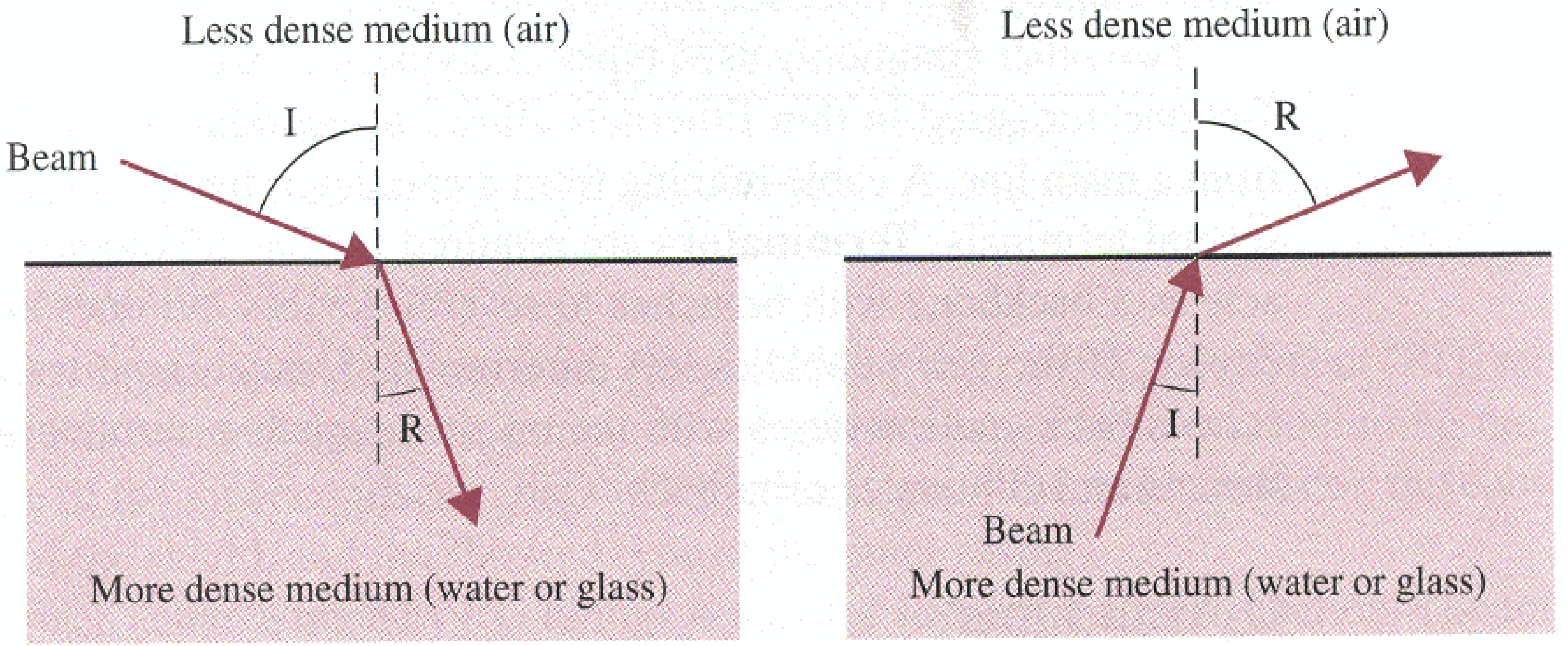
Not all portion of the spectrum are currently usable for telecommunications

Each portion of the spectrum requires a particular transmission medium

Classes of transmission media



Refraction



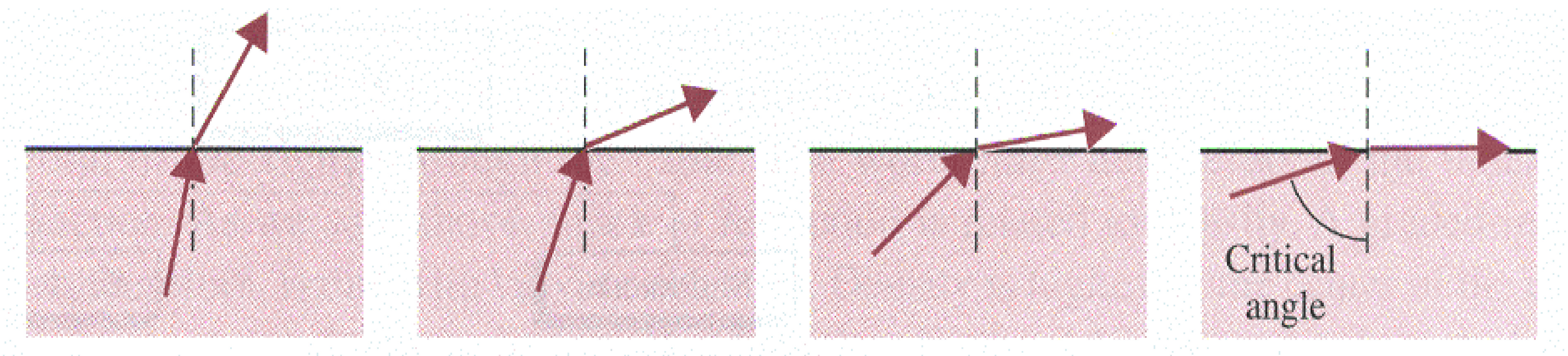
a. From less dense to more dense medium

b. From more dense to less dense medium

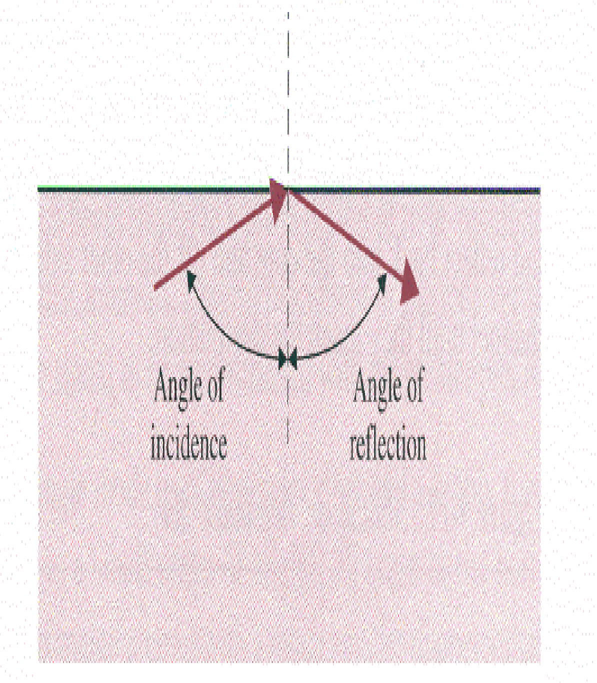
Critical angle

If the angle of incidence increases, so does the angle of refraction

The critical angle is defined to be an angle of incidence for which the angle of refraction is 90 degrees



Reflection



When the angle of incidence becomes greater than the critical angle, a new phenomenon occurs called **reflection**

Light no longer passes into the less dense medium at all

What are Fiber Optics?

Fiber optics (optical fibers) are long, thin strands of very pure glass about the diameter of a human hair. They are arranged in bundles called optical cables and used to transmit light signals over long distances

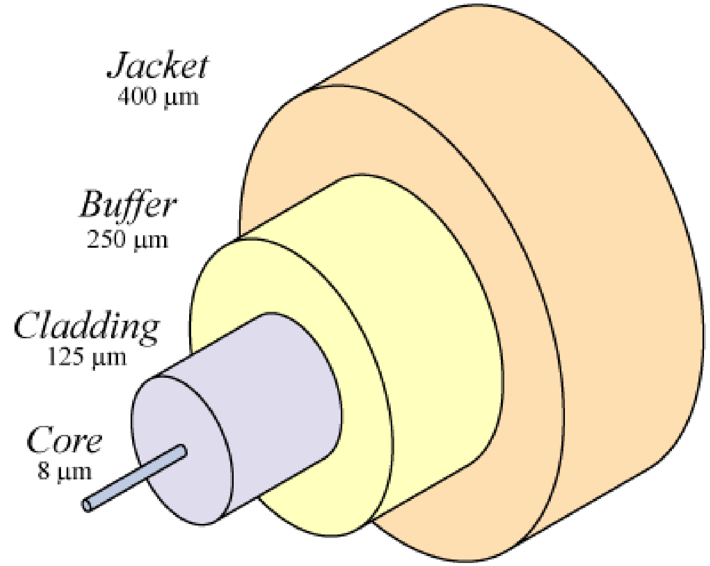
Configurations:

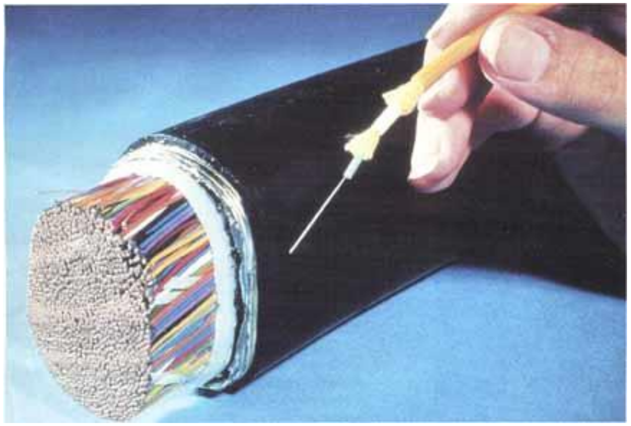
Core

Cladding

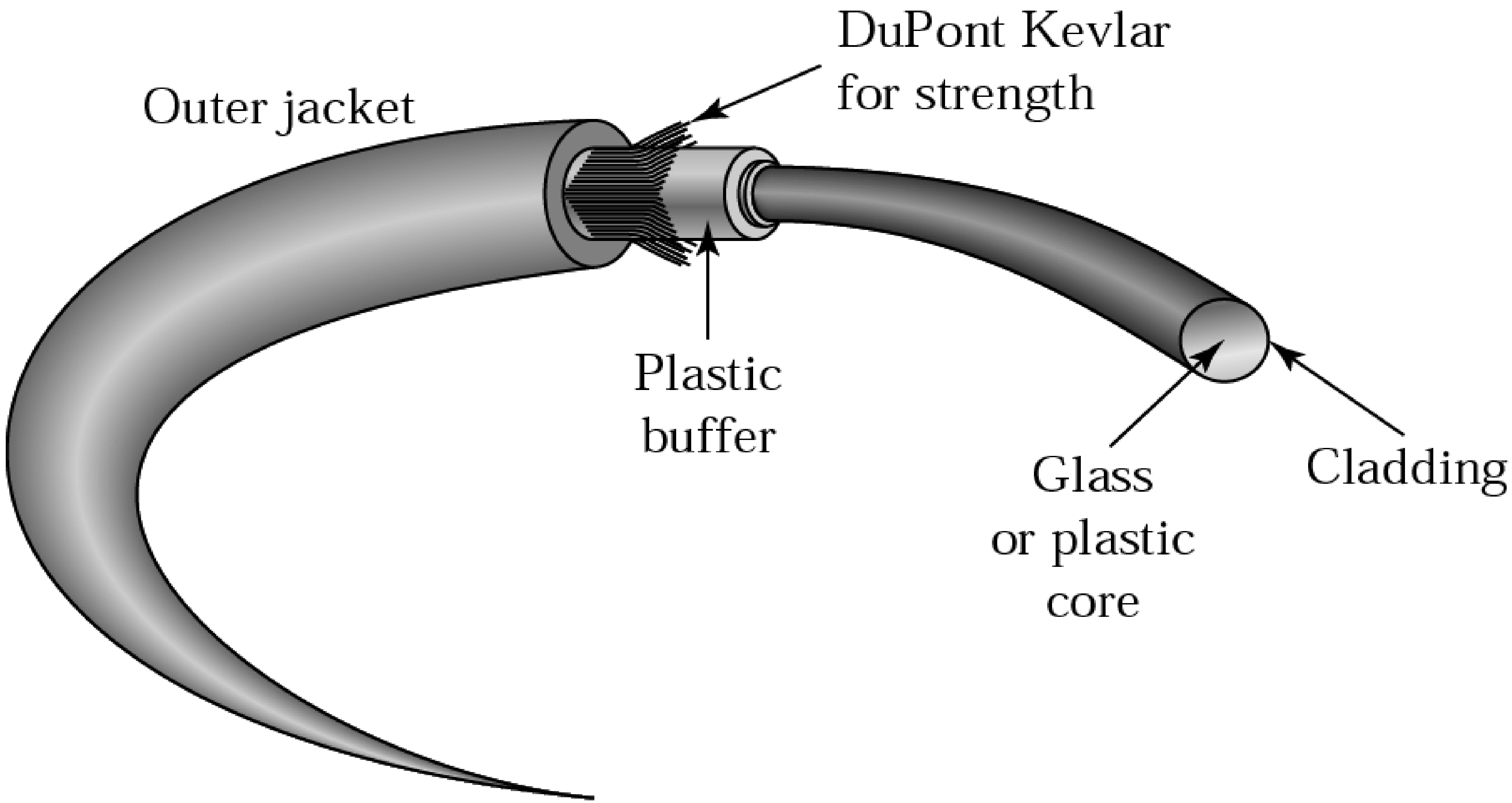
Buffer coating

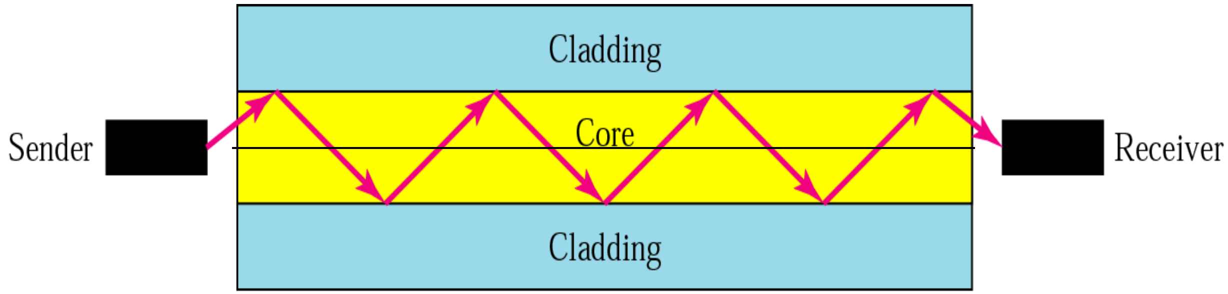
Jacket





Fiber construction

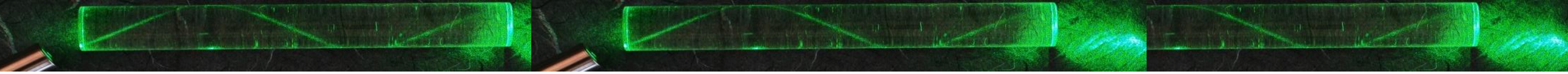


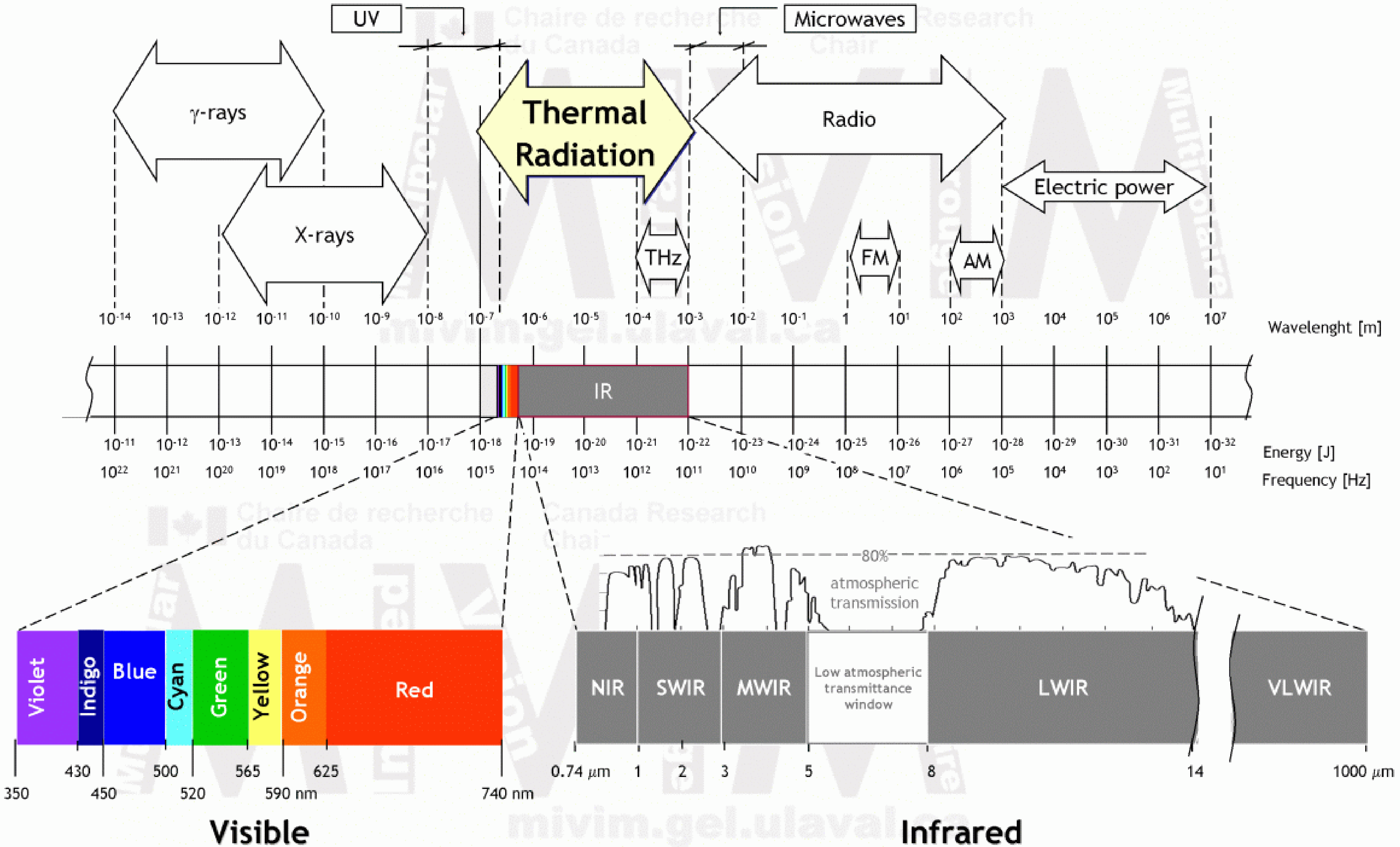


Optical fibers use **reflection to guide light** through a channel.

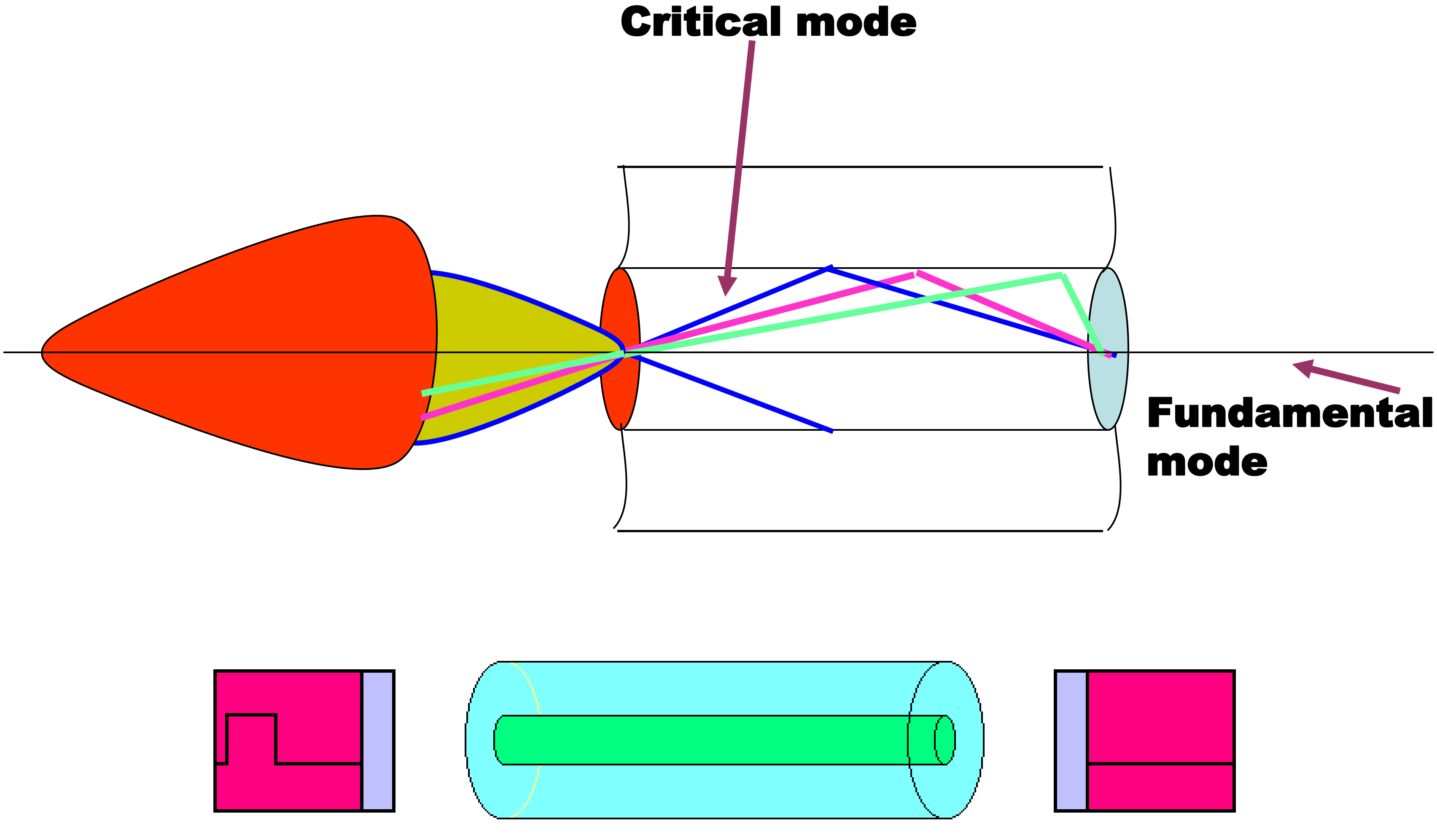
A glass or core is surrounded by a cladding of less dense glass or plastic. The difference in density of the two materials must be such that a beam of light moving through the core is reflected off the cladding instead of being into it.

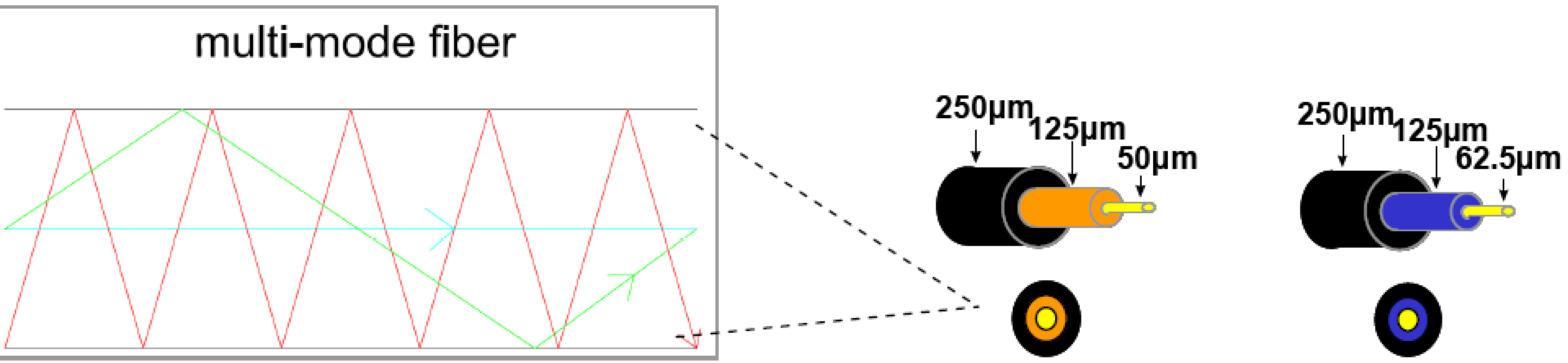
Information is encoded onto a beam of light as a series of on-off flashes that represent 1 and 0 bits.

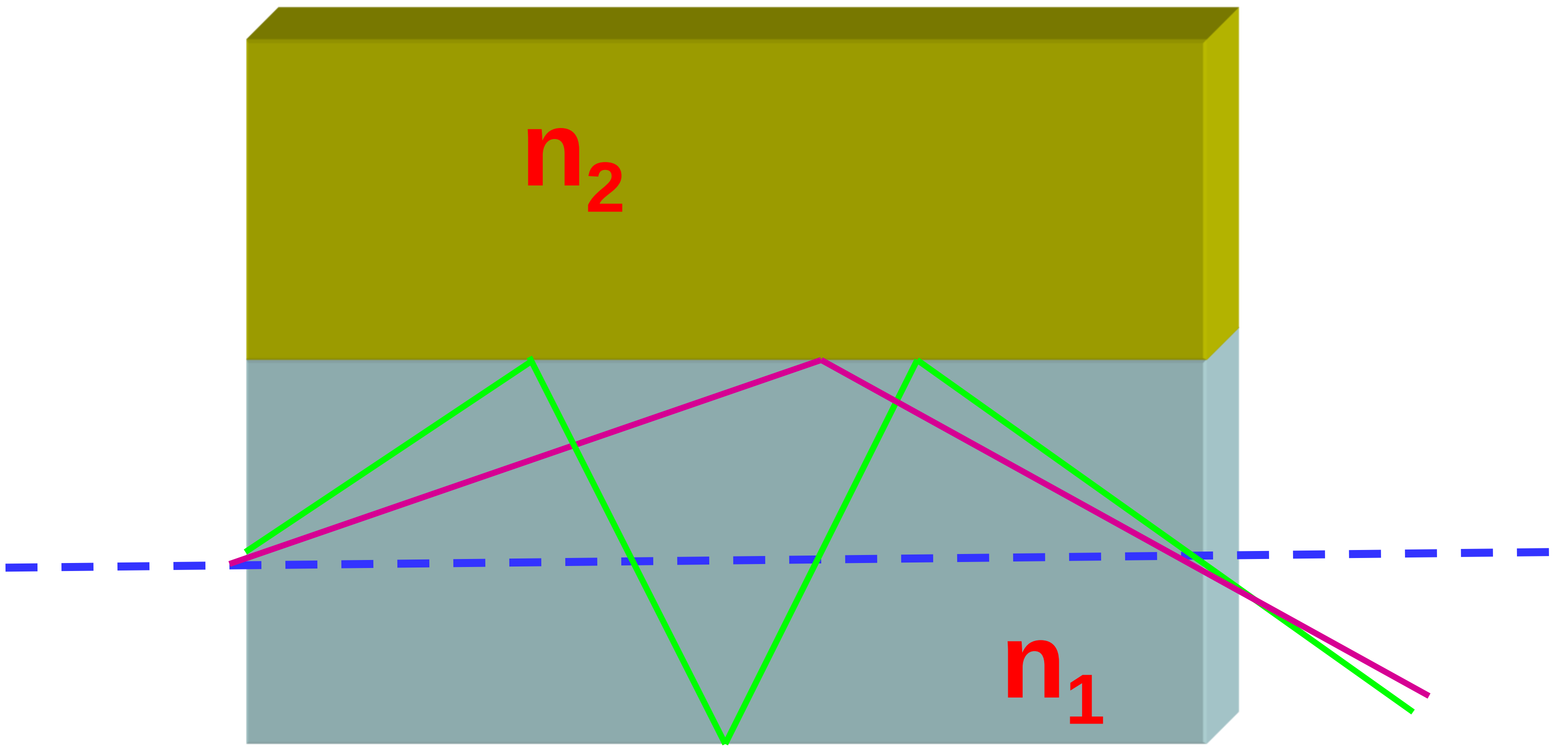



UV
Microwaves
γ-rays
Thermal Radiation
Radio
X-rays
Electric power
THz
FM
AM
10-14 10-13 10-12 10-11 10-10 10-9 10-8 10-7 10-6 10-5 10-4 10-3 10-2 10-1 1 10¹ 10² 10³ 10⁴ 10⁵ 10⁶ 10⁷
Wavelenght [m]
IR
10-11 10-12 10-13 10-14 10-15 10-16 10-17 10-18 10-19 10-20 10-21 10-22 10-23 10-24 10-25 10-26 10-27 10-28 10-29 10-30 10-31 10-32
Energy [J]
10²² 10²¹ 10²⁰ 10¹⁹ 10¹⁸ 10¹⁷ 10¹⁶ 10¹⁵ 10¹⁴ 10¹³ 10¹² 10¹¹ 10¹⁰ 10⁹ 10⁸ 10⁷ 10⁶ 10⁵ 10⁴ 10³ 10² 10¹
Frequency [Hz]
80%
atmospheric transmission
Violet
Indigo
Blue
Cyan
Green
Yellow
Orange
Red
NIR
SWIR
MWIR
Low atmospheric transmittance window
LWIR
VLWIR
350 430 450 500 520 565 590 nm 625 740 nm
0.74 µm 1 2 3 5 8 14 1000 µm
Visible
Infrared

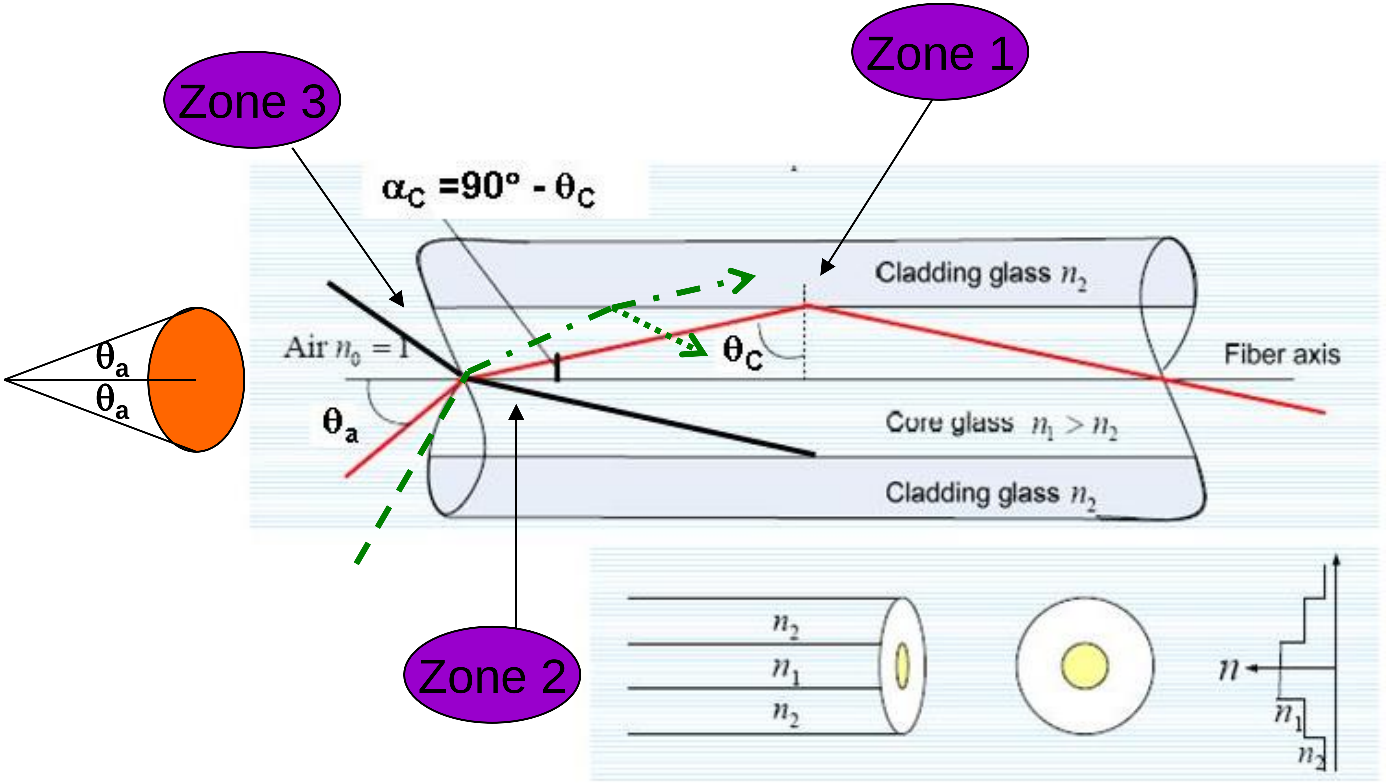
Concept of Modes in Fiber




multi-mode fiber
250μm
125μm
50μm
250μm
125μm
62.5μm


n_2
n_1

Conditions for light propagation in fiber



θ_C = Critical angle of incidence

α_C = Critical propagation angle

θ_a = Acceptance angle

θ_C or more
α_C or less
θ_a or less

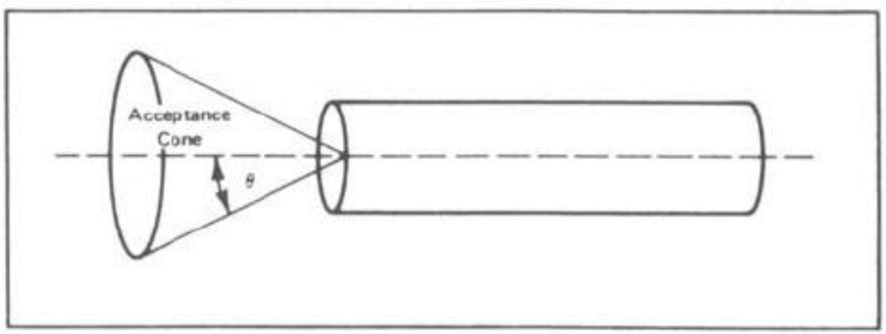
$\theta_C >> \theta_a > \alpha_C$

Conditions for light propagation in fiber

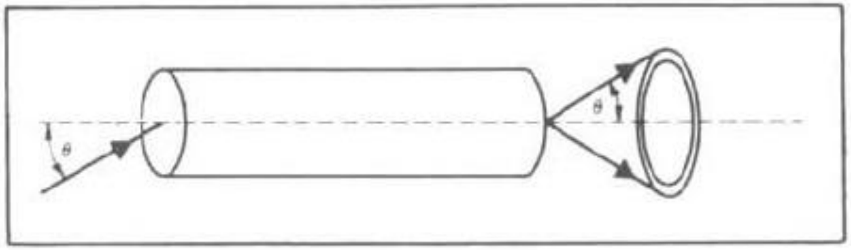
$$\mathbf{NA} = \mathbf{Sin}\ \theta_a = \sqrt{n_1^2 - n_2^2}$$

Relative index parameter (Δ) = $(n_1 - n_2)/n$

$$\mathbf{NA} = n_1 \sqrt{(2\Delta)} \qquad n_1 \cong n_2, \text{ but } n_1^2 \neq n_2^2$$



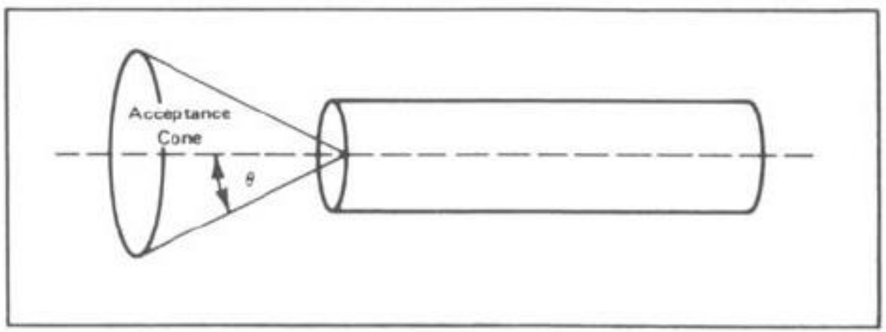
The light-gathering power or flux-carrying capacity of a fiber is numerically equal to the **square of the numerical aperture**



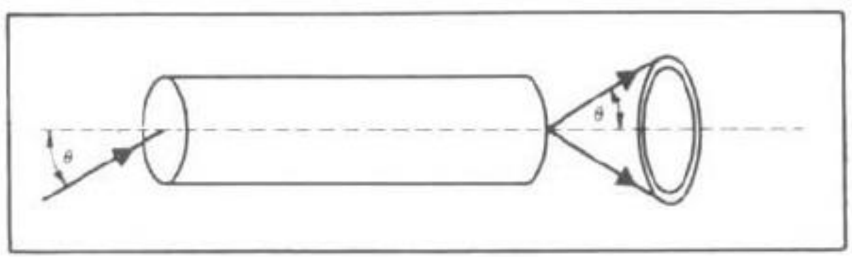
What is numerical aperture?

If a cone of light is incident on one end of the fiber, it will be guided through this fiber provided the half-angle of the cone is less than θ_a.

This half-angle is a measure of the light-gathering power of the fiber and is called NUMERICAL APERTURE



The light-gathering power or flux-carrying capacity of a fiber is numerically equal to the **square of the numerical aperture**



Transmission constraints

Linear

Attenuation

Mode **Dispersion**, if applicable

Chromatic Dispersion

Polarization-Mode Dispersion, PMD

Non-linear

Self-Phase Modulation, SPM

Cross-Phase Modulation,

XPM

Four-Wave Mixing, FWM

Stimulated Raman-

Scattering, SRS

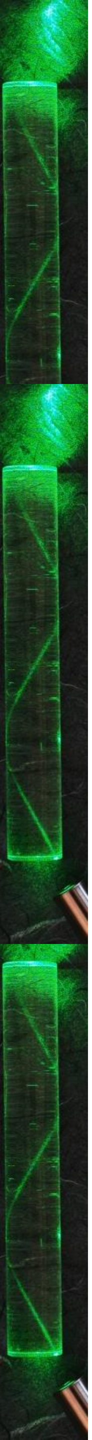
Stimulated Brillouin- Scattering, SBS

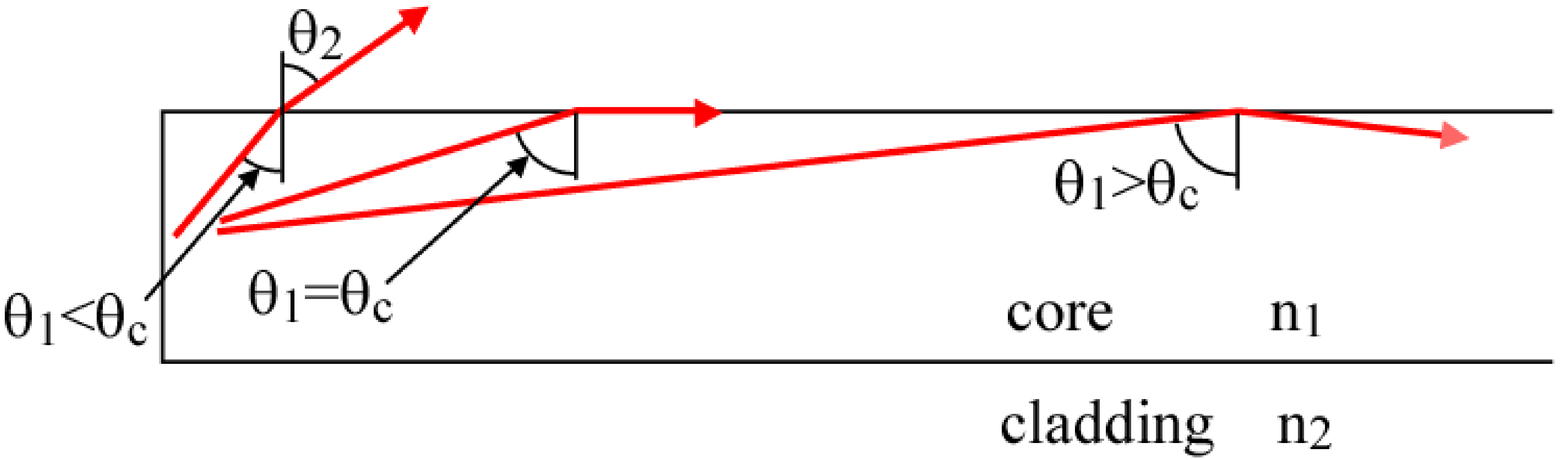
stimulated Brillouin scattering (SBS), stimulated Raman scattering (SRS), four wave mixing (FWM), self-phase modulation (SPM), cross-phase modulation (XPM), and intermodulation. Fiber nonlinearities represent the fundamental limiting mechanisms to the amount of data that can be transmitted on a single optic fiber

Dispersion

Dispersion is the spreading of light pulse as it travels down the length of an optical fiber. It basically limits the information carrying capacity. There are three types of dispersions

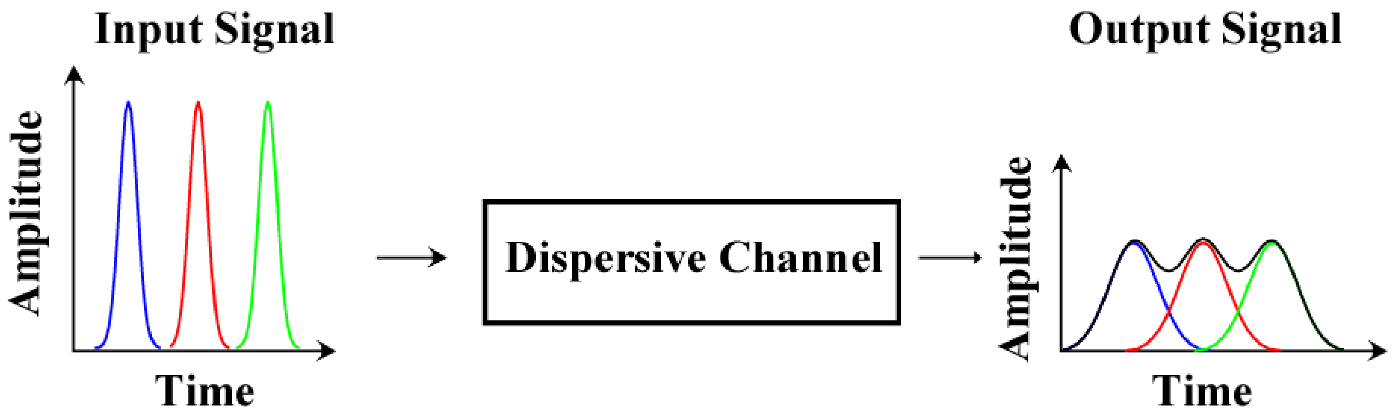
The different modes of the optical pulse with different propagation angles travel at different paths but at same velocity. They all reach at the receiving end at different times. This ultimately causes pulse widening. This is called modal dispersion.





θ_2
$\theta_1>\theta_c$
$\theta_1<\theta_c$
$\theta_1=\theta_c$
core n_1
cladding n_2

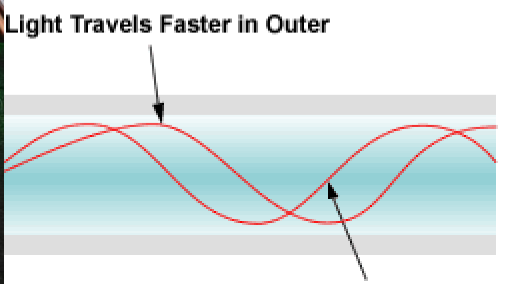
Dispersion



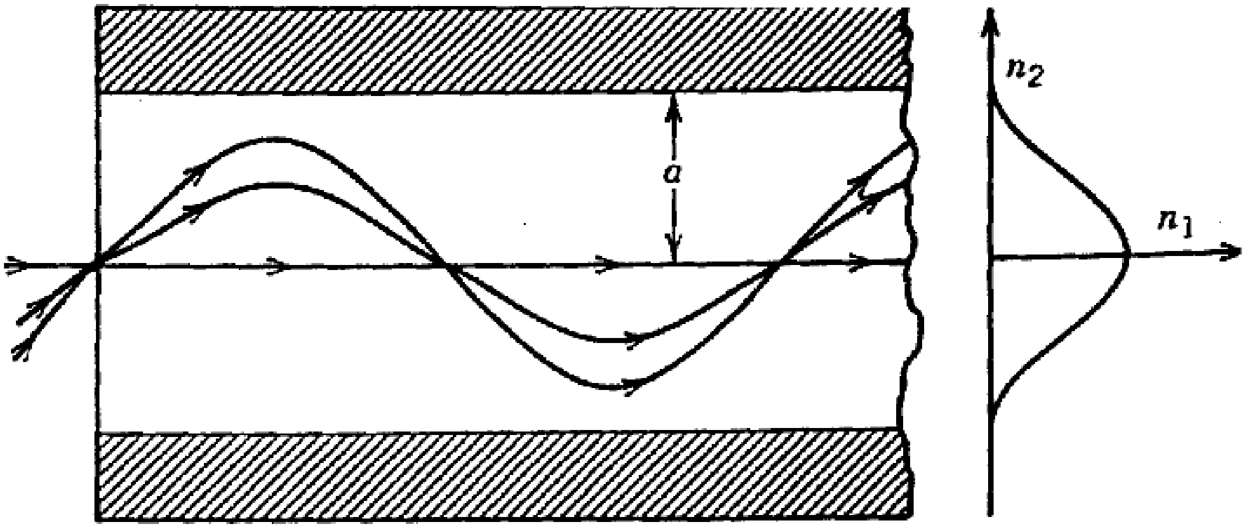
- Dispersive medium: velocity of propagation depends on frequency
- Dispersion causes temporal pulse spreading
  - Pulse overlap results in indistinguishable data
  - Inter symbol interference (ISI)
- Dispersion is related to the velocity of the pulse

Graded Index Multimode Fiber

- Higher order modes
  - Larger propagation length
  - Travel farther towards the cladding
  - Speed increases with distance away from the core (decreasing index of refraction)
  - Relative difference in propagation speed is less



Graded-Index Multimode Fiber



Intermodal Dispersion

In **multimode step index** fiber we derived the time delay between critical mode and fundamental mode

$$\Delta t_d = \frac{Ln_1}{c}\left(\frac{n_1 - n_2}{n}\right) = \left(\frac{Ln_1}{c}\right)\Delta$$

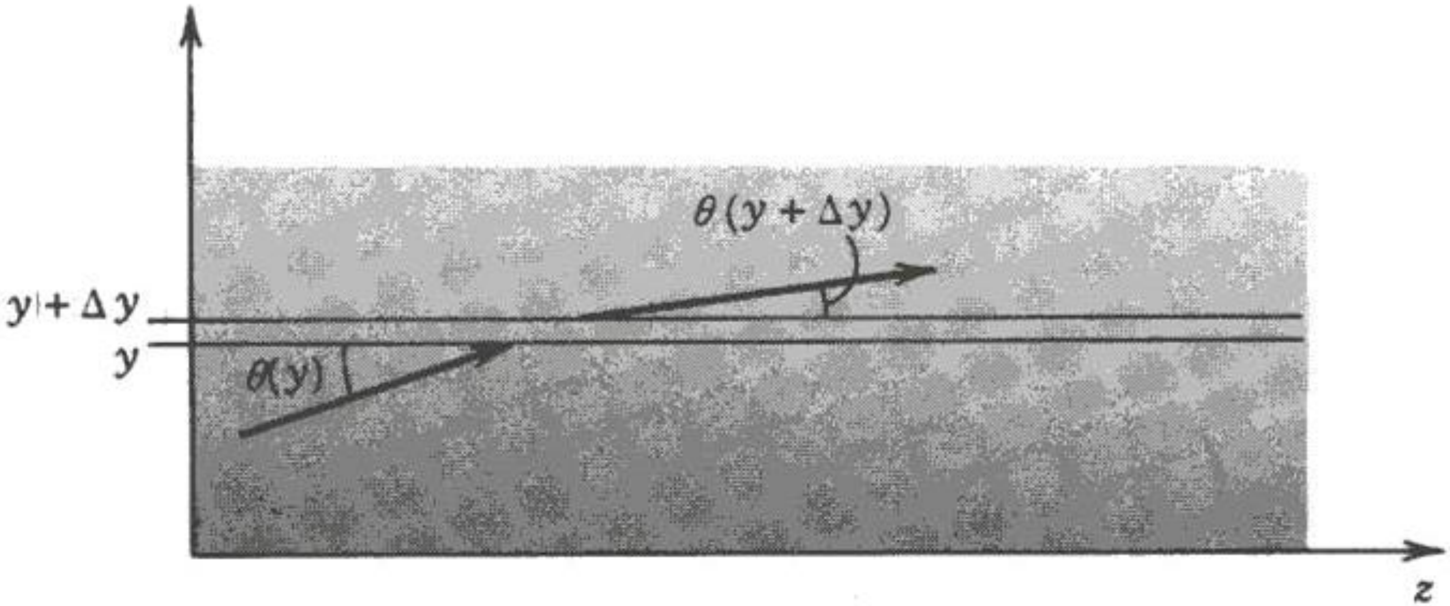
Dispersion is **highest** in this kind of fiber

In **graded or parabolic index** fiber the pulse dispersion i.e., time delay between critical mode and fundamental mode is **reduced to minimum** by varying the refractive index profile maximum to minimum from axis of the fiber to core-cladding boundary. Velocity of light is increased progressively and light in critical mode travel fastest while that in fundamental mode travels slowest. Thus all the rays reach the end at almost same time.

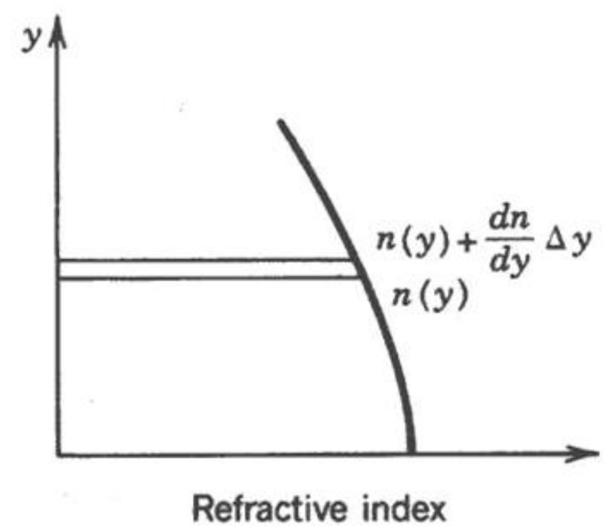
In **single mode** fiber the pulse dispersion (time delay) does not exist due to the fact that only fundamental mode of light transmission is allowed

You must explain all these with appropriate diagrams

Graded Index fiber: Reason for light bending



Graded Index Slab Uniform in X and Z



Single mode fiber

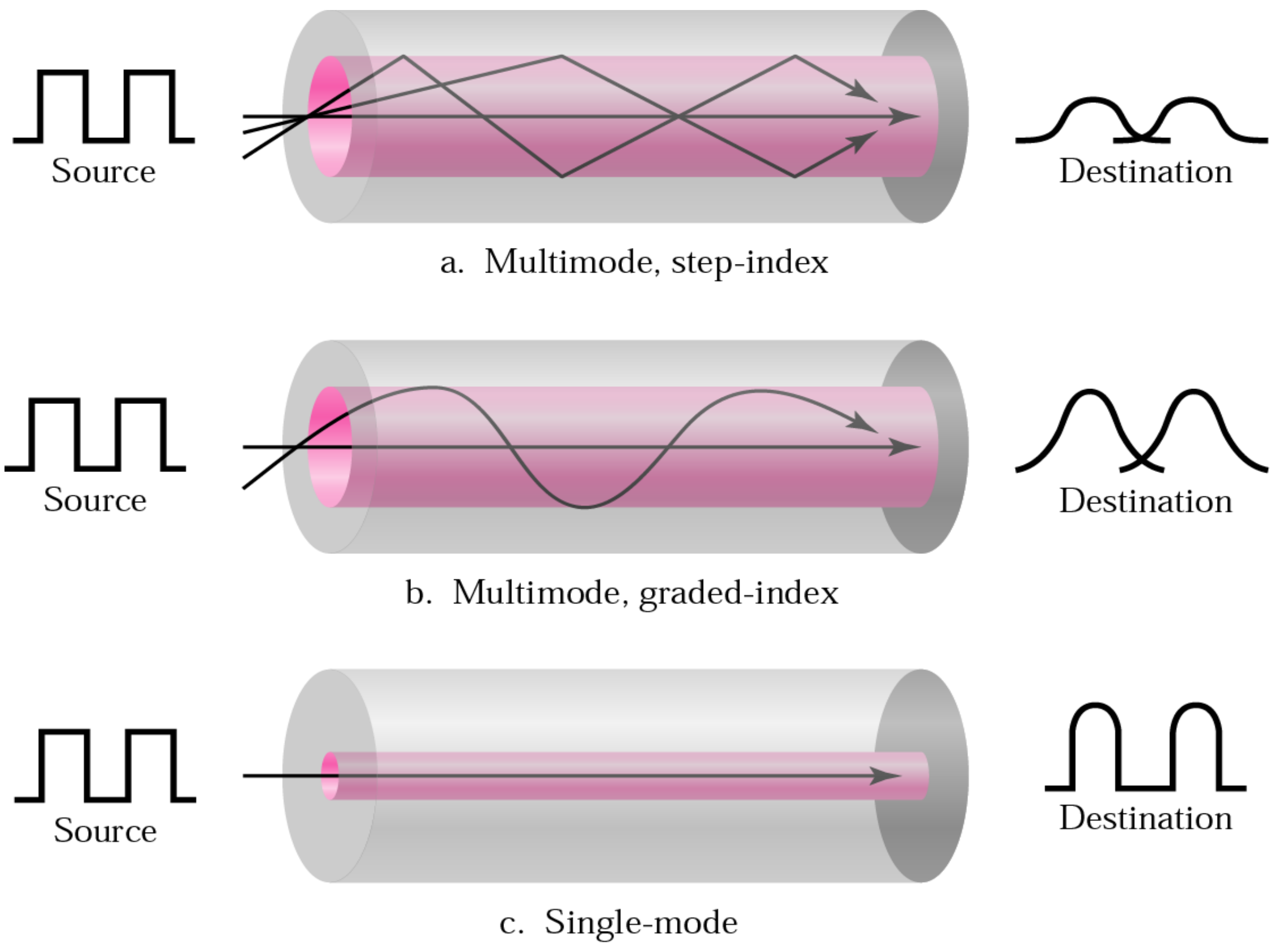
Only fundamental mode of propagation is allowed

Diameter of the core layer is very small ~ 4 μm

But expensive and used in very long distance communication only

V-number decides its quality of transmission

Propagation Modes



Types of Optical Fiber

- **There are two basic types of fiber: multimode fiber and single-mode fiber.**

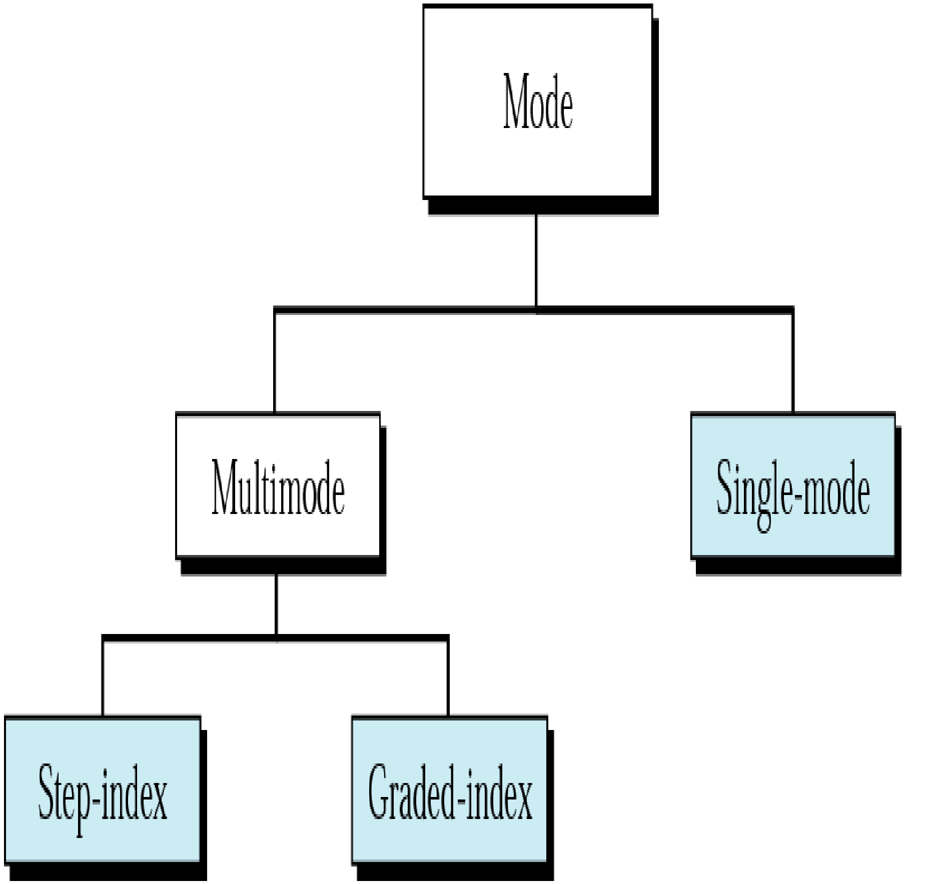
- **Multimode fiber is best designed for short transmission distances, and is suited for use in LAN systems and video surveillance.**

- **Single-mode fiber is best designed for longer transmission distances, making it suitable for long-distance telephony and multichannel television broadcast systems.**

Propagation Modes (Types of Optical Fiber)

- Current technology supports two modes for propagating light along optical channels, each requiring fiber with different physical characteristics: **Multimode and Single Mode.**

- Multimode, in turn, can be implemented in two forms: step-index or graded index.



Intramodal Dispersion

Material dispersion:

Material dispersion is the result of the finite line width of the light source and the dependence of refractive index of the material on wavelength. Material dispersion is a type of chromatic dispersion. Chromatic dispersion is the pulse spreading that arises because the velocity of light through a fiber depends on its wavelength. It reduces the band width of the single mode fiber

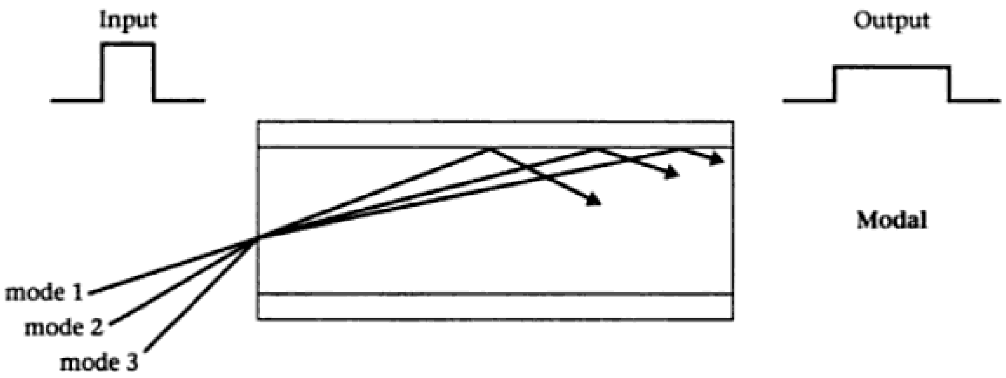
Intramodal Dispersion

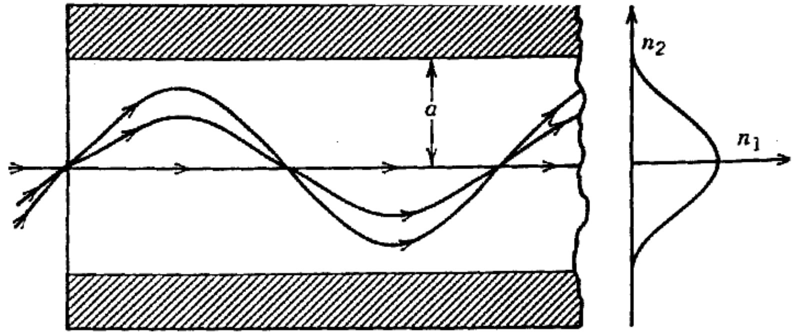
Waveguide dispersion

- Only important in single mode fibers
- The wave optics describes the light propagation
- It is caused by the fact that some light travels in the fiber cladding compared to most light travels in the fiber core. Since the r.i. of cladding is less than that of core, the portion of the light through cladding layer travel at different speed and hence the pulse dispersion occurs
- It is a function of fiber core size, **V-number**, wavelength and light source line width
- Technology can overcome this dispersion

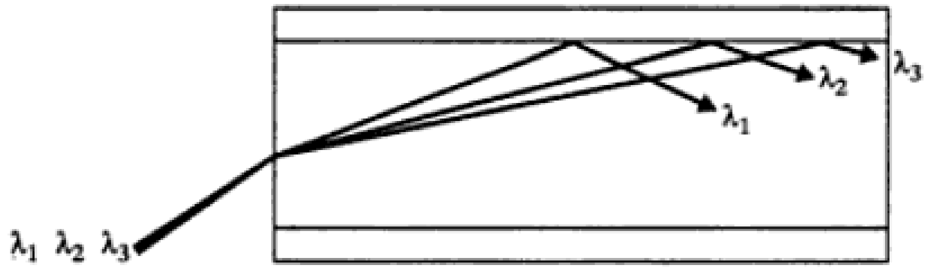
Types of Dispersion

INTERMODAL

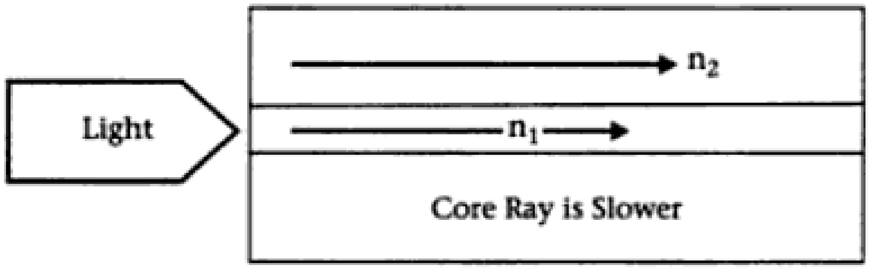




INTRAMODAL



Material



Waveguide

Attenuations

It is the reduction in the transmitted power in Fiber optics.
It has long been a problem for the fiber optics community.
It is measured by dB.

Absorption & scattering

Rayleigh **scattering**

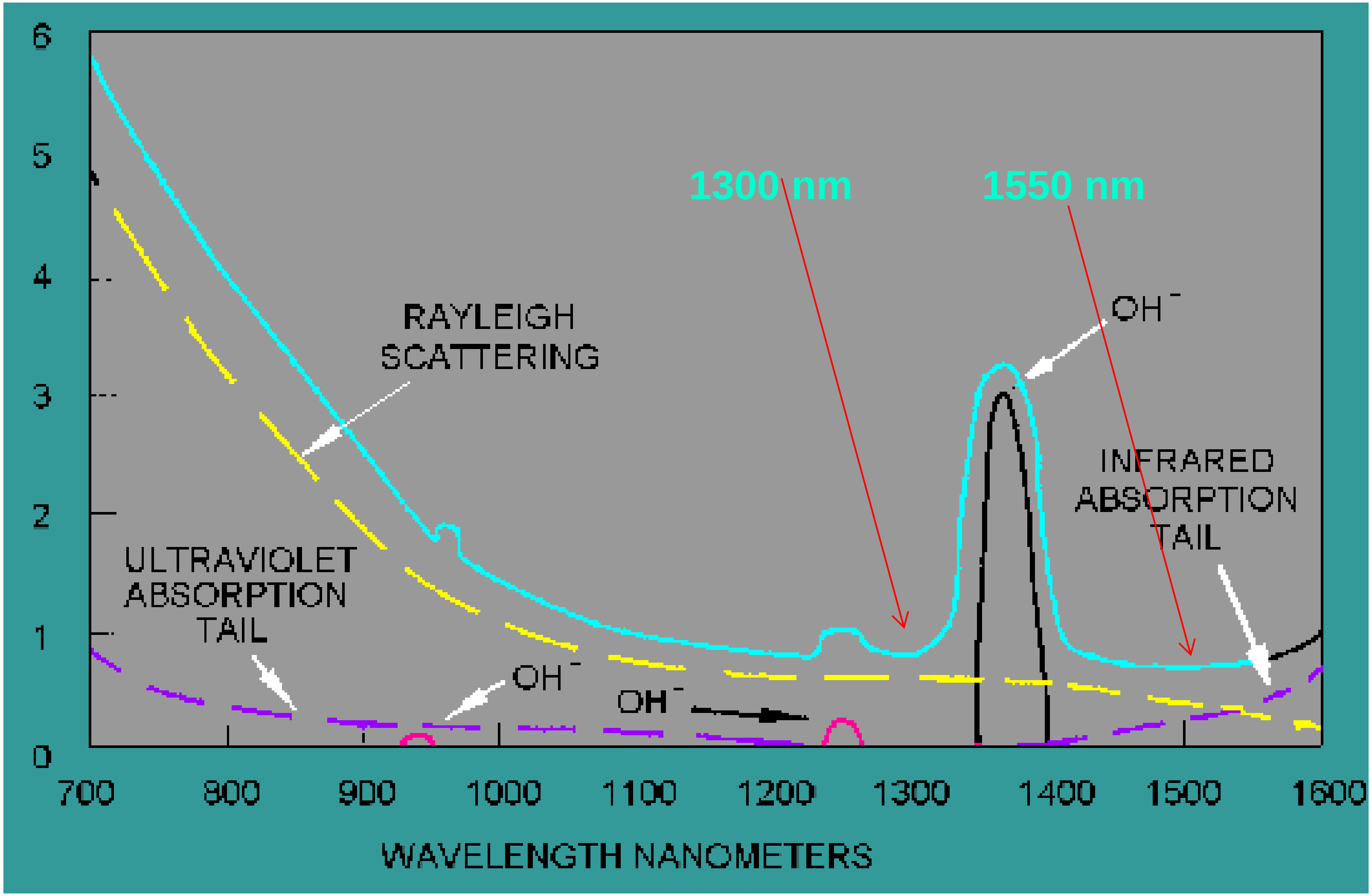
Absorption due to

metallic impurities and **water** in the fiber, and

intrinsic absorption by the **silica molecule** itself

Attenuations

Attenuation can be classified into two types:
(i) Intrinsic losses and (ii) Extrinsic losses



Mechanisms generating intrinsic losses

- Tail of infrared absorption by Si-O coupling—it is present at higher wavelengths around 1400 nm to 1600 nm

- Tail of ultraviolet absorption due to electron transition—it is present at lower wavelengths near 800 nm.

- Rayleigh scattering is due to spatial fluctuation of refractive index and is inversely proportional to λ^4—it produces a maximum loss in the ultraviolet region only

- Absorption by molecular vibration of OH impurity—fundamental absorption due to hydroxyl (OH) ions is present at λ = 2800 nm. But its harmonics occur at wavelengths 1380 nm and 950 nm respectively. This kind of absorption is almost eliminated by the modified best method of fabrication

- Absorption by transition metal impurities like Cr, V, Fe, Mn and Ni—this absorption produces a loss at wavelengths greater than 800 nm. In ultra low loss fibers, this absorption is practically negligible. Scattering is also another loss by metals

- Thus it is found that in the case of pure silica fibers the transmission losses are reduced to a minimum value at **1550 nm wavelength**. At 1300 nm also, the transmission losses are minimum but the net attenuation is slightly greater with respect to the wavelength 1550 nm

Mechanisms generating extrinsic losses:

1. Geometrical non-uniformity at the core-cladding boundary
2. Imperfect connection or alignment between fibers
3. Micro-bending
4. Radiation of leaky modes

Meridional and skew beam

Which crosses the axis of fiber

Which never crosses the axis of fiber

Classification of fiber

Material with which core and cladding layers are made

Low loss (core: glass & cladding: glass)

Medium loss (core: glass & cladding: plastic)

Higher loss (core: plastic & cladding: plastic)

Refractive index profile
Step index, graded or parabolic index fibers

Number of modes of light transmission
Both step index and parabolic index fibers can be single mode or multi mode classes

Home work:
Advantages and disadvantages of multi mode over single mode

Advantages of fiber optics communication

- Enormous potential bandwidth (>Terra b/s)
- The speed of communication is very high due to photon carrying info.
- Small size and weight
- Immunity to interference and crosstalk
- Low transmission loss (0.15 dB/Km)
- System reliability and ease of maintenance (require fewer repeaters)
- Potential low cost
- Electrical isolation
- Signal security
- Ruggedness and flexibility

Applications

Voice
- Telephone trunk
- Subscriber service
- Near power plants
- Along power lines
- Along electric railways
- Field communications

Video
- Broadcast TV
- CATV
- Surveillance
- Remote monitoring
- Fiber-guided missile
- Fiber-to-the-home

Sensors
- Gyroscope
- Hydrophone
- Position
- Temperature
- Electric and magnetic fields

Data
- Computers
- Interoffice data links
- Local-area networks
- Fiber-to-the-home
- Aircraft/ship wiring
- Satellite ground stations

Digital 3

Distinguish between time division multiplexing and wavelength division multiplexing with examples

Hollow core fiber technology and its advantages

Semiconductors and its properties

Semiconductor junctions

Digital submission : n1 and n2

Project presentation on 31 Oct

A photodiode is simple, robust, solid-state, low cost device that:

- does not degrade over time
- requires low voltage for its operation and
- is less susceptible current leak and breakdown
- is not susceptible to shocks, vibration and damage

Photodiodes basics

Principle of operations

Quantum efficiency & Responsivity

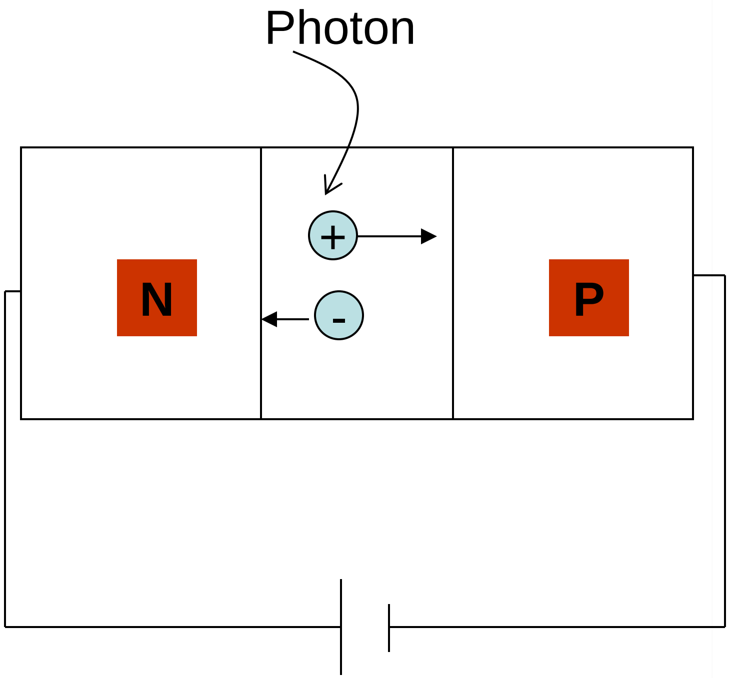
Photodiodes basics

Most important requirements

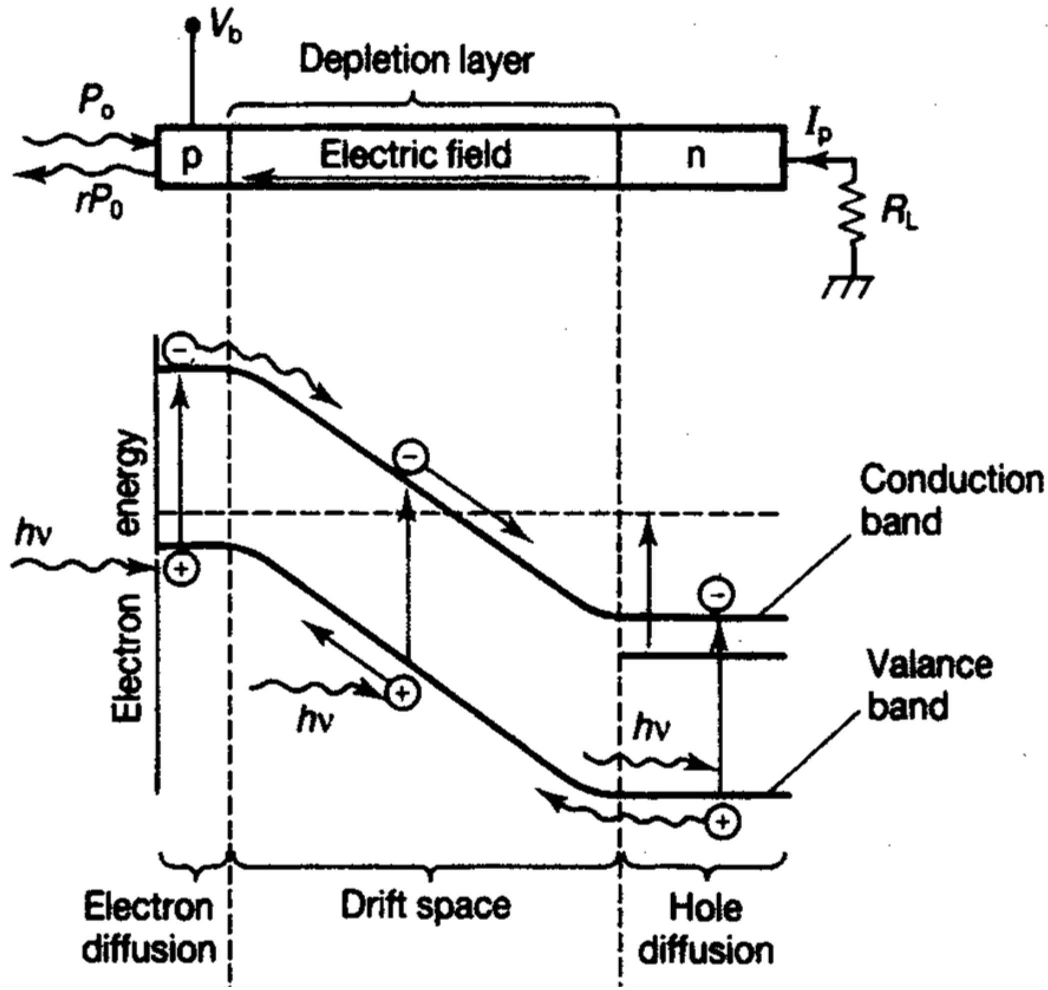
- High sensitivity in the wavelength region of the light source (800 nm-900 nm or 1300-1500 nm)
- Sufficient bandwidth or speed of response (100 MHz to 100 GHz)
- Little excess noise, dark current, parasitic induction and capacitance from the detector
- Low sensitivity to temperature changes

Semiconductor photodiodes meet all these requirements and are also small, relatively cheap, and can be coupled

P-N junction



Homojunction



Principle of operation

Generation of hole-electron pairs by photons

Two different detection modes are available:

- Photovoltaic mode
  - unbiased
  - diffusion of electrons in one direction and holes in the other direction → **slow**
  - resulting in a voltage across the junction or current when loaded
- Photoconductive mode
  - reverse biasing
  - drift of the carriers in the depletion region induces a current in the outer circuit

Photodiodes basics

- Light is absorbed in the depletion region of the p-n junction and hole electron pairs are created. The strong electrical field then separates the holes and electrons.
- Carriers generated outside the depletion region, but within the diffusion length of each side of the layer also contributes to the photocurrent

The <u>thickness</u> of the depletion region is a compromise:

- • A thick depletion layer will give a high quantum efficiency (# electron/hole pairs per incoming photon)

- • A thin depletion layer gives a short drift time and thus a fast response

P-N Photodiodes

Trade-off: efficiency versus speed

Effect of reverse bias:

Increase of the reverse bias
widening of the depletion layer $\rightarrow$ more sensitive
decease of the capacitance $\rightarrow$ faster
Increase of drift velocity $\rightarrow$ faster

Very high reverse voltage is not desirable

If depletion layer has to increase then P-I-N diode structure is useful

PIN photodiode: wider depletion region due to very lightly doped n-layer $\rightarrow$ enhanced sensitivity for longer wavelengths (larger penetration depth))

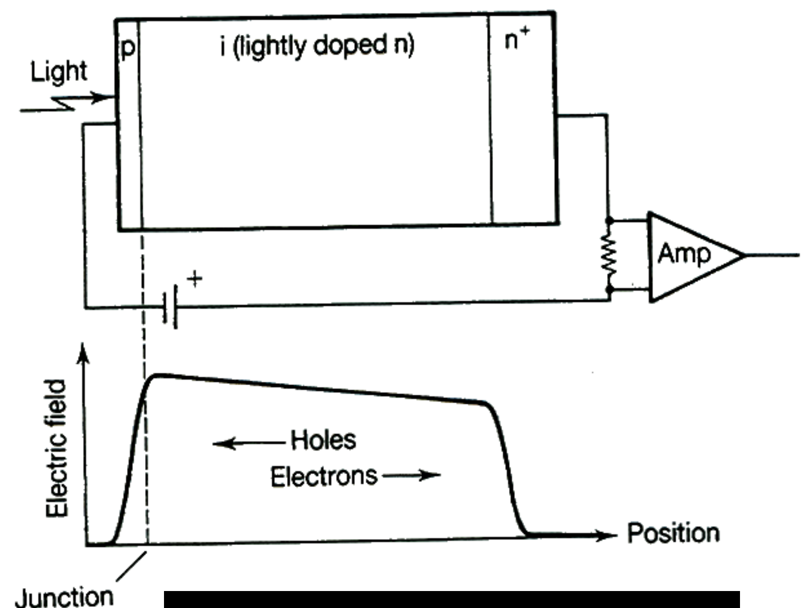
Depletion width is high

Quantum efficiency high

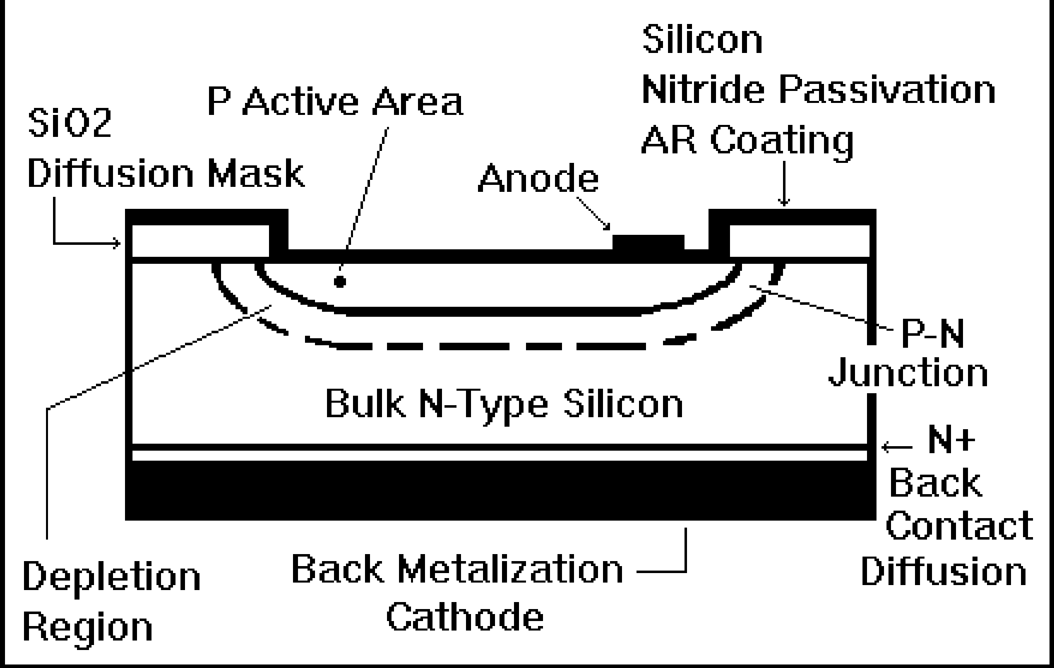
Low reverse bias voltage

Band width is high (1 GHz)

But large dark current & excess noise



I is intrinsic



A thin "p" layer is formed on the front surface of the device by thermal diffusion or ion implantation of the appropriate doping material (usually boron). The interface between the "p" layer and the "n" silicon is known as a p-n junction

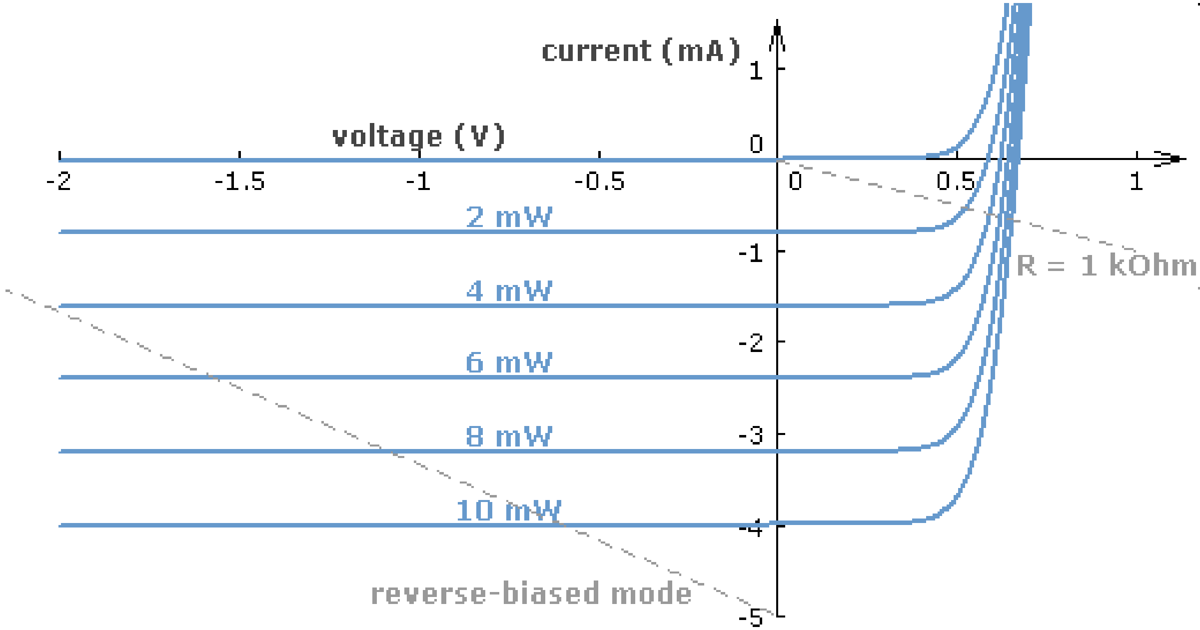
The active area is coated with either silicon nitride, silicon monoxide or silicon dioxide for protection and to serve as an anti-reflection coating. The thickness of this coating is optimized for particular irradiation wavelengths

Photodiodes basics

Quantum efficiency & responsivity

$$R = \frac{N_e}{N_p}\left(\frac{e\lambda}{hc}\right) = \eta\left(\frac{e\lambda}{hc}\right)$$

Current-voltage characteristics of a photodiode for different optical powers.



Semiconductor Materials

Silicon (Si): low dark current, high speed, good sensitivity between roughly 400 and 1000 nm

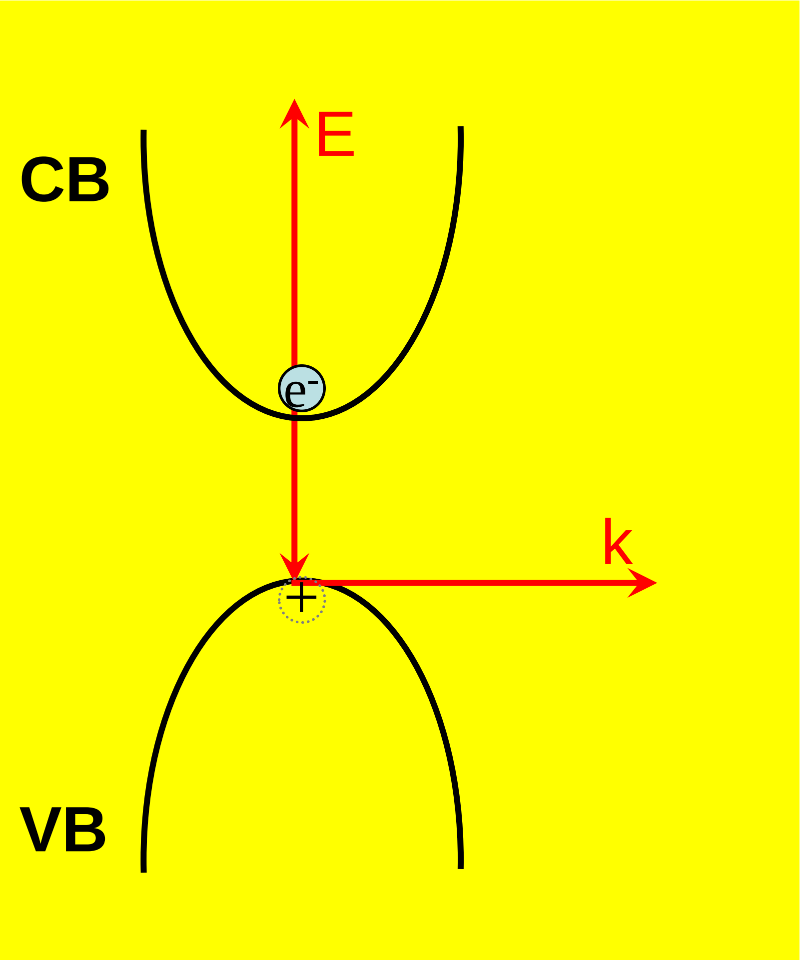
Ge: high dark current, slow speed due to large parasitic capacity, good sensitivity between roughly 900 and 1600 nm (best around 1400–1500 nm)

Indium gallium arsenide phosphide (InGaAsP): expensive, low dark current, high speed, good sensitivity roughly between 1000 and 1350 nm (best around 1100–1300 nm)

LED

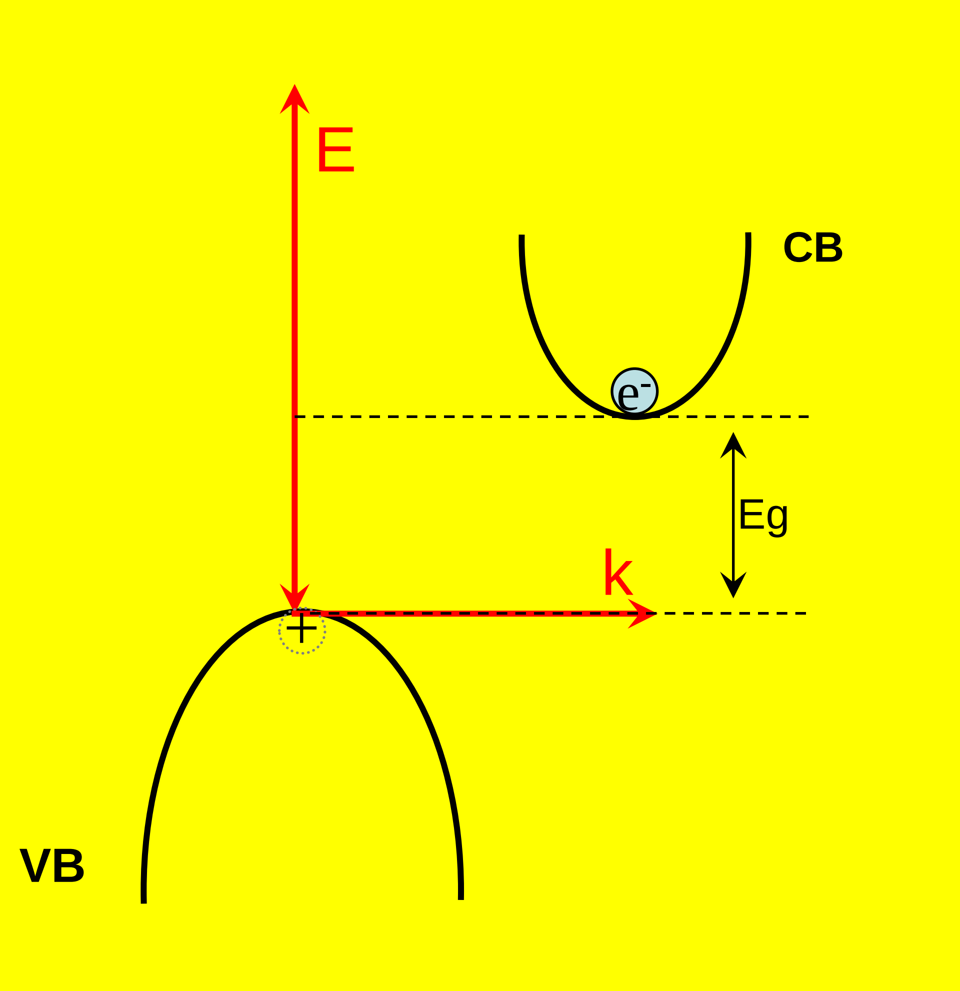
Direct an indirect-band gap materials :

Direct-band gap : GaAs, InP, AlGaAs



- For a ***direct-band gap material***, the minimum of the conduction band and maximum of the valance band lies at the same momentum, k, values.
- When an electron sitting at the bottom of the CB recombines with a hole sitting at the top of the VB, there will be no change in momentum values.
- Energy is conserved by means of emitting a photon, such transitions are called as radiative transitions.

Indirect band gap :Si, Ge



- For an indirect-band gap material; the minimum of the CB and maximum of the VB lie at different k-values.
- When an e⁻ and hole recombine in an indirect-band gap s/c, phonons must be involved to conserve momentum.

Phonon

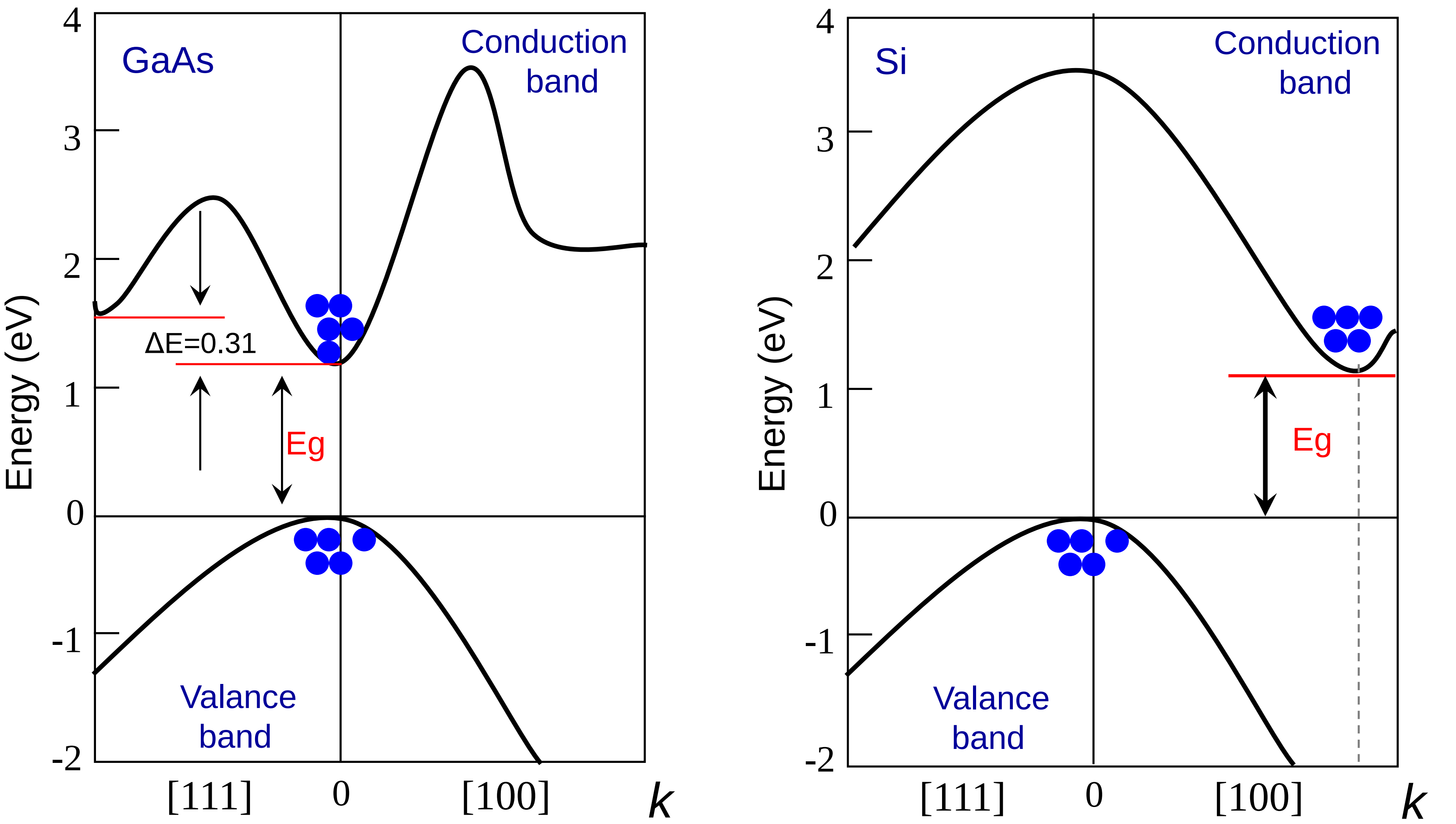
- Atoms vibrate about their mean position at a finite temperature.These vibrations produce vibrational waves inside the crystal.
- Phonons are the quanta of these vibrational waves. Phonons travel with a velocity of sound .
- Their wavelength is determined by the crystal lattice constant. Phonons can only exist inside the crystal.

- The transition that involves phonons without producing photons are called *nonradiative (radiationless) transitions*.

- These transitions are observed in an *indirect band gap* s/c and result in inefficient photon producing.

- So in order to have efficient LED's and LASER's, one should choose materials having direct band gaps such as compound s/c's of GaAs, AlGaAs, etc…

Energy band structures of *GaAs* and *Si*

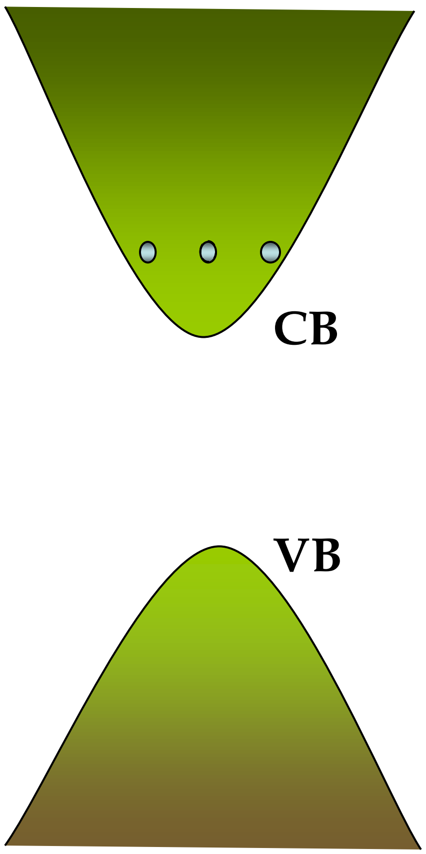


Light emitting diode (LED) as source of light in fiber optical communication

When the electron falls down from conduction band and fills in a hole in valence band, there is an obvious loss of energy

The change of energy due to electron-hole recombination is released and depending on the type of band structure (E-k diagram) the emitted energy is either radiative or non-radiative

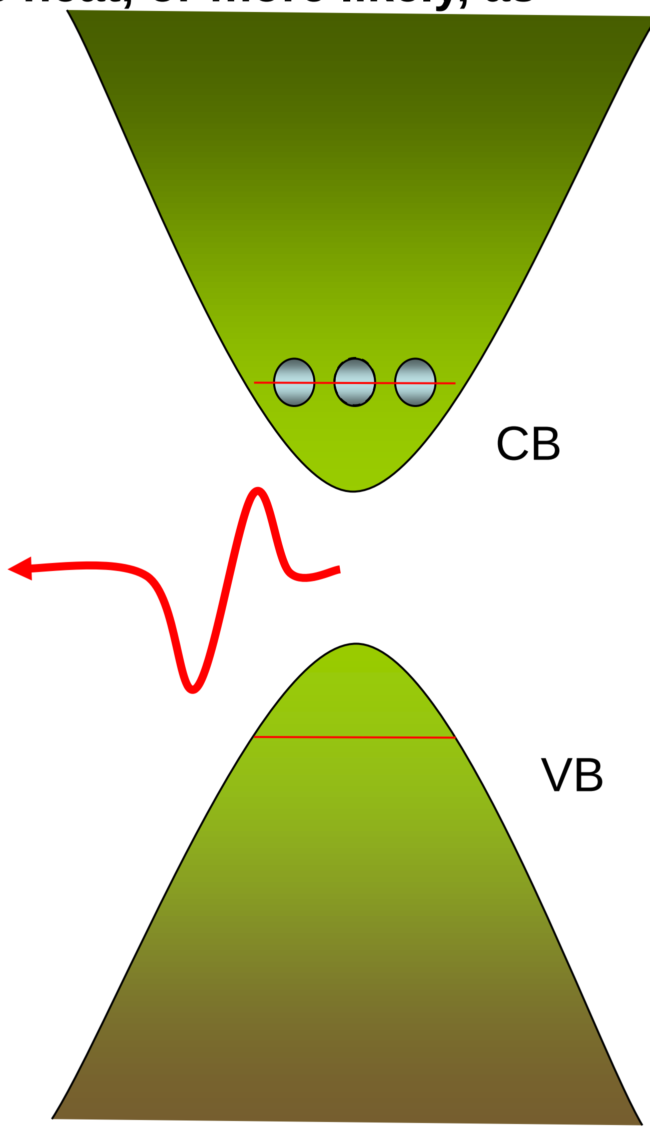
To emit photon in such a transition efficiently, direct band gap semiconductor is preferred over indirect band gap semiconductor



What are direct band gap and indirect band gap semiconductors?

Photon emission and LED material

- Thus, for a direct band gap material, the excess energy of the electron-hole recombination can either be taken away as heat, or more likely, as a photon of light.
- This radiative transition then conserves energy and momentum by giving off light whenever an electron and hole recombine.



This gives rise to (for us) a new type of device;
the light emitting diode (LED).

In the mid 1920s, Russian Oleg Vladimirovich Losev independently created the first LED, although his research was ignored at that time

In 1955, Rubin Braunstein of the Radio Corporation of America reported on infrared emission from gallium arsenide (GaAs) and other semiconductor alloys

Experimenters at Texas Instruments, Bob Biard and Gary Pittman, found in 1961 that gallium arsenide gave off infrared radiation when electric current was applied. Biard & Pittman received the patent for the infrared light-emitting diode

In 1962, Nick Holonyak Jr., of the General Electric Company and later with the University of Illinois at Urbana-Champaign, developed the first practical visible spectrum LED. He is seen as the "father of the light-emitting diode“

In 1972, M. George Craford, Holonyak's former graduate student, invented the first yellow LED and 10x brighter red and red-orange LEDs

S. Nakamura of Nichia Corporation of Japan demonstrated the first high brightness blue LED based on InGaN. The 2006 Millennium Technology Prize was awarded to Nakamura for his invention

Basic LED device structure

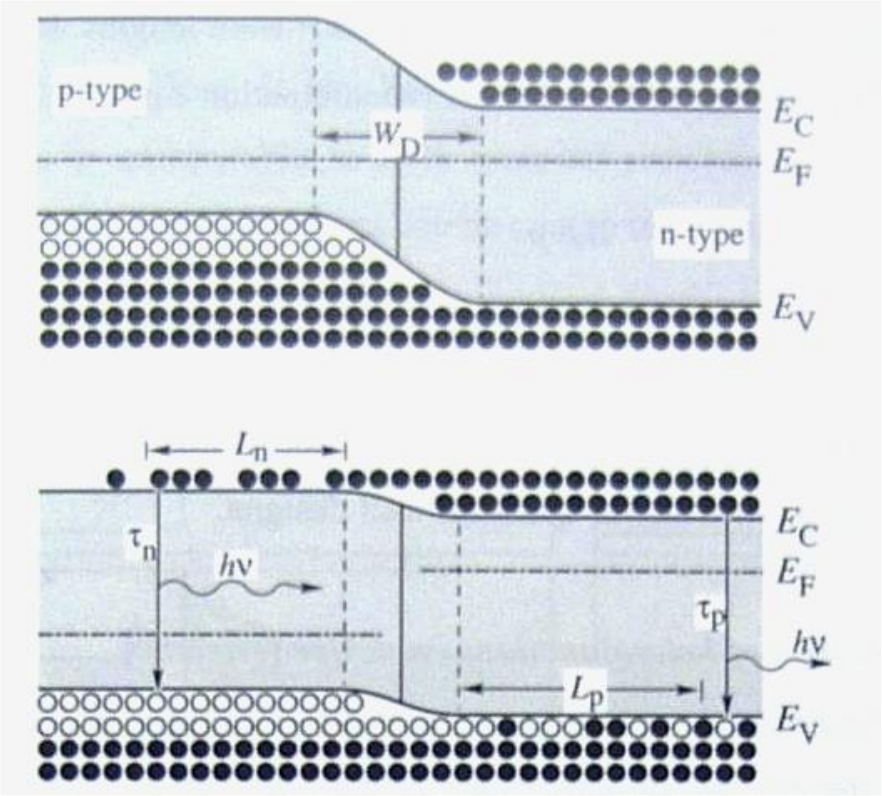
PN (HOMO) junction diode in forward bias, the electron-hole recombination leads to photon emission

Mechanism is “injection Electroluminescence”

Luminescence part tells us that we are producing photons
&
Electro part tells us that the photons are being produced by an electric current

Basic LED device operation

p-n+ junction

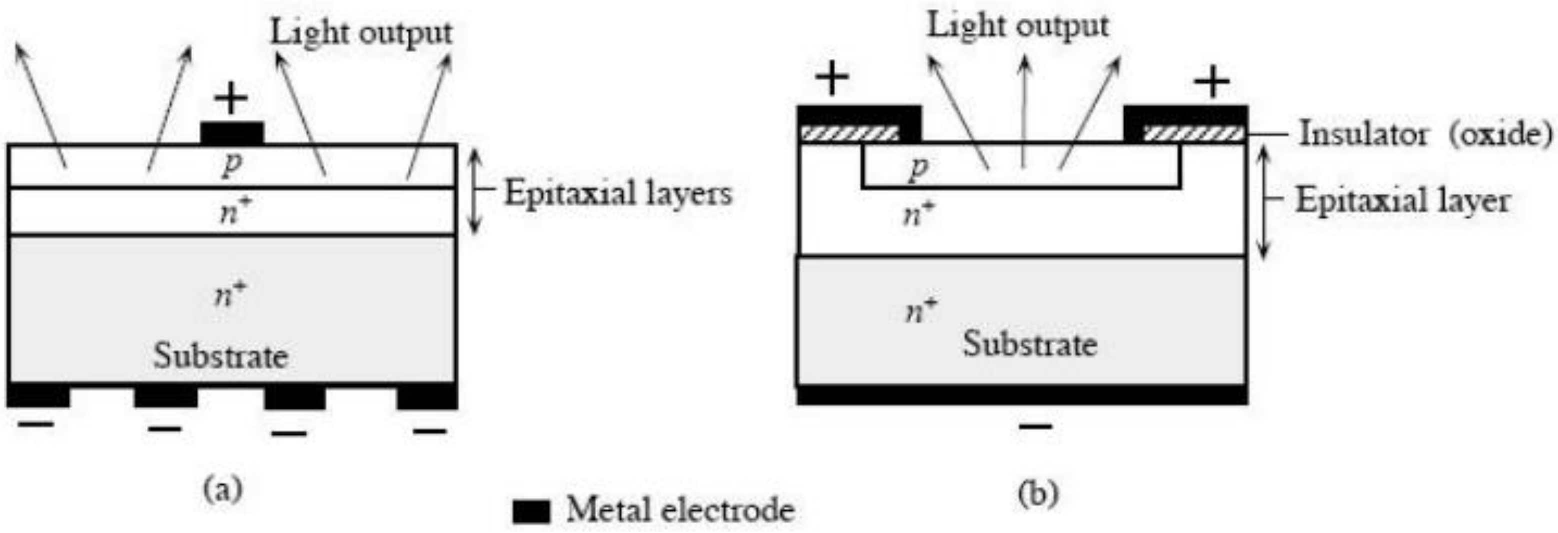


a

b

Forward biasing a p-n junction will inject lots of e-'s from n-side, across the depletion region into the p-side where they will be combine with the high density of majority carriers

Photon emission occurs whenever we have injected minority carriers recombining with the majority carriers



Device structure

Output of a LED

- **When we talk about light ,it is conventional to specify its wavelength, λ, instead of its frequency.**
- **Visible light has a wavelength on the order of nanometers.**

$$\lambda(nm) = \frac{hc}{E(eV)}$$

$$\lambda(nm) = \frac{1242}{E(eV)}$$

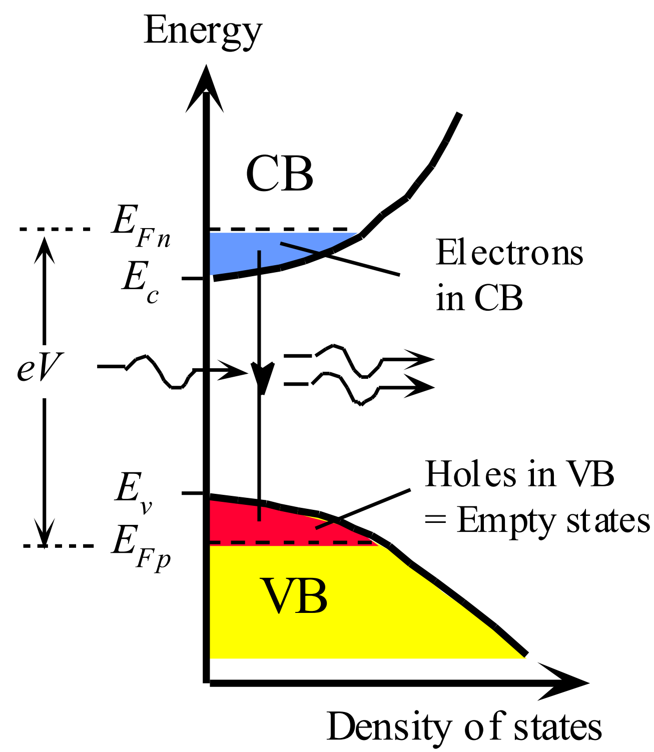
- **Thus, a semiconductor with a 2 eV band-gap should give a light at about 620 nm (in the red). A 3 eV band-gap material would emit at 414 nm, in the violet.**
- **The human eye, of course, is not equally responsive to all colors.**

Semiconductor laser as source of light in fiber optical communication

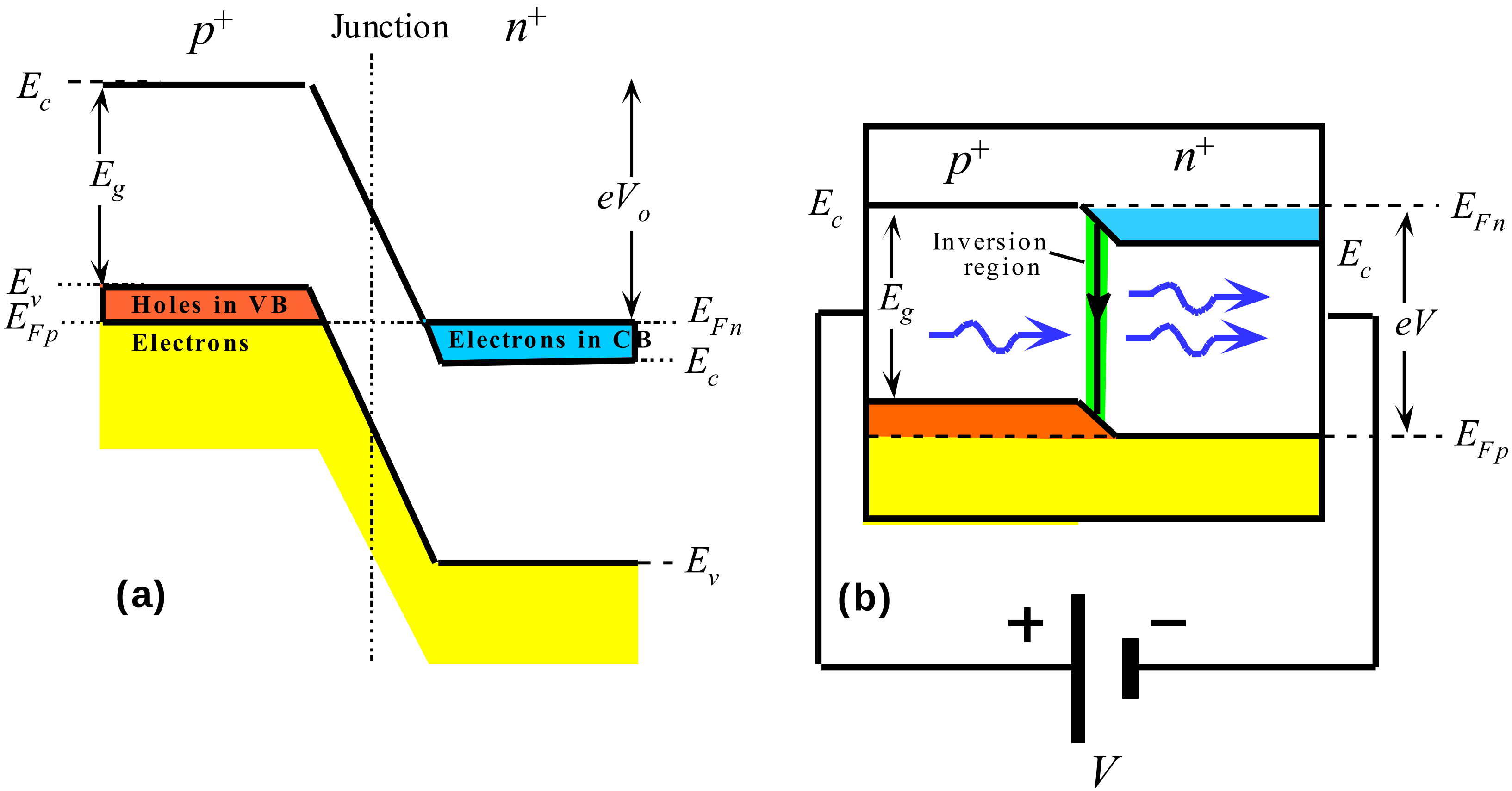
Laser diode is similar in principle to an LED but it require an optical cavity that will facilitate feedback in order to generate stimulated emission

The basic structure is p-n junction with either homo or hetero junctions configurations.

Unlike LED structure, here both p and n are degenerate semiconductors. It means that in either case the Fermi level is within the valance and conduction band respectively



Basics



(a) The energy band diagram of a degenerately doped p-n with no bias

(b) With sufficiently large forward bias to cause population inversion and hence stimulated emission

- Energy levels up to the Fermi level are occupied by electrons
- When there is no applied voltage the Fermi level is continuous across the diode

Basics

- Depletion layer is very narrow due to degenerate nature of p & n
- At zero bias, Vo (built in voltage) prevents electrons in CB (n+-side) from diffusing into CB of p+-side
- There is a similar barrier preventing hole diffusion from p+ to n+ sides
- Now, assuming an applied voltage (eV) greater than the band gap energy, E_{Fn} and E_{Fp} are now separated by eV
- eV diminishes barrier potential to zero, allowing electrons to flow into depletion and over to p+-side to establish diode current
- A similar reduction in barrier potential for holes from p+-side to n+-side occurs
- Result → depletion layer is no longer depleted

$$E_{Fn} - E_{Fp} = eV > E_g$$

Basics

More electrons in the CB at energies near Ec than electrons in VB near Ev

This is the result of a *Population Inversion* in energies near E_C and E_V

The region where the population inversion occurs develops a layer along the junction called an *inversion layer* or *active region*

Two things can happen

- An incoming photon with energy of Ec-Ev will not see electrons to excite from E_V to E_C due to the absence of electrons at VB
- The photon can cause an electron to fall down from E_C to E_V

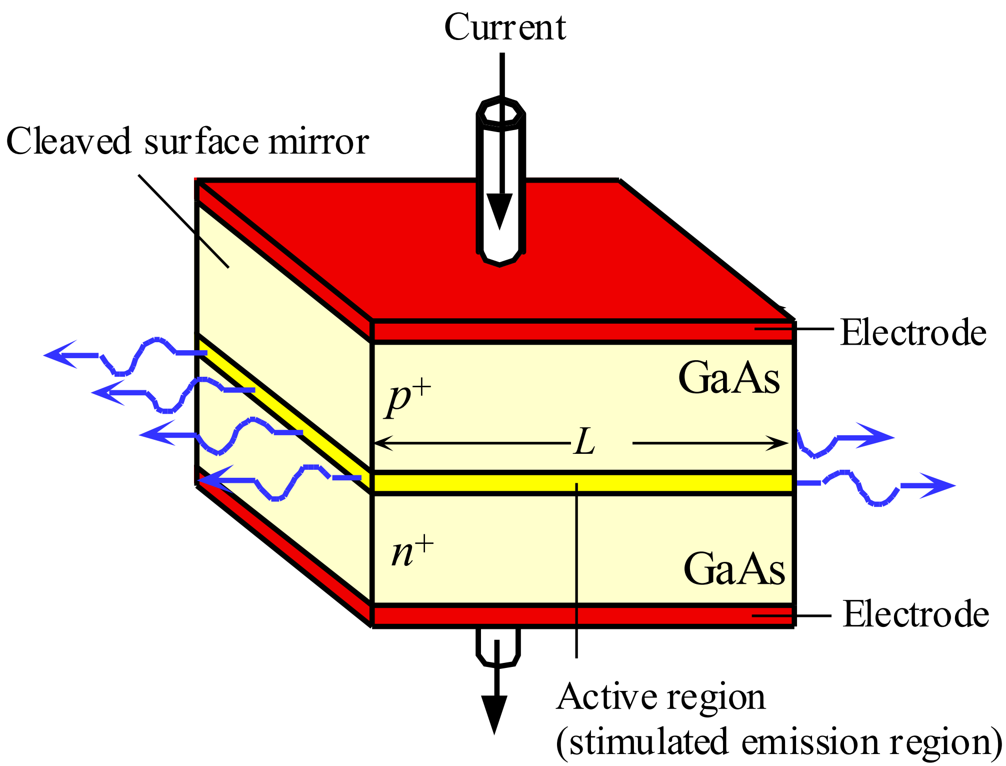
Thus, the incoming photon is stimulating *direct recombination*

Photons with energy > Eg but < E_{Fn} - E_{Fp} cause stimulated emission

Photons with energy > E_{Fn} - E_{Fp} are absorbed

Adequate forward bias current is needed for achieving the population inversion and this process is called the injection pumping

Basics



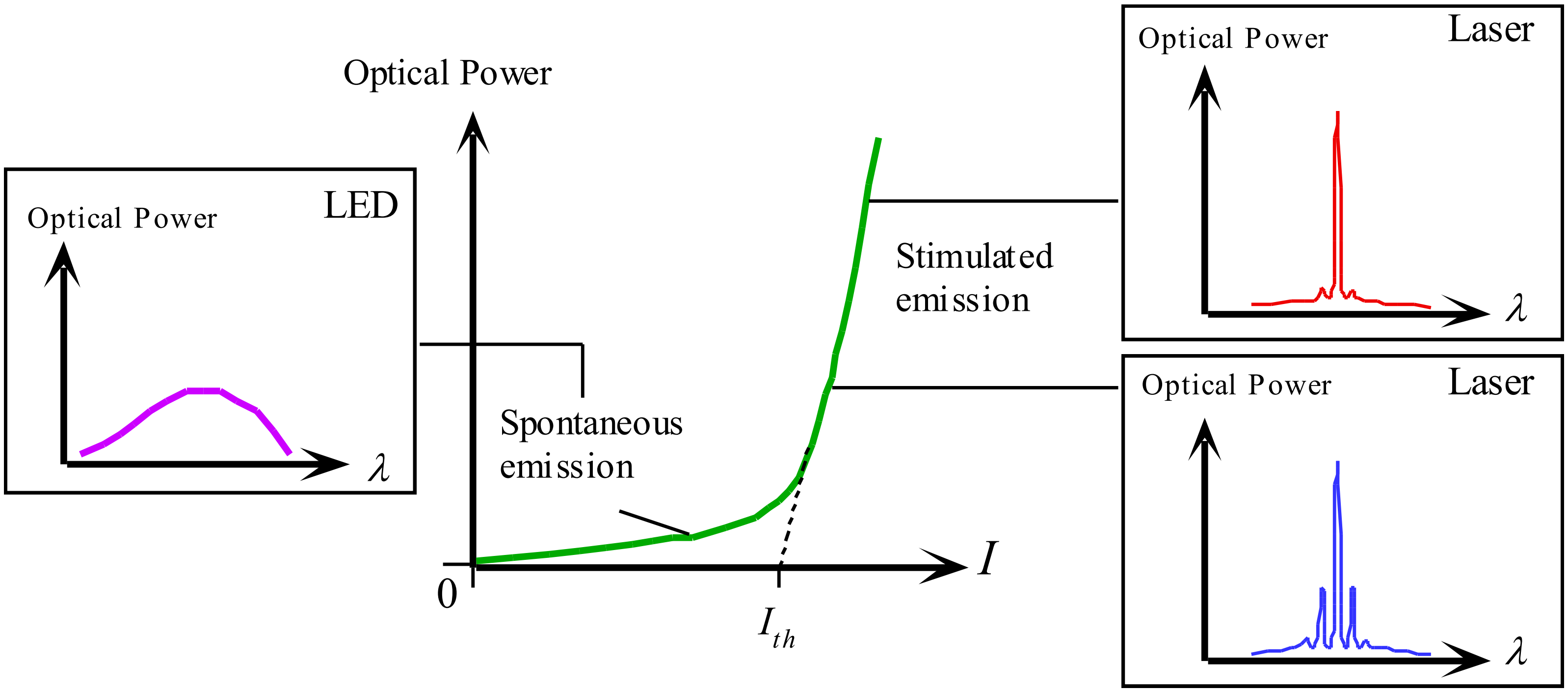
An optical cavity is implemented to elevate the intensity of stimulated emission. (*optical resonator*)

Provides an output of continuous **coherent radiation**

The ends of the crystal are cleaved to a flatness and the ends are polished to provide reflection

Photons reflected from cleaved surface stimulate more photons of the same frequency

Basics



Optical power vs. diode current and the corresponding output spectra for **LED** and **LASER**

Endoscopy

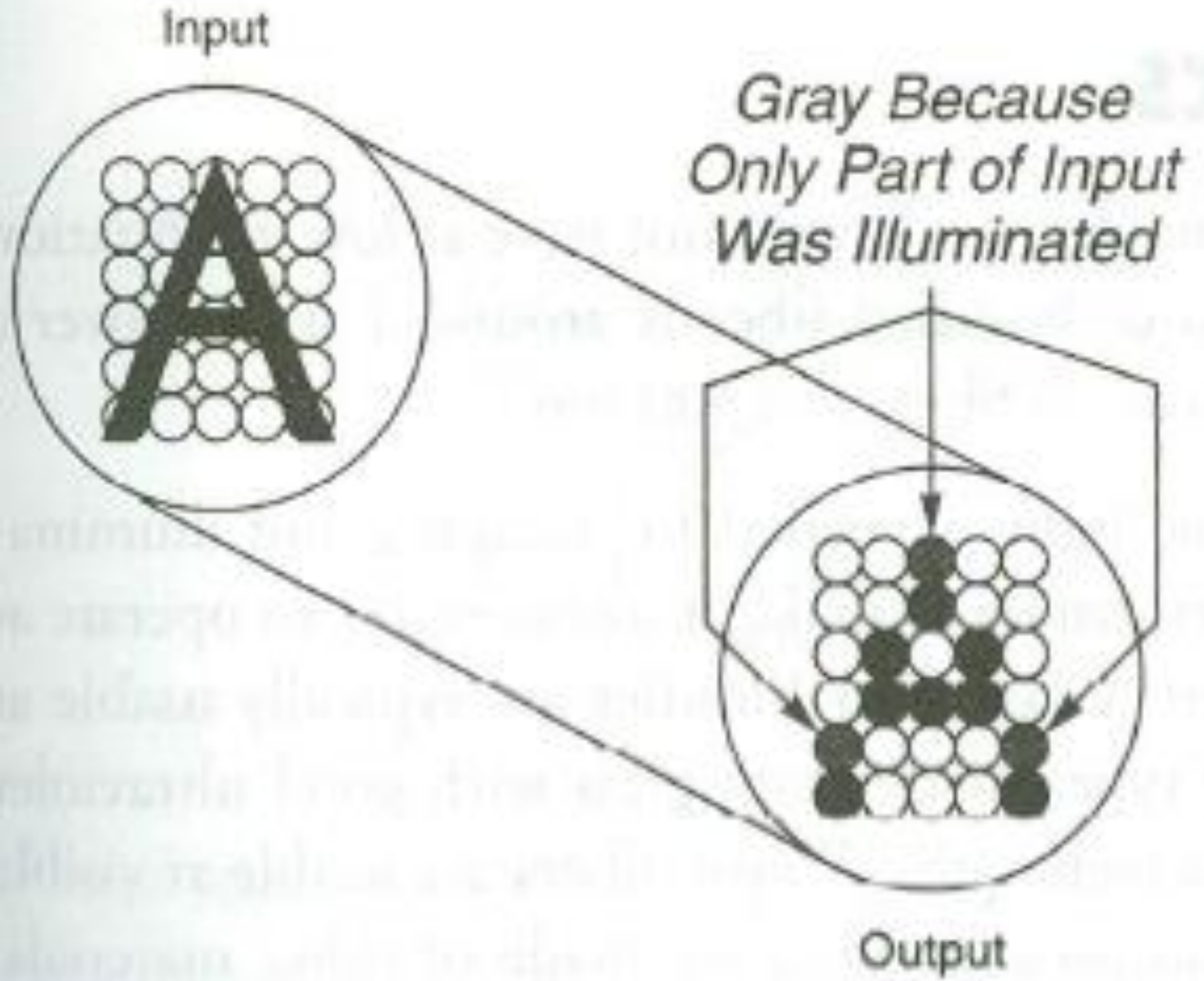
A large number of fibers put together form what is known as a bundle

If the fibers are not aligned, i.e. they are all jumbled up, the bundle is said to be an *incoherent bundle*

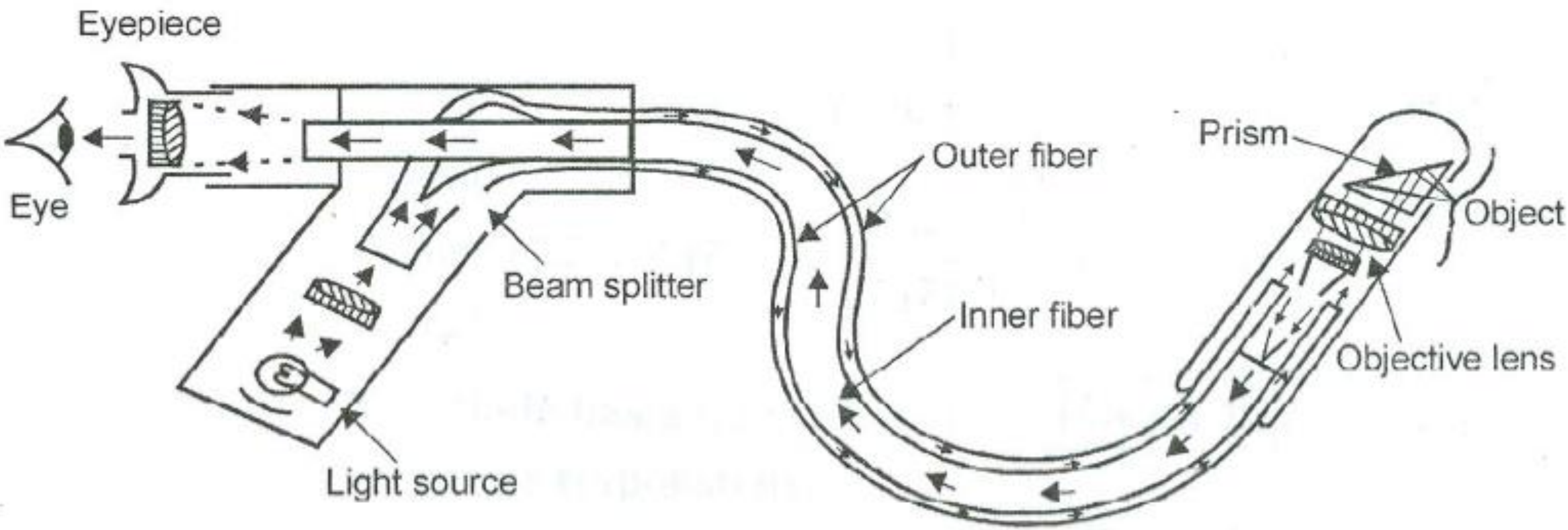
However, if the fibers are aligned properly, i.e., if the relative positions of the fibers in the input and output ends are the same, the bundle is said to be a coherent bundle

If a particular fiber in this coherent bundle is illuminated at one of its ends, there will be a bright spot at the other end of the same fiber. Thus a coherent bundle will transmit the image from one end to another

They can be used as cold light sources (i.e., light sources giving only light and no heat) by cutting off the heat radiation with a filter at the input to the fiber bundle. The light emerging from the bundle is also free from UV radiation and is suitable for illumination of paintings in museums


Input
Gray Because Only Part of Input Was Illuminated
Output

: fiber
d


Eyepiece
Eye
Prism
Outer fiber
Object
Beam splitter
Inner fiber
Objective lens
Light source

Endoscope