COURSE: *OPTICAL COMMUNICATION* (EC317)
UNIT-I

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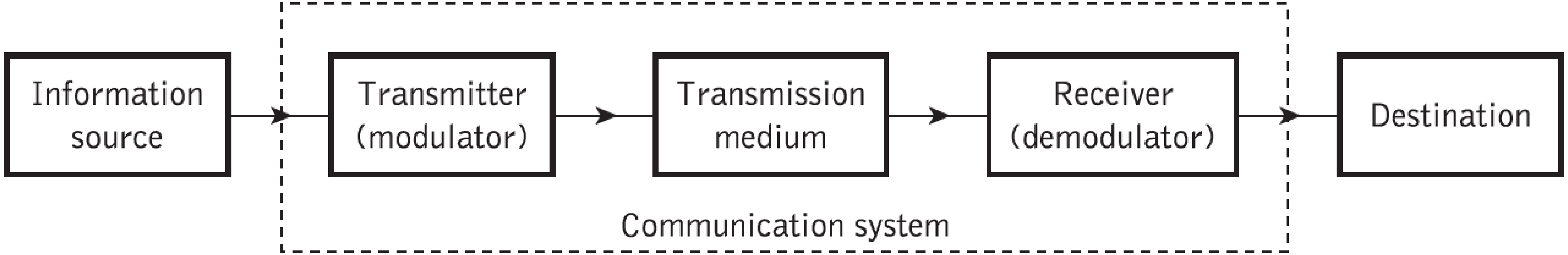
UNIT-I

- Motivation for optical communications,
- Advantages of optical fibers
- Key elements of optical fiber communication link
- Optical bands
- Optical windows, standards

INTRODUCION

- Communication system- transfer of the information from one point to another and consists of transmitter, transmission medium and receiver
- Transmitter comprising electrical and electronic components
  - which converts the information signal into a suitable form for propagation over the transmission medium.
  - achieved by modulating the information onto an electromagnetic wave which acts as a carrier for the information signal.
- This modulated carrier is then transmitted trough the transmission medium to the required destination where it is received and the original information signal is obtained by demodulation.
- The transmission medium can consist of a pair of wires, a coaxial cable or a radio link through free space down which the signal is transmitted to the receiver



MOTIVATION

- Pair of wires- low data rates, lossy at RF, used for telephone lines
- Coaxial cable- data rates in Mbps, moderate loss, used in LANs,
- Radio link- large bandwidth, long distance, more free space losses
- Satellite - large bandwidth (in GHz), large delay
- The first two media have a very limited bandwidth
- Microwave links and Satellite communication has comparable bandwidths as in principle their mode of operation is same but the spatial reach of satellite is far greater

MOTIVATION

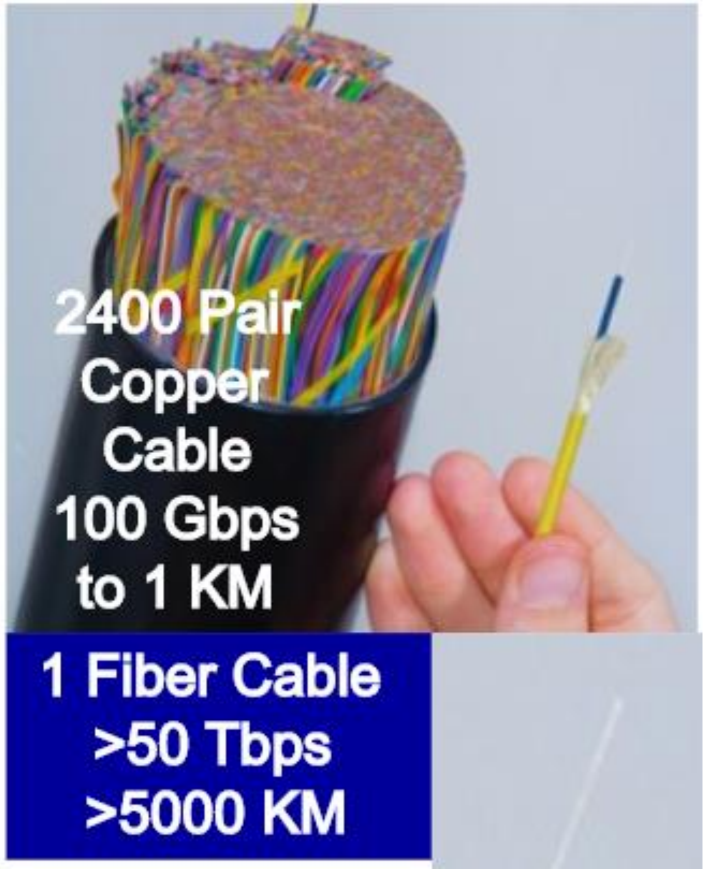
- The resources for good communication system
  - **Bandwidh (BW)-**
    - the amount of information that can be transmitted is directly related to the frequency range over which the carrier operates
    - increasing the carrier frequency theoretically increases the available transmission bandwidth and, consequently, provides a larger information capacity
  - **Signal Power- Good signal to noise ratio (SNR) i.e. low loss**
- Optical Communication is the most modern mode of wired communication because of it bandwidth (10 to 100 times more than the radio/microwave links)

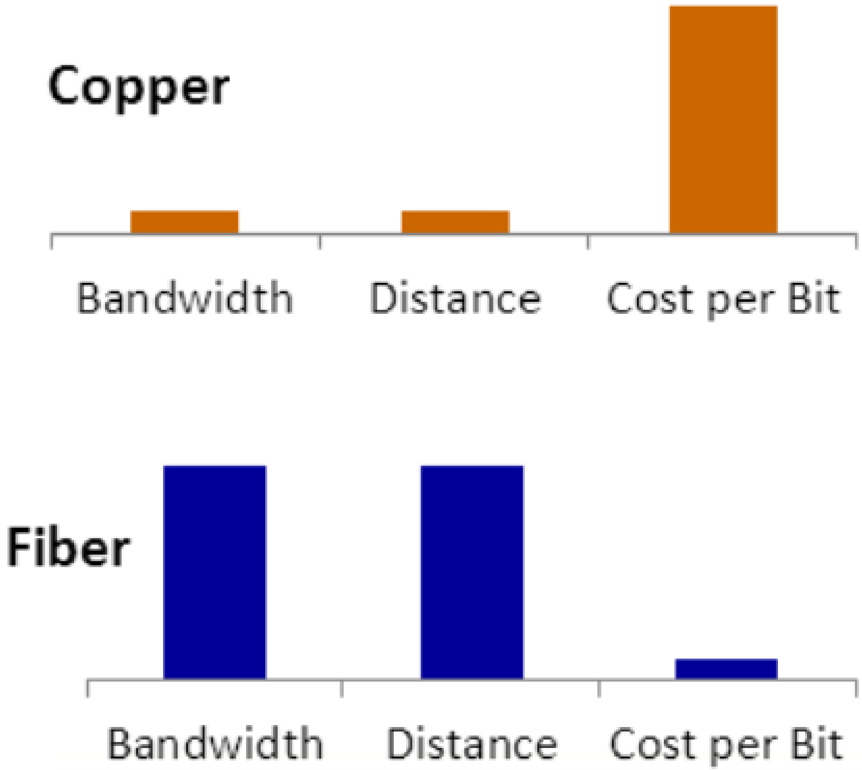
For example a system operating around the 1500 nm wavelength can use the following channel bandwidth:

Assume upper band = 1530 nm, or 196.078 THz

Assume lower band = 1550 nm, or 193.548 THz

and therefore a bandwidth of 196.078 − 193.548 = 2.530 THz.

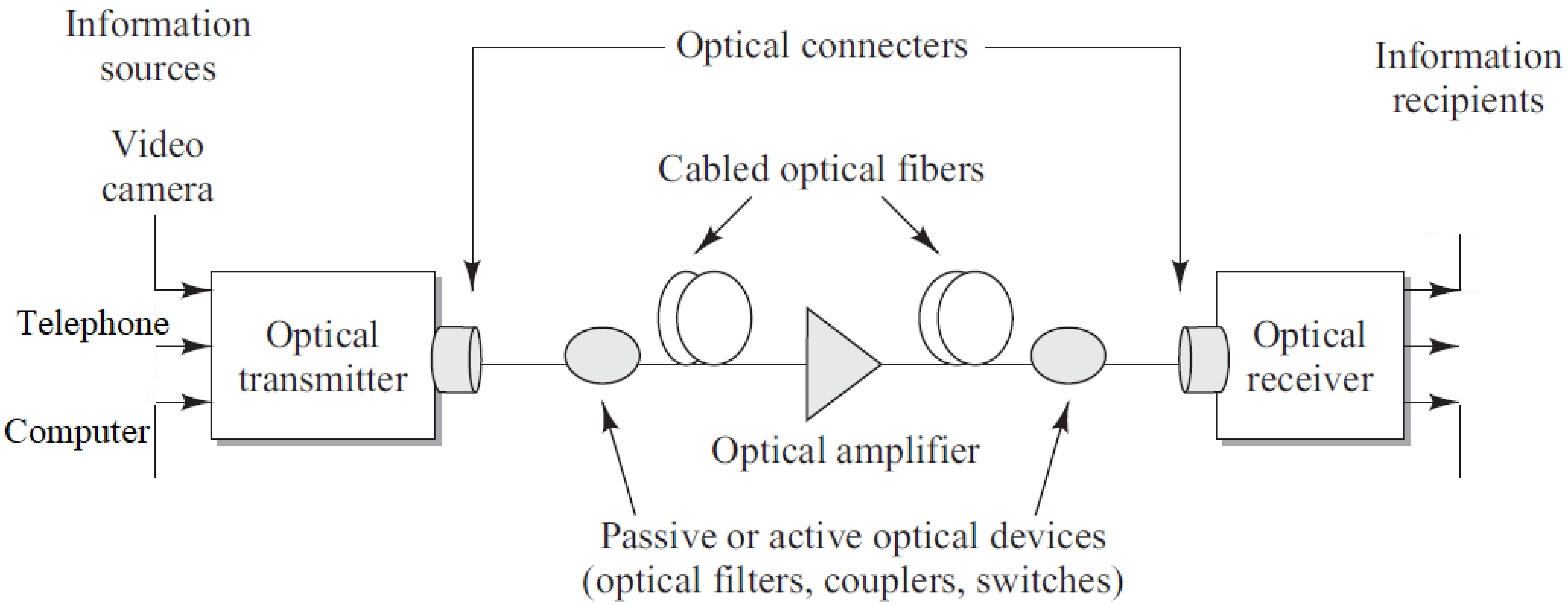




ADVANTAGES AND DISADVANTAGES

- **Advantages** :
  - High bandwidth (in THz) - Large capacity of information transmission
  - Low transmission loss (0.2 dB/km) - long distance transmission without repeaters- less expensive
  - Small size and lighter weight than copper
  - No metallic conductors - immunity to electromagnetic interference (EMI)
  - Higher melting point than copper
- **Disadvantages:**
  - Connections and taps are more difficult to make than for copper
  - Fiber is not as flexible than as copper wire

OPTICAL FIBER COMMUNICATION SYSTEM

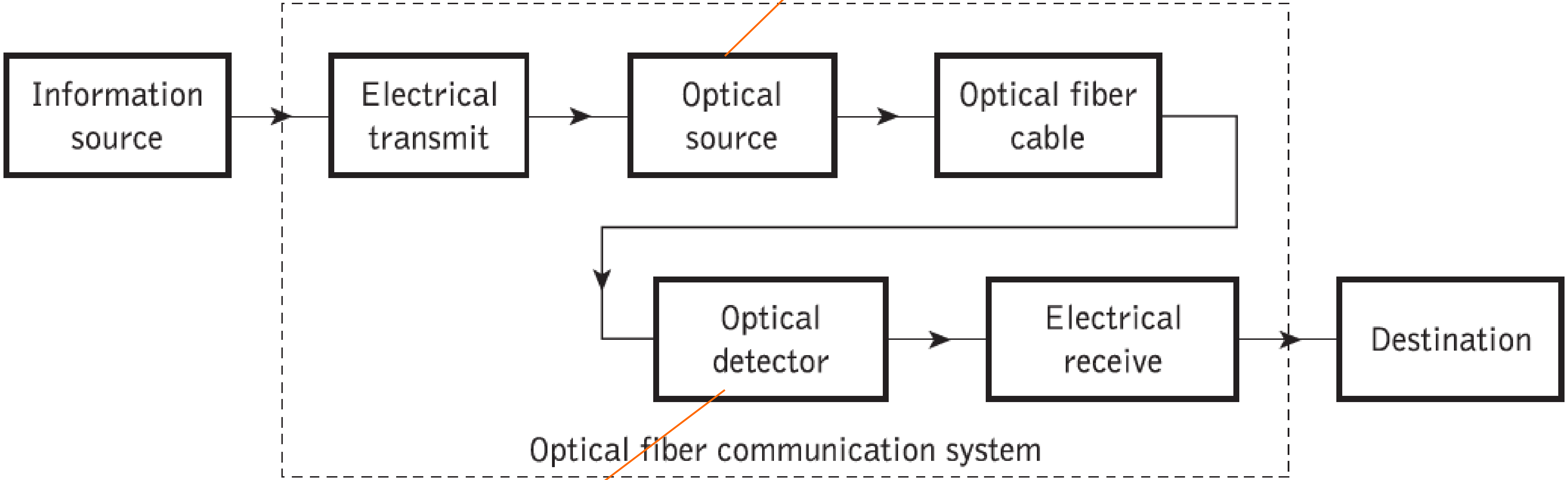


Key Elements of Optical Fiber Systems

- On transmitter side:
  - Electrical transmitter, light source and its associated drive circuitry,
  - a cable offering mechanical and environmental protection to the optical fibers contained inside
- On receiver side:
  - a photodetector plus amplification and electrical receiver
  - Additional components: optical amplifiers, connectors, splices, couplers, signal-restoring circuitry (regenerators) etc.

General block diagram of optical communication system

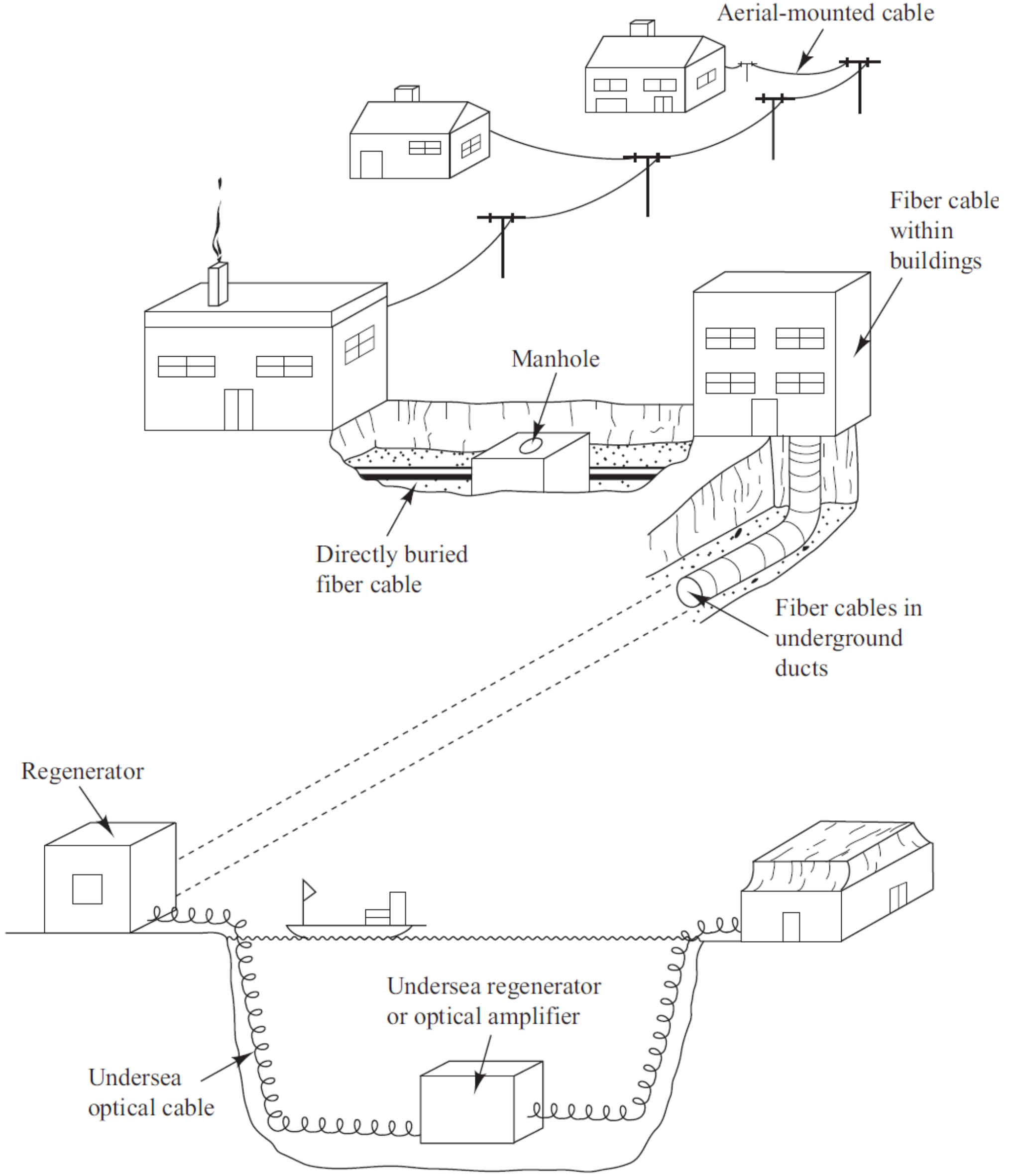
provides the electrical–optical conversion may be either a semiconductor laser or light-emitting diode (LED)



Provides optical–electrical conversion. Photodiodes (*p–n*, *p–i–n* or avalanche), phototransistors and photoconductors are utilized for the detection of the optical signal

Applications:

- Extensively used for data transmission including video data stream, perfect choice for HDTV
- Intelligent transport systems: smart highways with intelligent traffic lights, tool booths etc.
- Bio-medical industry: telemedicine devices for transmission of digital diagnostic images
- Space, Defense Automotive, and Industrial sector

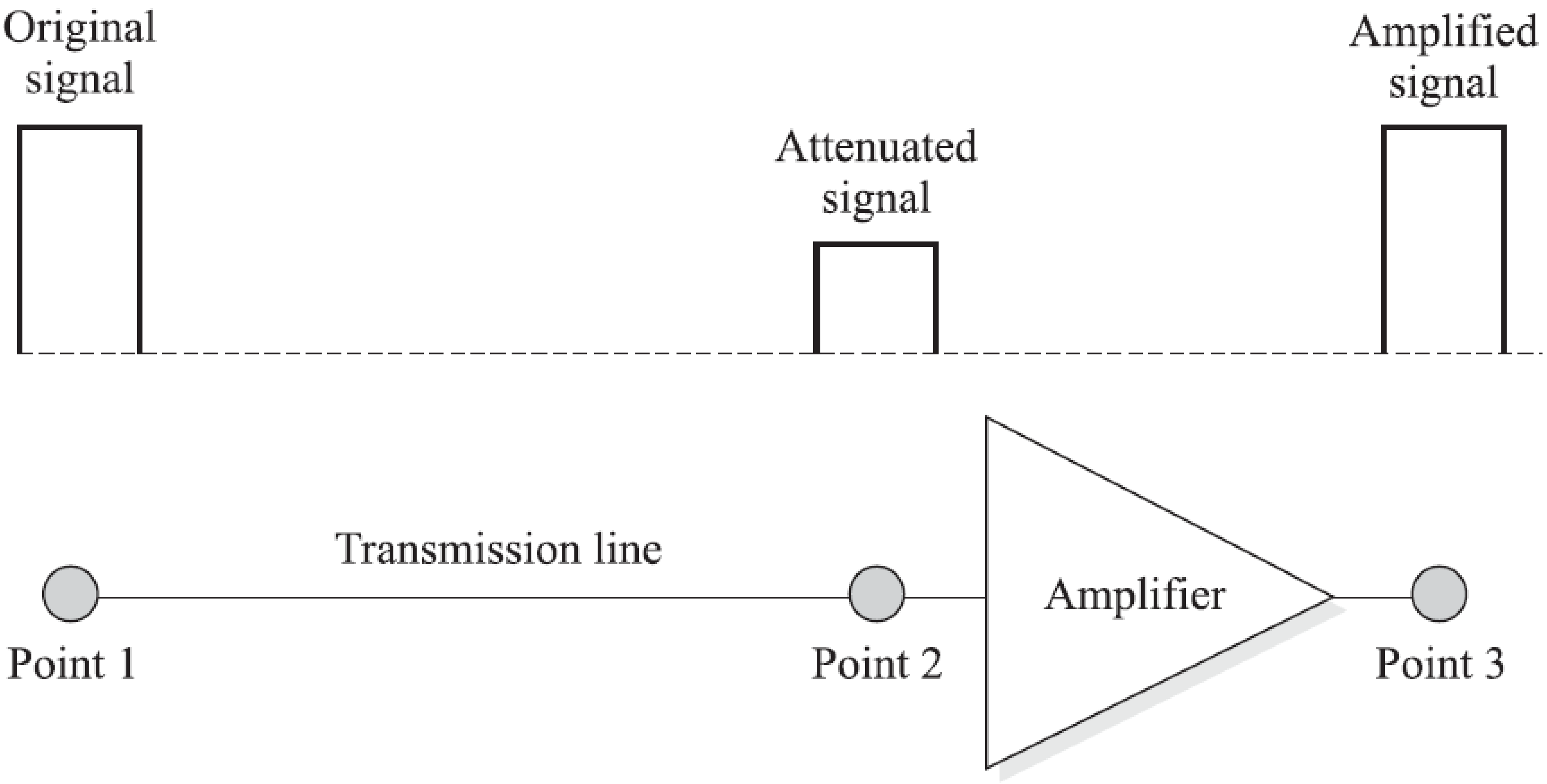


Measuring attenuation in decibels

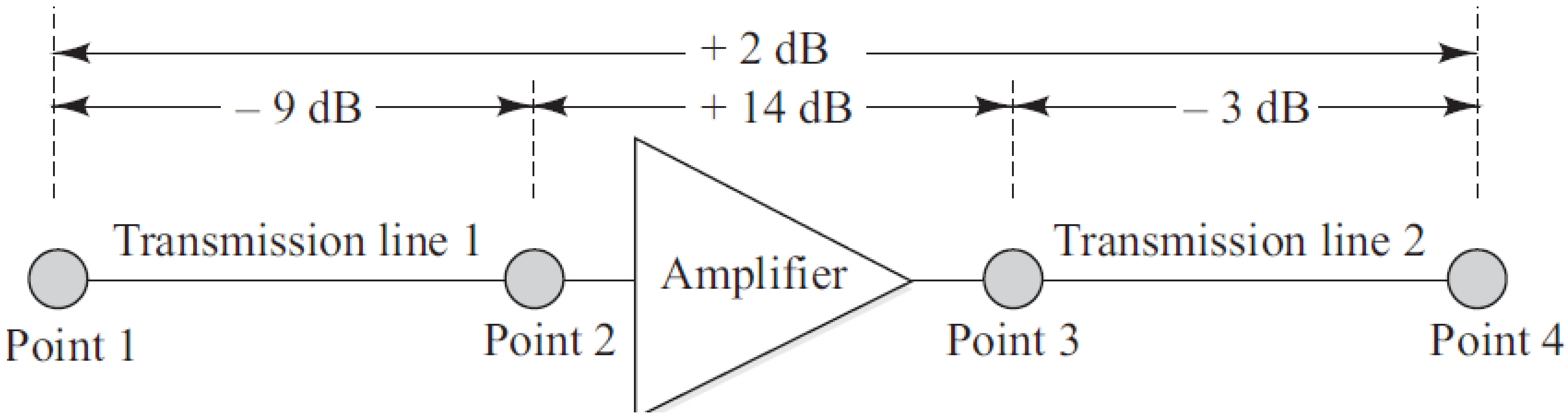
- Reduction or attenuation of signal strength arises from various loss mechanisms in a transmission medium.
- when designing and implementing an optical fiber link
  - Required to measure, and/or interrelate the optical signal levels at each of the elements of a transmission link.
  - Necessary to know parameter values such as the optical output power from a light source, the power level needed at the receiver to properly detect a signal, and the amount of optical power lost at the constituent elements of the transmission link
- A standard and convenient method for measuring attenuation through a link or a device is to reference the output signal level to the input level.
- For convenience it can designate in terms of a logarithmic power ratio measured in decibels (dB). The dB unit is defined by

$$Power\ ration\ in\ dBs = 10\log_{10}\left(\frac{P_2}{P_1}\right)$$

- To compensate for these energy losses, amplifiers are used periodically along a channel path to boost the signal level

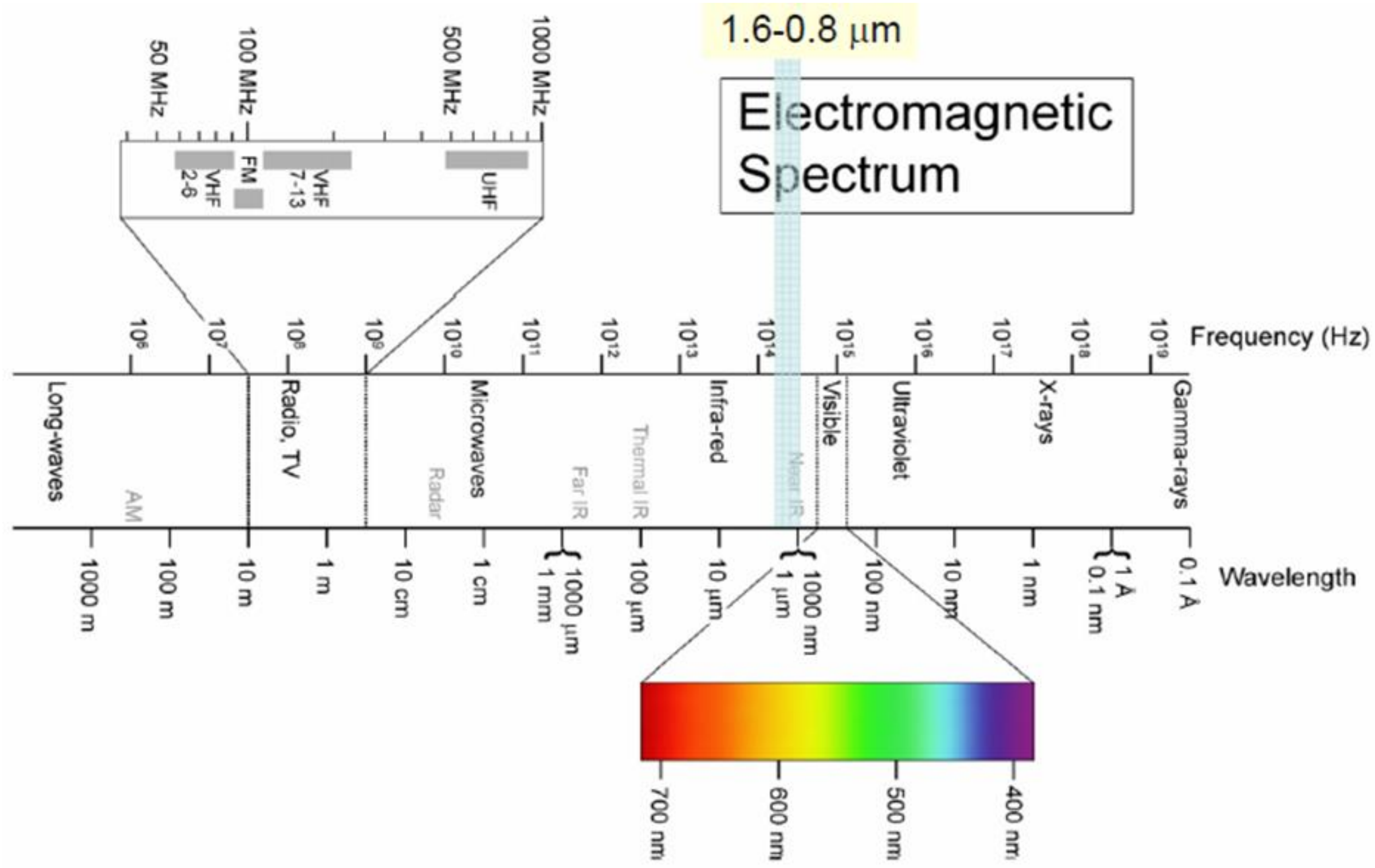

Original
signal
Attenuated
signal
Amplified
signal
Transmission line
Amplifier
Point 1
Point 2
Point 3

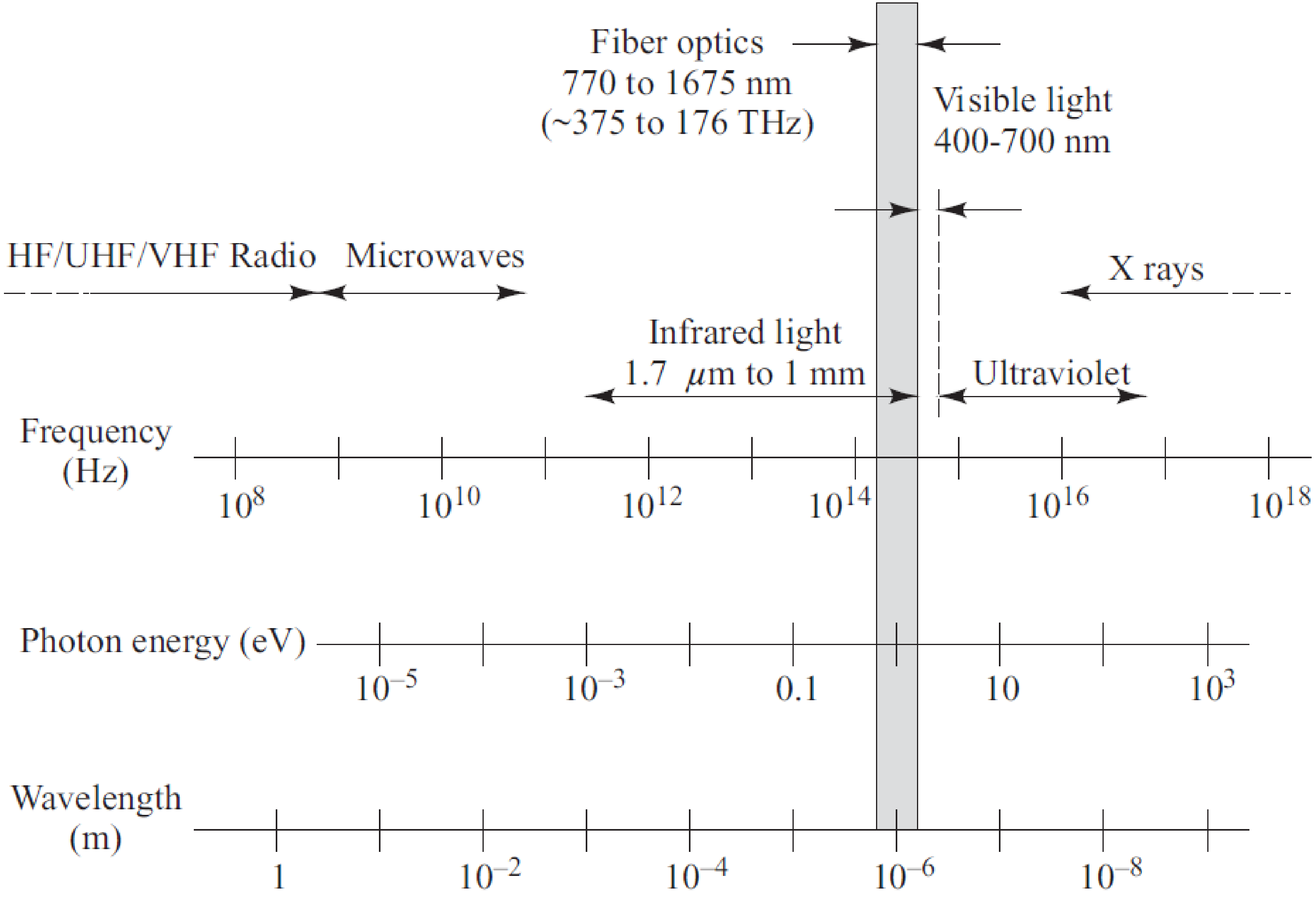
Example


+ 2 dB
– 9 dB
+ 14 dB
– 3 dB
Transmission line 1
Amplifier
Transmission line 2
Point 1
Point 2
Point 3
Point 4

OPTICAL SPECTRAL BANDS

- All telecommunication systems use some form of electromagnetic energy to transmit signals.





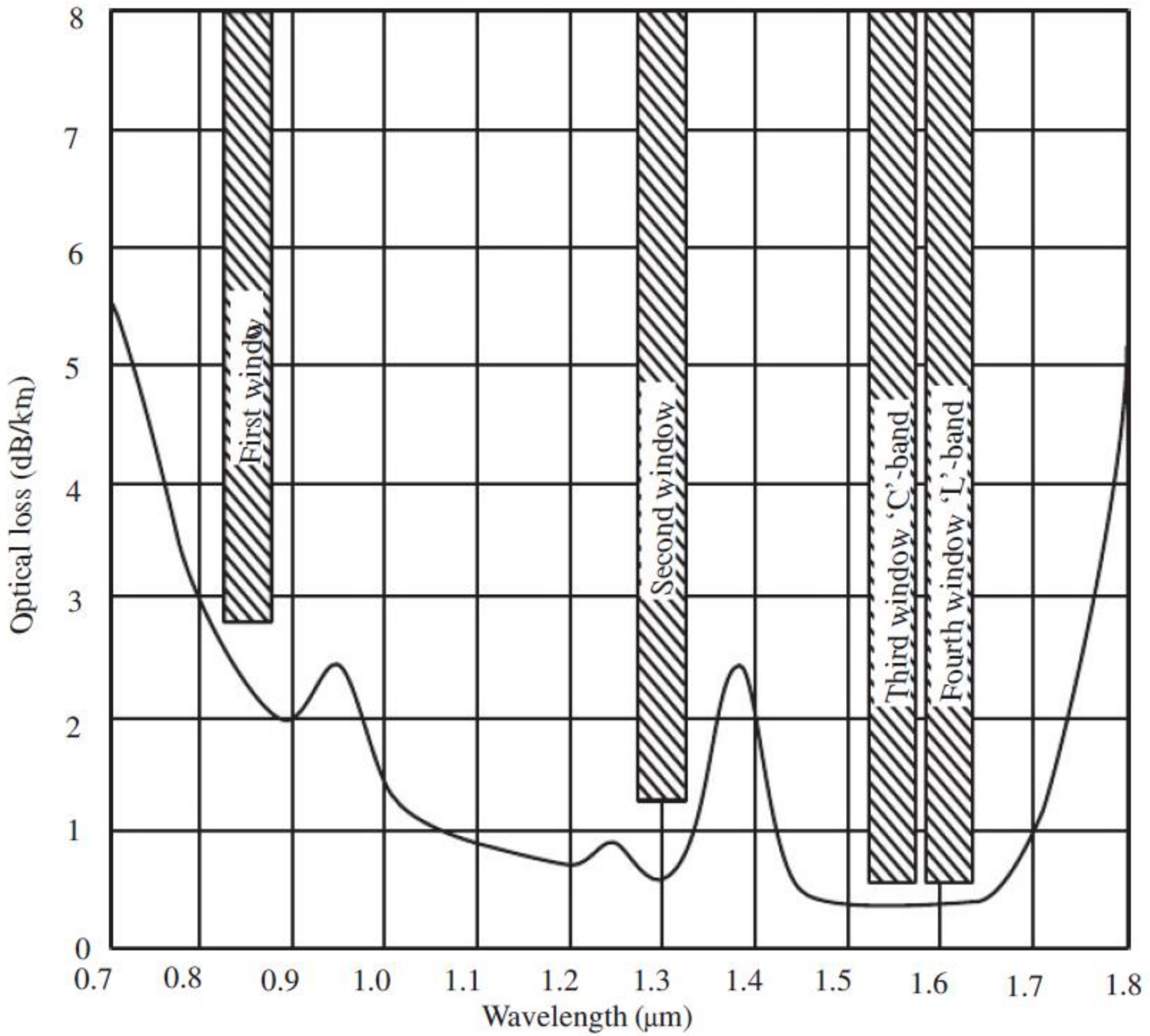
The spectrum of electromagnetic radiation

Spectral band designations used in optical fiber communications

Name	*Designation*	*Spectrum (nm)*
Original band	O-band	1260 to 1360
Extended band	E-band	1360 to 1460
Short band	S-band	1460 to 1530
Conventional band	C-band	1530 to 1565
Long band	L-band	1565 to 1625
Ultra-long band	U-band	1625 to 1675

OPTICAL WINDOWS

- In early 1970s due to technology limitation, the optical fiber had a low loss window around 850nm. Also the semiconductor optical sources were made of GaAs which emitted light at 850nm. Due to compatibility of the medium properties and the sources, the optical communication started in **850nm band** so called the **'First window'**. This window exhibited a relatively high loss of the order of 3 dB/km.
- As the glass purification technology improved, the true silica loss profile emerged in 1980s. The loss profile shows two low loss windows, one around 1300nm and other around 1550nm. In 1980s the optical communication shifted to **1300nm band** , so called the ' **Second Window'** . This window is attractive as it can support the highest data rate with theoretically **zero dispersion** for silica fibers and attenuation around **0.5 dB/km**.
- In 1990s the communication was shifted to **1550nm** window, so called **'Third Window'** due to invention of the Erbium Doped Fiber Amplifier (EDFA). The EDFA can amplify light only in a narrow band around 1550nm. Also this window has intrinsically lowest loss of about **0.2 dB/Km** . This band has higher dispersion, meaning lower bandwidth. However, this problem has been solved by use of so called 'dispersion shifted fibers'.



Optical loss (dB/km)
8
7
6
5
4
3
2
1
0
0.7
0.8
0.9
1.0
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
Wavelength (μm)
First window
Second window
Third window 'C'-band
Fourth window 'L'-band

STANDARDS FOR OPTICAL FIBER COMMUNICATIONS

- Three basic standard classes for fiber optics: primary standards, component testing standards, and system standards
- **Primary standards**
  - refer to measuring and characterizing fundamental physical parameters such as attenuation, bandwidth, operational characteristics of fibers, and optical power levels and spectral widths
  - National Institute of Standards and Technology (NIST)
- **Component testing standards**
  - define tests for fiber-optic component performance and establish equipment-calibration procedures
  - Telecommunications Industry Association (TIA) in association with the Electronics Industries Alliance (EIA), Telecommunication Sector of the International Telecommunication Union (ITU-T), International Electrotechnical Commission (IEC)
- **System standards**
  - refer to measurement methods for links and networks.
  - The major organizations are the American National Standards Institute (ANSI), the Institute for Electrical and Electronic Engineers (IEEE), and the ITU-T.

EVOLUTION OF OPTICAL COMMUNICATION SYSTEMS/NETWORKS

First generation:

- Operating at 850 nm; GaAs semiconductor lasers, fiber losses were high
- Bit rate: 45 Mb/s;
- repeater spacing upto 10 km;

Second generation:

- Operating wavelength: 1.3 μm, minimum dispersion; fiber losses <0.5 dB/km
- bit rate: 100 Mb/s (Multimode fibers); Single-mode fibers (1987), 1.7 Gb/s
- Repeater spacing: 50 km

Third generation:

- Operating at 1.55 μm, fiber losses <0.2 dB/km, dispersion-shifted fibers
- bit rate : 2.5 Gb/s - 10 Gb/s
- Repeaters every 60 Km, E - O conversion

EVOLUTION OF OPTICAL COMMUNICATION SYSTEMS/NETWORKS

Fourth generation:

- Operating wavelength: 1.45 to 1.62 μm, WDM,
- Optical amplifiers (EDFAs)
- bit rate: 10 Tb/s
- Repeater spacing: > 10,000 km

Fifth generation:

- uses Roman amplification technique and optical solitiors.
- Bit rate: 40 - 160 Gb/s
- Repeater spacing: 24000 km - 35000 km
- Operating wavelength: 1.53 to 1.57 μm

TEXT BOOKS

- Gerd Keiser, Optical Fiber Communications, TMH India, Fourth Edition, 2010.
- Senior John M., Optical Fiber Communications, Pearson Education India, Third Edition, 2009.
- R.P. Khare, *Fiber optics and optoelectronics*, *Oxford University Press 2004*

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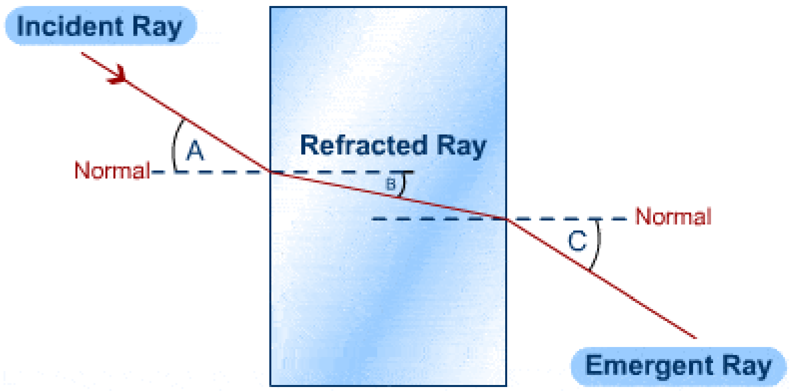
Refractive index

- The most important optical parameter of any medium is its refractive index n.
- The refractive index of a medium is defined as the ratio of the velocity of light in a vacuum (c) to the velocity of light in the medium (*v*).

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

- As *v* is always less than c, n is always greater than 1. For air, $n_a = 1$.

Material	*Refractive index*
Acetone	1.356
Air	1.000
Diamond	2.419
Ethyl alcohol	1.361
Fused quartz (SiO_2): varies with wavelength	1.453 @ 850 nm
Gallium arsenide (GaAs)	3.299 (infrared region)
Glass, crown	1.52–1.62
Glycerin	1.473
Polymethylmethacrylate (PMMA)	1.489
Silicon (varies with wavelength)	3.650 @ 850 nm
Water	1.333

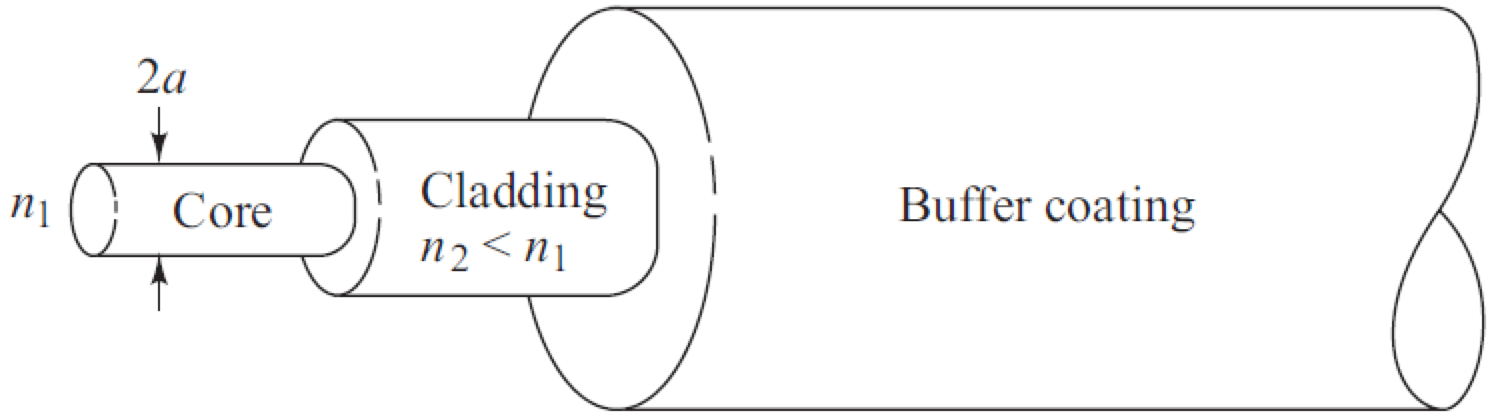


As the light wave goes into the block of higher refractive index it **slows down** and **bends towards the normal line,** so angle A is always bigger than angle B.

As the ray comes out of the block the light wave **speeds up** again and **bends away from the normal line**, so angle B is always smaller than angle C.

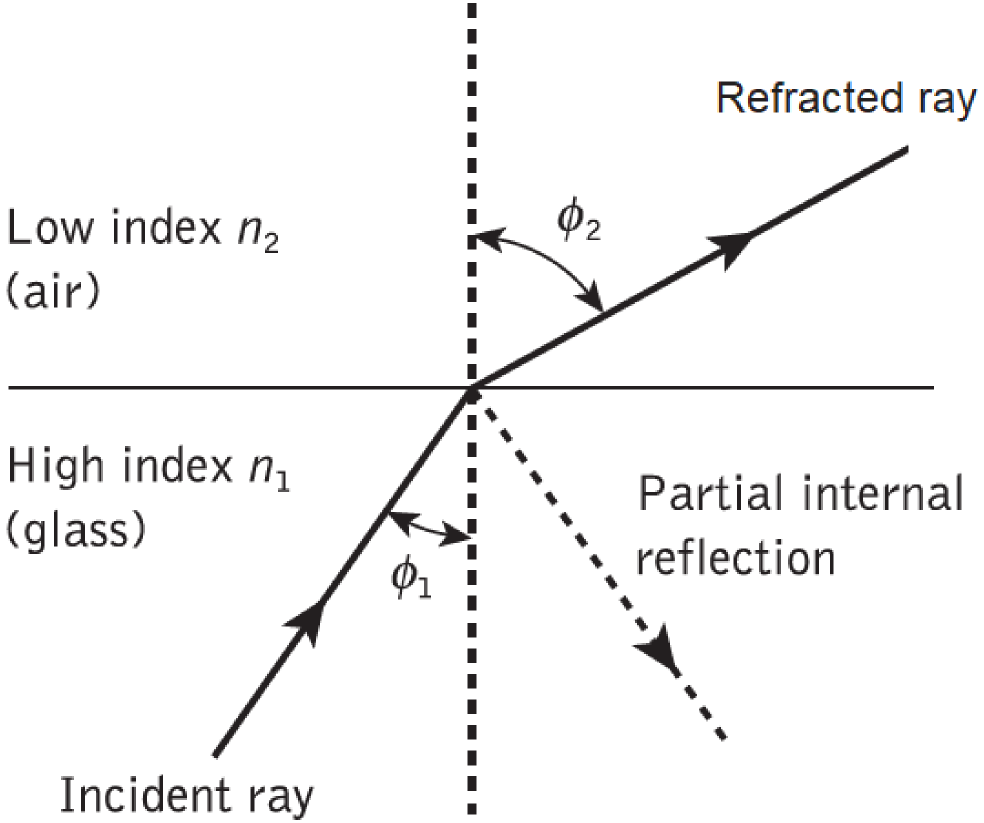
OPTICAL FIBER

- Optical fiber is backbone of the optical network and is a dielectric waveguide that operates at optical frequencies
- It consists of a cylindrical dielectric core surrounded by dielectric cladding.
- A polymer buffer coating is commonly used to enhance its mechanical strength and protect it from environmental effects.
- Both the core and the cladding are made of silica (SiO_2) or plastics
- It carrying information in the form of light



Basic optical laws

- When a ray is incident on the interface between two dielectrics of differing refractive indices (e.g. glass–air), refraction occurs
- As n_1 is greater than n_2, the angle of refraction is always greater than the angle of incidence.



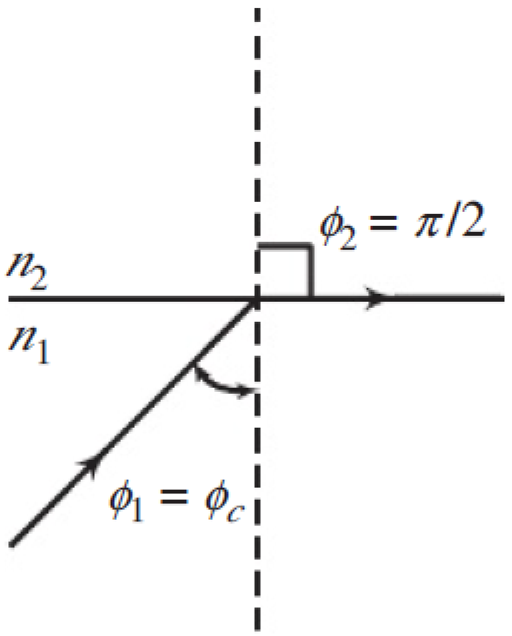
By Snell's law

$$n_1 \sin \emptyset_1 = n_2 \sin \emptyset_2$$

BASIC OPTICAL LAWS

Critical angle :

- As $n_1 > n_2$, if the angle of incidence $\emptyset_1$ increases , the angle of refraction $\emptyset_2$ will go on increasing until a critical situation is reached, when for a certain value of $\emptyset_1 = \emptyset_c$, $\emptyset_2$ becomes 90^0, and the refracted ray passes along the interface. This angle $\emptyset_1 = \emptyset_c$ is called the **critical angle**.

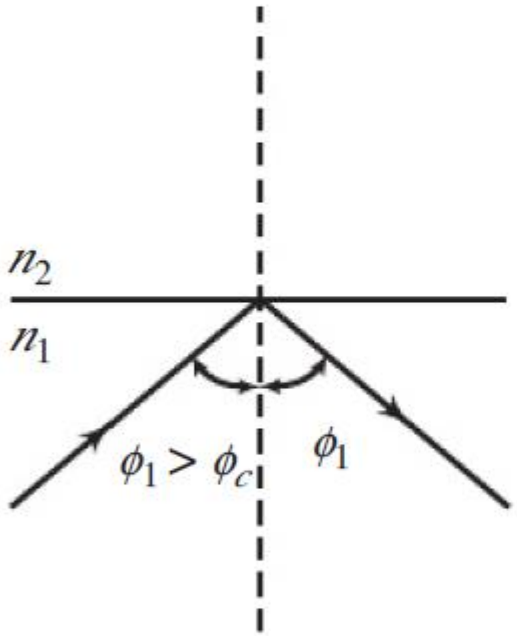


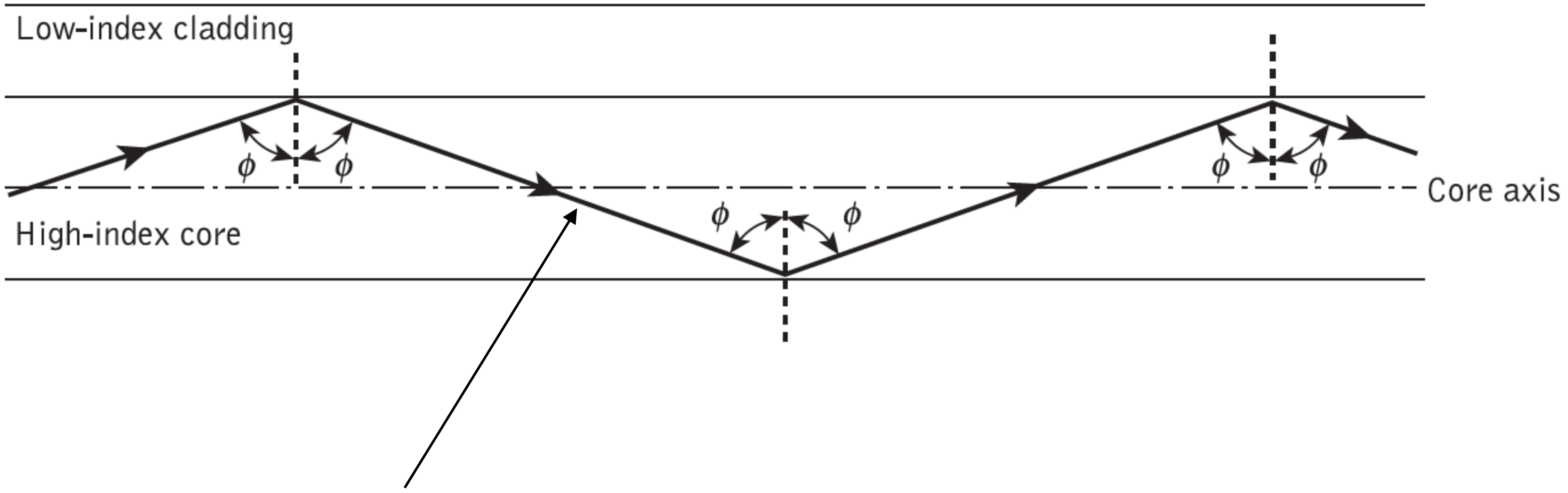
$$\sin \emptyset_c = \frac{n_2}{n_1}$$

BASIC OPTICAL LAWS

Total internal reflection:

- If the angle of incidence $\emptyset_1$ is further increased beyond $\emptyset_c$, the ray is no longer refracted but is reflected back into the same medium. This is called total internal reflection. This phenomenon is responsible for the propagation of light through optical fibers.





meridional ray

RAY OPTICS REPRESENTATION

- The two types of rays that can propagate in a fiber: **meridional rays** and **skew rays**.

Meridional rays:

- confined to the meridian planes of the fiber, which are the planes that contain the axis of symmetry of the fiber (the core axis).
- these rays lies in a single plane, so its path is easy to track as it travels along the fiber.
- Meridional rays can be divided into two general classes: **bound rays** that are trapped in the core and propagate along the fiber axis according to the laws of geometrical optics, and **unbound rays** that are refracted out of the fiber core.

Skew rays:

- not confined to a single plane, but instead tend to follow a helical-type path along the fiber.
- more difficult to track as they travel along the fiber because they do not lie in a single plane.

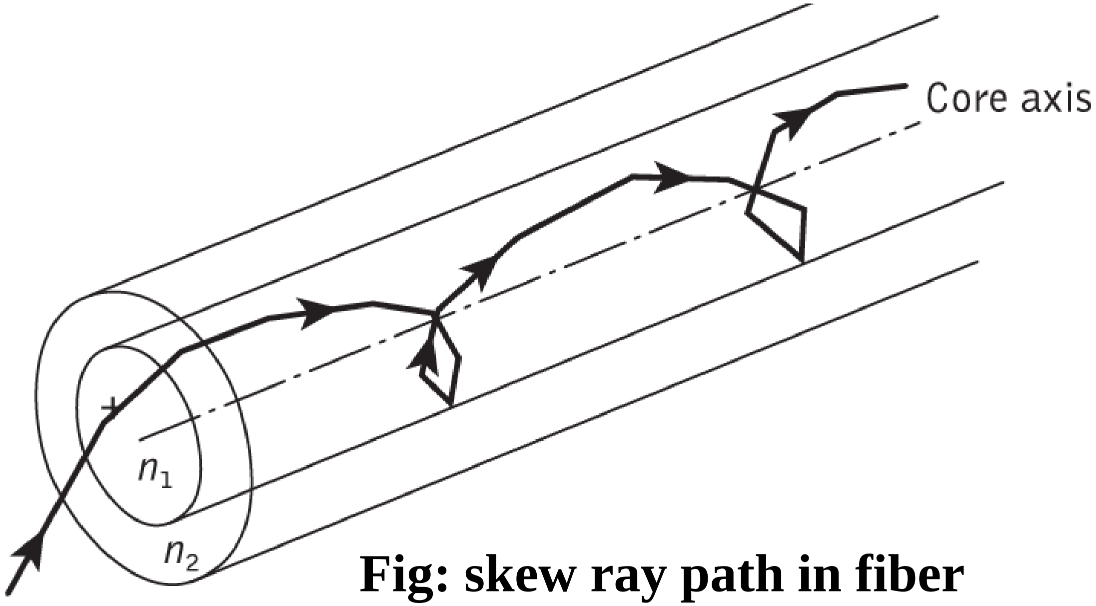
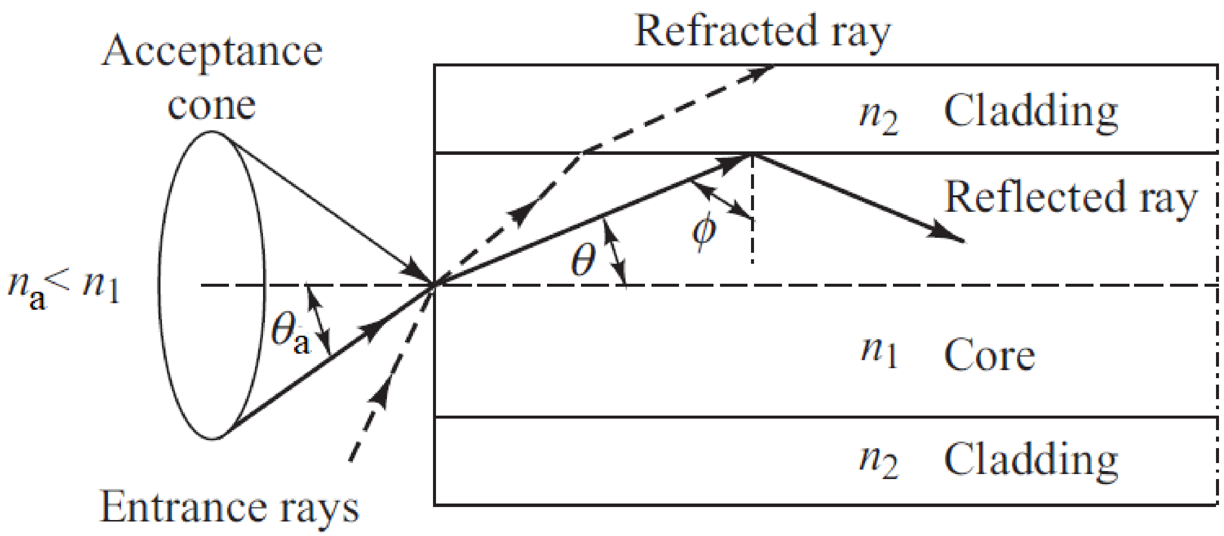


Fig: skew ray path in fiber

Acceptance angle

- It may be observed that the ray enters the fiber core at an angle θ_a to the fiber axis and is refracted at the air–core interface before transmission to the core–cladding interface at the critical angle.
- Any rays which are incident into the fiber core at an angle greater than θ_a will be transmitted to the core–cladding interface at an angle less than ϕ_c, and will not be totally internally reflected (refract out of the core and be lost in the cladding, as the dashed line shows).
- The rays to be transmitted by total internal reflection within the fiber core, they must be incident on the fiber core within an acceptance cone defined by the conical half angle θ_a.



- The maximum angle (θ_a) to the axis at which light may enter the fiber in order to be propagated is referred to as the **acceptance angle** for the fiber.

NUMERICAL APERTURE

At the air–core interface, by Snell's law: $n_a \sin\theta_a = n_1 \sin\theta$

Where $\theta = \frac{\pi}{2} - \emptyset$

$$n_a \sin\theta_a = n_1 \cos\emptyset = n_1\sqrt{1 - sin^2\emptyset}$$

for total internal reflection is considered, $\emptyset$ becomes equal to the critical angle for the core–cladding interface

$$\sin\emptyset = \frac{n_2}{n_1}$$

$$n_a \sin\theta_a = \sqrt{{n_1}^2 - {n_2}^2}$$

- The term $n_a \sin\theta_a$ is called the numerical aperture (NA) of the fiber; it determines the light-gathering capacity of the fiber.

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

- The *NA* may also be defined in terms of the relative refractive index difference Δ between the core and the cladding which is defined as

$$NA = n_1\sqrt{2\Delta}$$

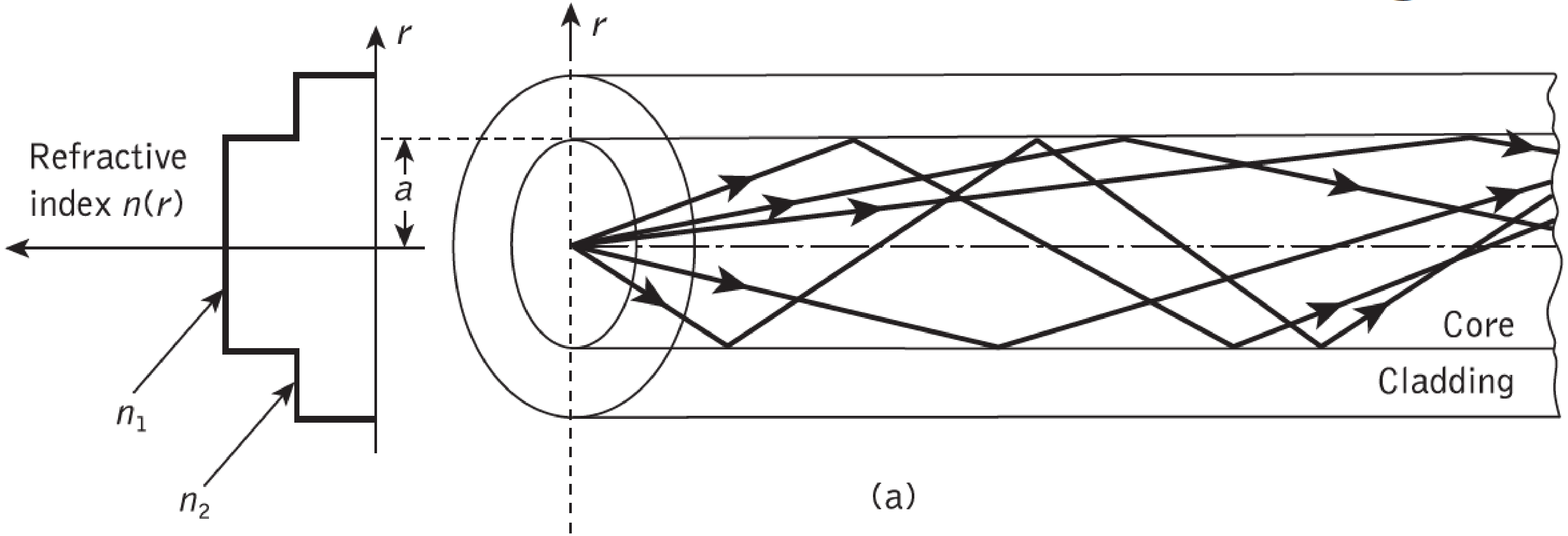
Where $\Delta = \frac{{n_1}^2 - {n_2}^2}{2{n_1}^2}$

Optical Fiber types

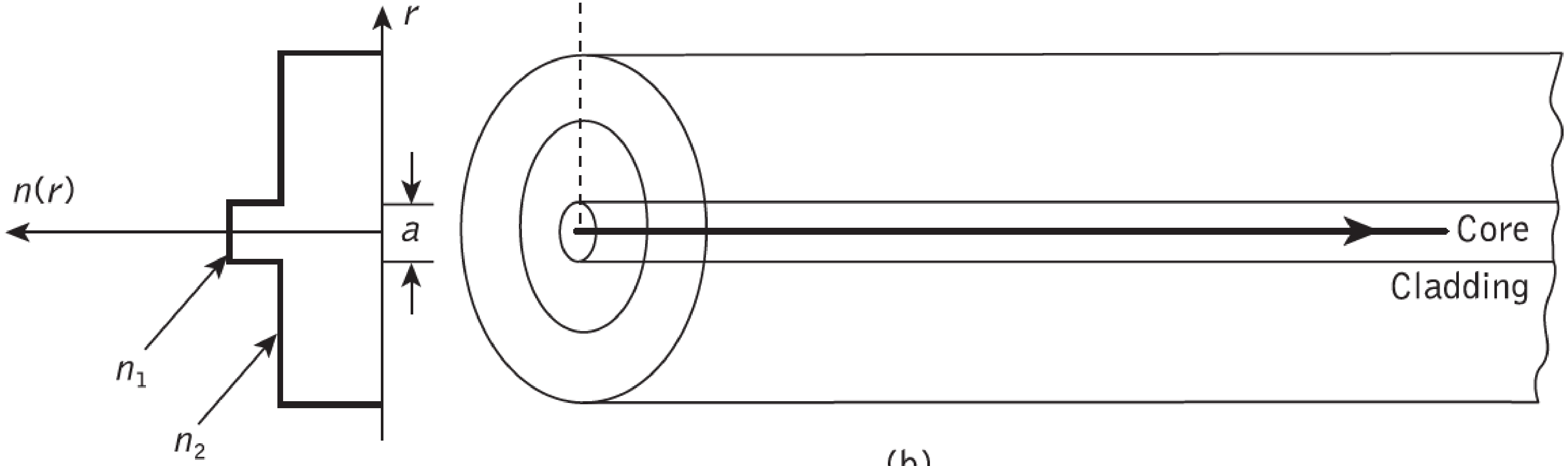
- Variations in the material composition of the core give rise to the two commonly used fiber types
- **Step index fiber**: the refractive index of the core is uniform throughout and undergoes an abrupt change (or step) at the cladding boundary
- **Graded index fiber**: the core refractive index is made to vary as a function of the radial distance from the center of the fiber

Step index fiber

$$n(r) = \begin{cases} n_1 & r < a \quad \text{(core)} \\ n_2 & r \geq a \quad \text{(cladding)} \end{cases}$$



(a)

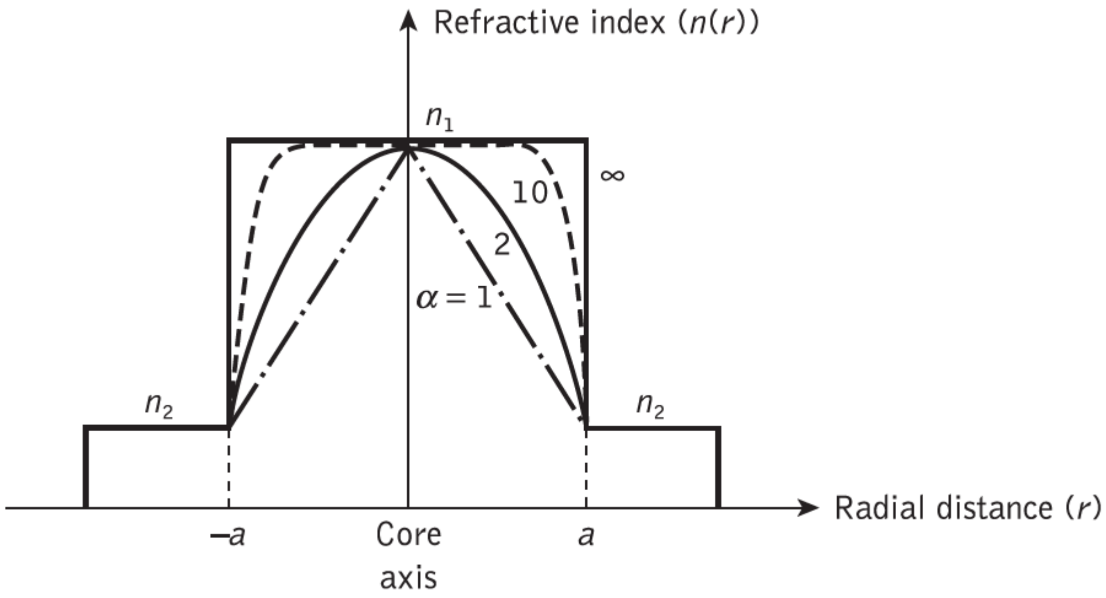


(b)

Graded index fiber

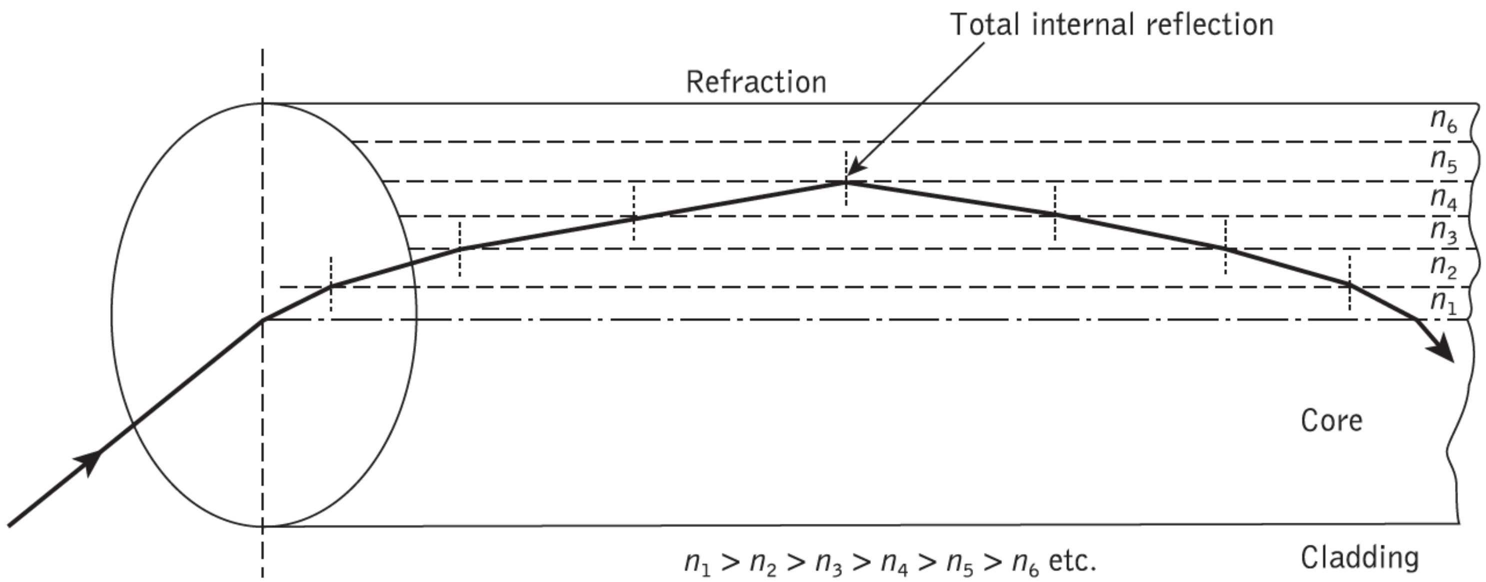
$$n(r) = \begin{cases} n_1(1 - 2\Delta(r/a)^{\alpha})^{\frac{1}{2}} & r < a \quad \text{(core)} \\ n_1(1 - 2\Delta)^{\frac{1}{2}} = n_2 & r \geq a \quad \text{(cladding)} \end{cases}$$

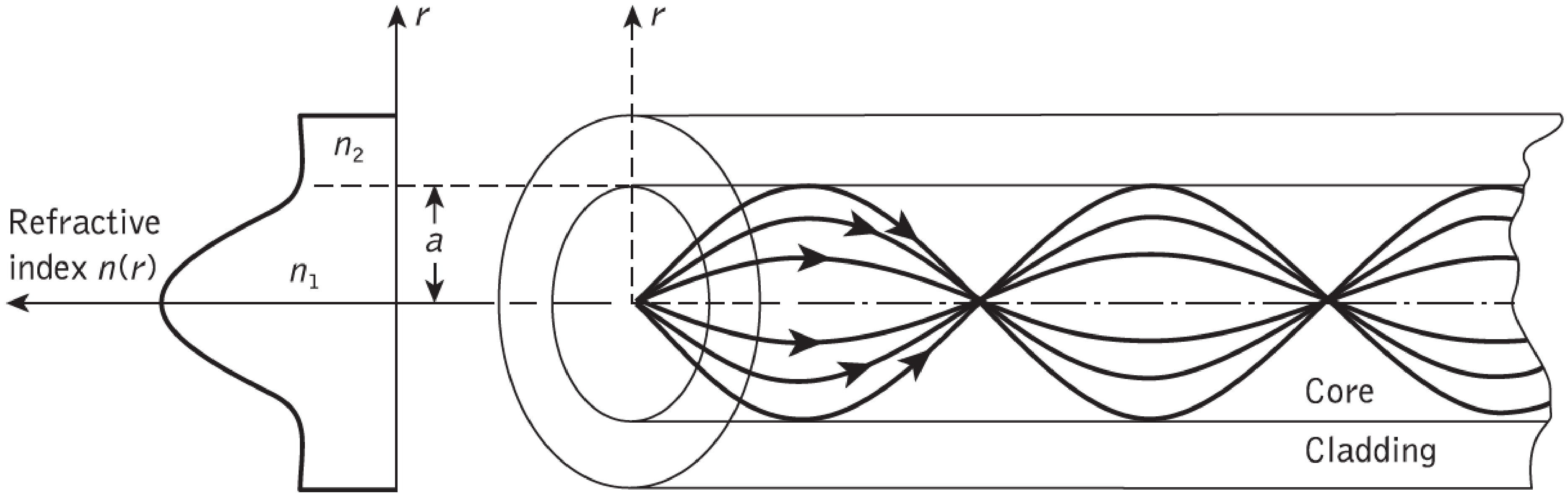
where Δ is the relative refractive index difference and α is the profile parameter which gives the characteristic refractive index profile of the fiber core.



- It may be observed that the meridional rays shown appear to follow curved paths through the fiber core.
- Using the concepts of geometric optics, the gradual decrease in refractive index from the center of the core creates many refractions of the rays as they are effectively incident on a large number or high to low index interfaces where a ray is shown to be gradually curved, with an ever-increasing angle of incidence, until the conditions for total internal reflection are met, and the ray travels back towards the core axis, again being continuously refracted

Ray propagation in Graded index fiber





PROBLEMS

1. A silica optical fiber with a core diameter large enough to be considered by ray theory analysis has a core refractive index of 1.50 and a cladding refractive index of 1.47. *Determine:* (a) the critical angle at the core–cladding interface; (b) the *NA* for the fiber; (c) the acceptance angle in air for the fiber. (**Ans: (a) 78.5°; (b) 0.3; (c) 17.4°)**
2. The velocity of light in the core of a step index fiber is 2.01×10^8 m/s, and the critical angle at the core–cladding interface is 80°. Determine the numerical aperture and the acceptance angle for the fiber in air, assuming it has a core diameter suitable for consideration by ray analysis. The velocity of light in a vacuum is 2.998×10^8 m/s.
3. A step index fiber with a large core diameter compared with the wavelength of the transmitted light has an acceptance angle in air of 22° and a relative refractive index difference of 3%. Estimate the numerical aperture and the critical angle at the core–cladding interface for the fiber.
4. A step index fiber has a solid acceptance angle in air of 0.115 radians and a relative refractive index difference of 0.9%. Estimate the speed of light in the fiber core.

TEXT BOOKS

- Gerd Keiser, Optical Fiber Communications, TMH India, Fourth Edition, 2010.
- Senior John M., Optical Fiber Communications, Pearson Education India, Third Edition, 2009.
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MODES IN A PLANAR WAVEGUIDE

- Only a finite set of rays at certain discrete angles greater than or equal to the critical angle $\emptyset_c$ is capable of propagating along a fiber.
- These angles are related to a set of electromagnetic wave patterns or field distributions called ***modes*** that can propagate along a fiber.
- The ray model does not predict correctly that even after total internal reflection there will be some field in the cladding
- For an accurate and complete description of light propagation inside an optical fiber we have to go for the wave model**.** Here we treating light as an electromagnetic wave.

ELECTROMAGNETIC MODE THEORY FOR OPTICAL PROPAGATION

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \times \mathbf{H} = \frac{\partial \mathbf{D}}{\partial t}$$

$$\nabla \cdot \mathbf{D} = 0 \qquad \text{(no free charges)}$$

$$\nabla \cdot \mathbf{B} = 0 \qquad \text{(no free poles)}$$

The four field vectors are related by the relations:

$$\mathbf{D} = \varepsilon \mathbf{E}$$
$$\mathbf{B} = \mu \mathbf{H}$$

$$\nabla^2 \mathbf{E} = \mu\varepsilon \frac{\partial^2 \mathbf{E}}{\partial t^2}$$

$$\nabla^2 \mathbf{H} = \mu\varepsilon \frac{\partial^2 \mathbf{H}}{\partial t^2}$$

$$\nabla^2 \psi = \frac{1}{\upsilon_p^2} \frac{\partial^2 \psi}{\partial t^2}$$

Phase velocity

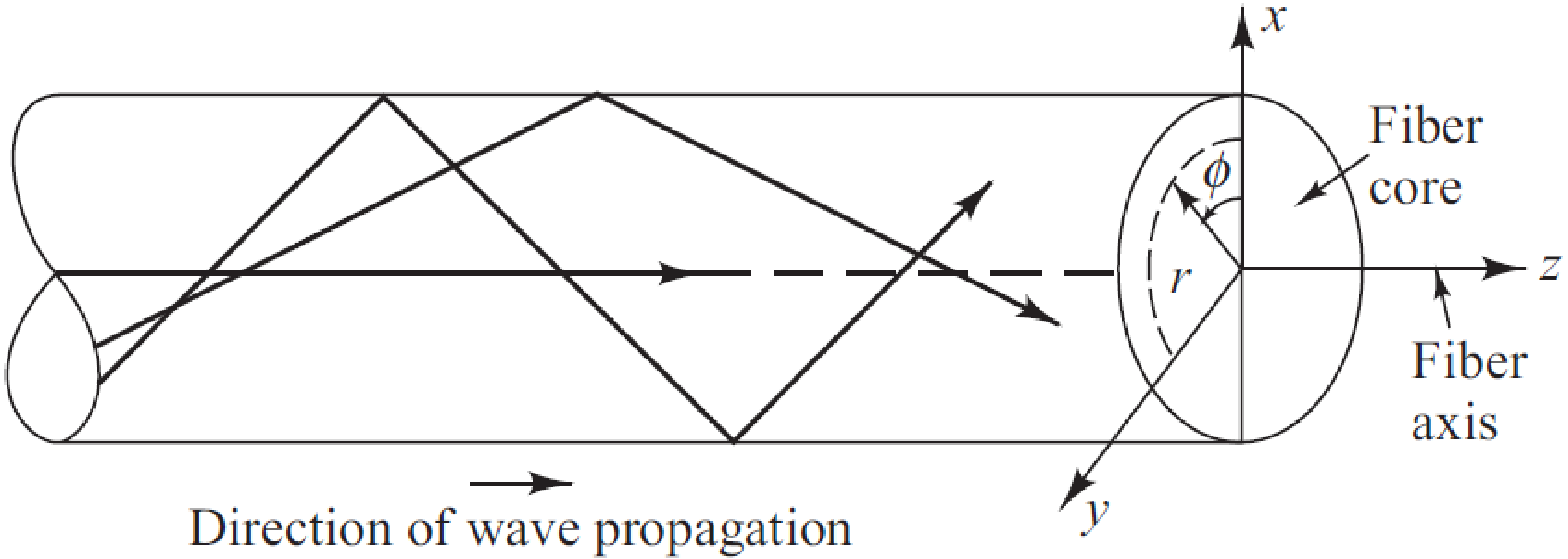
$$\upsilon_p = \frac{1}{(\mu\varepsilon)^{\frac{1}{2}}} = \frac{1}{(\mu_r \mu_0 \varepsilon_r \varepsilon_0)^{\frac{1}{2}}}$$

For an isotropic medium , the refractive index n is related as $v_p = c/n$

The planar wave guides described by rectangular coordinates (x,y,z) and the circular fibers described by cylindrical polar coordinates (r,Φ,z).

$$\Psi = \Psi_0(x, y)\, e^{j(\omega t-\beta z)}\ ;planar$$

$$\Psi = \Psi_0(r, \phi)\, e^{j(\omega t-\beta z)};circular$$



$$\mathbf{E} = \mathbf{E}_0(r, \phi)\, e^{j(\omega t-\beta z)}$$

$$\mathbf{H} = \mathbf{H}_0(r, \phi)\, e^{j(\omega t-\beta z)}$$

- The electric field and magnetic filed are a vector quantities, each having three components. So we have total six field components.
- However all these components are not independent of each other, only two components are independent components and express the remaining four components in terms of the independent components.
- Since in this case the wave propagates along the axis of the fiber i.e. in the z direction, E_z and H_z (also called the longitudinal components) are taken as independent components and the other four transverse field components (E_r , $E\phi$, H_r , and $H\phi$) are expressed in terms of E_z and H_z components.

$$E_r = -\frac{j}{q^2}\left(\beta\frac{\partial E_z}{\partial r} + \frac{\omega\mu}{r}\frac{\partial H_z}{\partial \phi}\right) \qquad and \qquad E_\phi = -\frac{j}{q^2}\left(\frac{\beta}{r}\frac{\partial E_z}{\partial \phi} - \omega\mu\frac{\partial H_z}{\partial r}\right)$$

$$H_r = -\frac{j}{q^2}\left(\beta\frac{\partial H_z}{\partial r} - \frac{\omega\epsilon}{r}\frac{\partial E_z}{\partial \phi}\right) \qquad and \qquad H_\phi = -\frac{j}{q^2}\left(\frac{\beta}{r}\frac{\partial H_z}{\partial \phi} + \omega\epsilon\frac{\partial E_z}{\partial r}\right)$$

Where $q^2 = \omega^2\mu\epsilon - \beta^2$

- The wave equation for the cylindrical homogeneous core waveguide

$$\frac{\partial^2 E_z}{\partial r^2} + \frac{1}{r}\frac{\partial E_z}{\partial r} + \frac{1}{r^2}\frac{\partial^2 E_z}{\partial \phi^2} + q^2 E_z = 0$$

$$\frac{\partial^2 H_z}{\partial r^2} + \frac{1}{r}\frac{\partial H_z}{\partial r} + \frac{1}{r^2}\frac{\partial^2 H_z}{\partial \phi^2} + q^2 H_z = 0$$

- If the boundary conditions do not lead to coupling between the field components, mode solutions can be obtained in which either $E_z = 0$ or $H_z = 0$.
- When $E_z = 0$ the modes are called transverse electric or TE modes, and when $H_z = 0$ they are called transverse magnetic or TM modes.
- Hybrid modes exist if both E_z and H_z are non-zero. These are designated as HE or EH modes, depending on whether H_z or E_z, dominates to the transverse field.

WAVE EQUATIONS FOR STEP-INDEX FIBERS

- For a general solution of the wave equation, apply separation of variables

$$E_z = A\, F_1(r)F_2(\phi)F_3(z)F_4(t)$$

- From the general wave equation model, the time- and z-dependent factors are given by

$$F_3(z)F_4(t) = e^{j(\omega t-\beta z)}$$

- Because of the circular symmetry of the waveguide, each field component does not change when the coordinate f is increased by 2π. The fields must be periodic in ϕ with a period of 2π and which is of the form

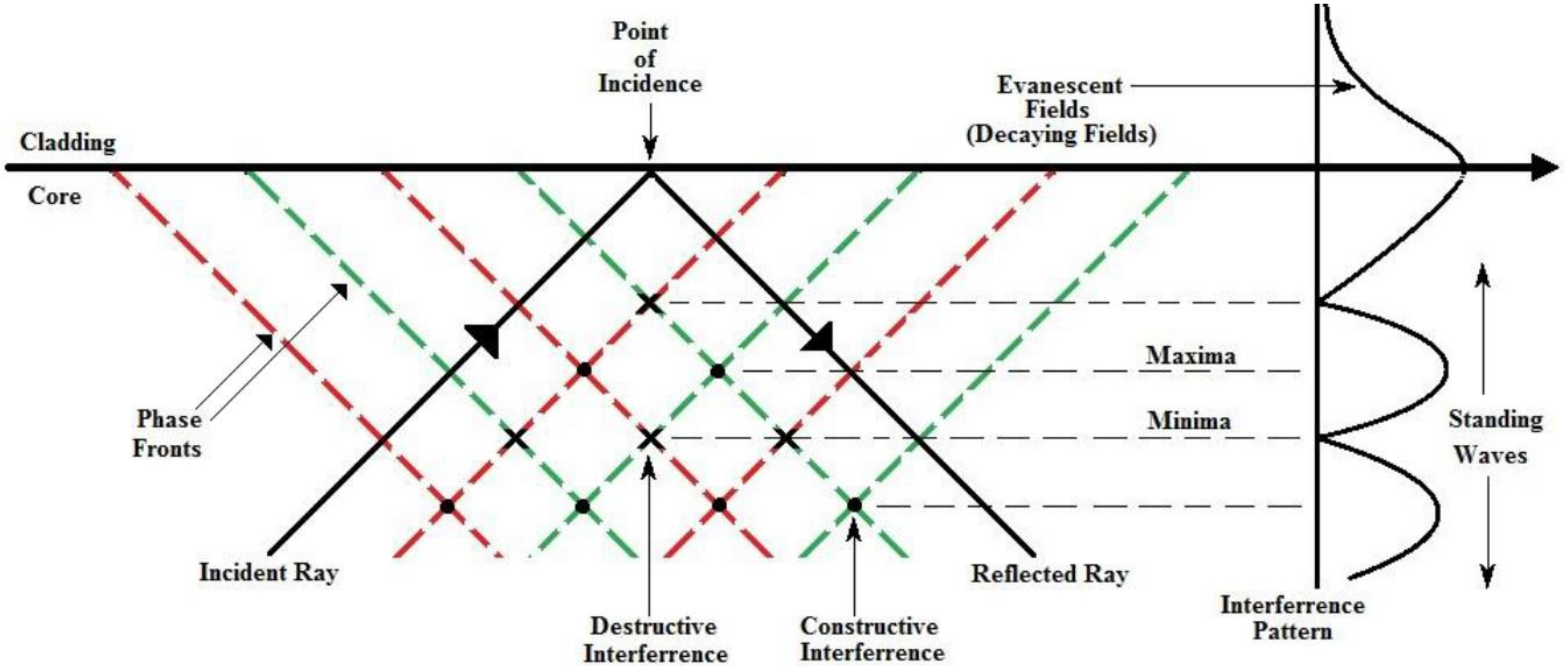
$$F_2(\phi) = e^{j\nu\phi}$$

- Where the constant *v* can be positive or negative, but it must be an integer

$$\frac{\partial^2 F_1(r)}{\partial r^2} + \frac{1}{r}\frac{\partial F_1(r)}{\partial r} + \left(-\frac{v^2}{r^2} + q^2\right)F_1(r) = 0$$

which is a well-known differential equation for Bessel functions.

- A variety of solutions to the Bessel's equation depending upon the parameters '*v*' (integer and positive quantity) and '*q*' (real/ imaginary/ complex)



Total Internal Reflection of Light inside a fiber core

- For guided mode propagation, a mode is guided when its fields are confined to the guide (core), and outside the guide the fields decay monotonically.
- Thus, for r < a the solutions are Bessel functions of the first kind of order *v*. The expressions for Ez and Hz inside the core are

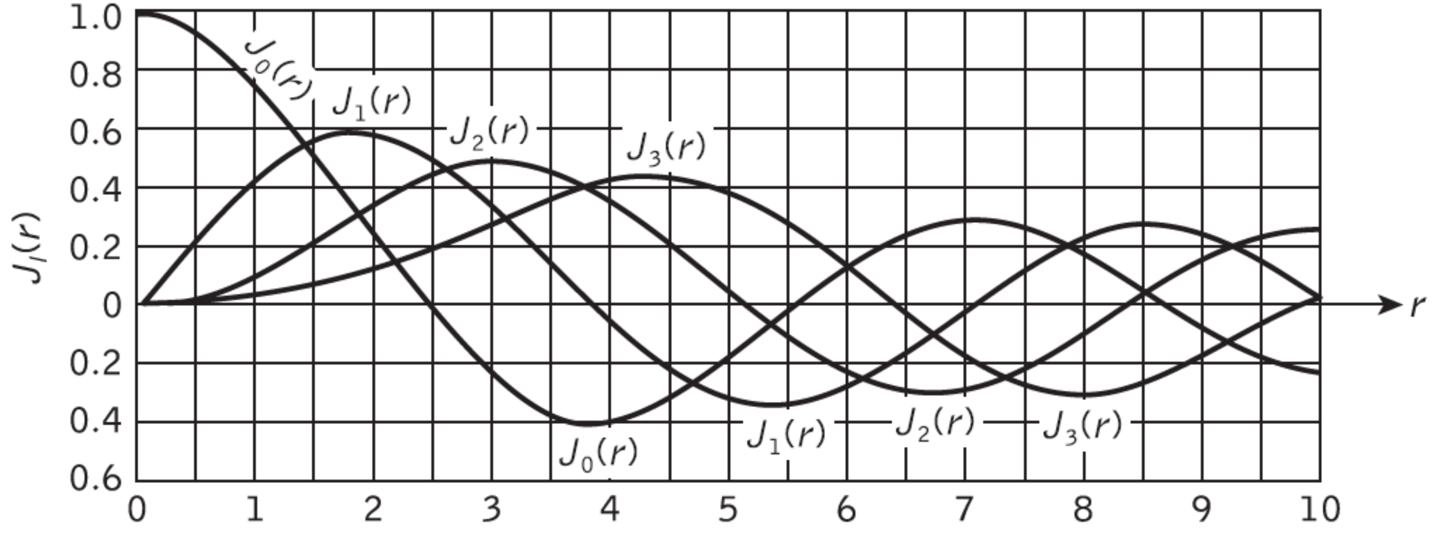
$$E_z(r < a) = A\,J_v(qr)\,e^{jv\phi}e^{j(\omega t-\beta z)}$$
$$H_z(r < a) = B\,J_v(qr)\,e^{jv\phi}e^{j(\omega t-\beta z)}$$

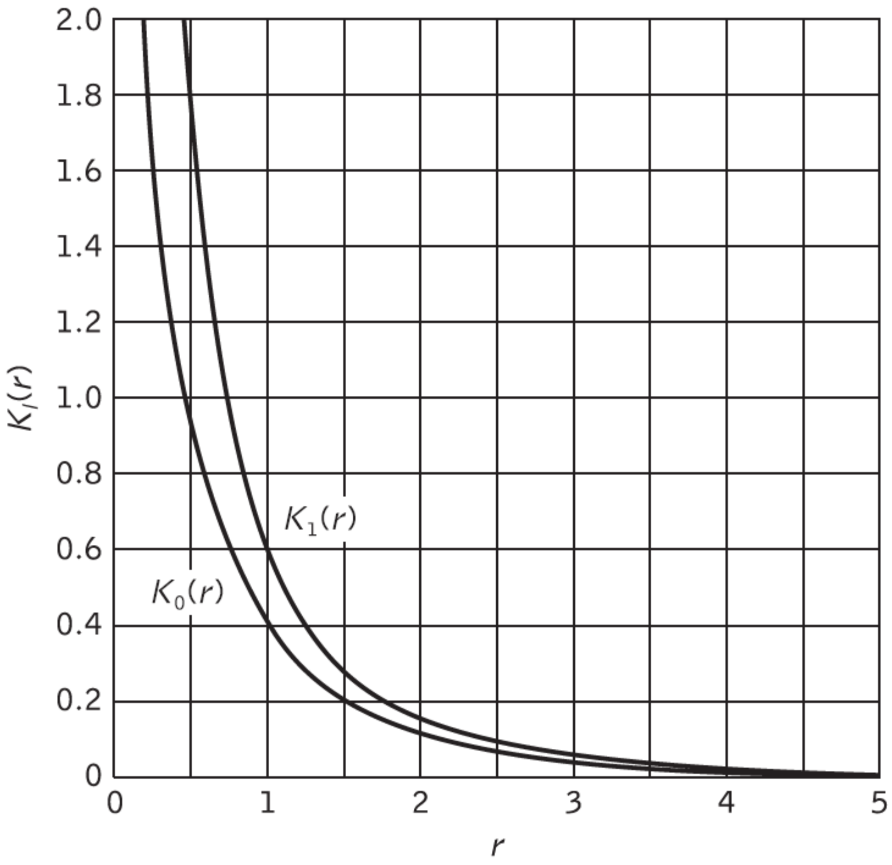
where A and B are arbitrary constants.

- For r > a (Outside of the core) the solutions are given by modified Bessel functions of the second kind order *v*. The expressions for Ez and Hz inside the core are

$$E_z(r > a) = C\,K_v(qr)\,e^{jv\phi}e^{j(\omega t-\beta z)}$$
$$H_z(r > a) = D\,K_v(qr)\,e^{jv\phi}e^{j(\omega t-\beta z)}$$

where C and D are arbitrary constants.





Variation of the Bessel function and modified Bessel function

Inside the core of the optical fiber **r < a** and ***q²* > *0*** and therefore $\omega^2\mu\epsilon_1 > \beta^2$

$$\omega\sqrt{\mu\epsilon_1} = \frac{2\pi n_1}{\lambda} = kn_1 = k_1; where\ k = \frac{2\pi}{\lambda}$$

In the cladding of the optical fiber **r > a** and ***q²* < *0*** and therefore $\omega^2\mu\epsilon_2 < \beta^2$; $\omega\sqrt{\mu\epsilon_2} = \frac{2\pi n_2}{\lambda} = kn_2 = k_2$

$$k_2 < \beta < k_1$$

Where we can defined

$$q = U = \sqrt{{k_1}^2 - \beta^2} \qquad for\ r < a$$

$$q = W = \sqrt{\beta^2 - {k_2}^2} \qquad for\ r > a$$

Thus the expressions for longitudinal components of electric and magnetic fields can be written as:

Inside the core $(r < a)$

$$E_{z1} = A\, J_v(Ur)\, e^{jv\phi}\, e^{j(\omega t - \beta z)}$$
$$H_{z1} = B\, J_v(Ur)\, e^{jv\phi}\, e^{j(\omega t - \beta z)}$$

Inside the cladding $(r > a)$

$$E_{z2} = C\, K_v(Wr)\, e^{jv\phi}\, e^{j(\omega t - \beta z)}$$
$$H_{z2} = D\, K_v(Wr)\, e^{jv\phi}\, e^{j(\omega t - \beta z)}$$

- The solutions for β must be determined from the boundary conditions.
- Since the core-cladding boundary is a purely dielectric-dielectric boundary, the following boundary conditions are applicable at the boundary (r=a) where ‘a’ is the radius of the optical fiber core.
- The tangential components of the electric field (E_ϕ and E_z) and magnetic field (E_ϕ and E_z) are continuous across the boundary.

$$E_{z1} - E_{z2} = A\, J_v(Ua) \ - C\, K_v(Wa) = 0$$
$$H_{z1} - H_{z2} = B\, J_v(Ua) \ - D\, K_v(Wa) = 0$$
$$E_{\emptyset 1} - E_{\emptyset 2} = -\frac{j}{U^2}\left(A\frac{jv\beta}{a} J_v(Ua) - B\omega\mu U\, J_v{}'(Ua)\right) + \frac{j}{W^2}\left(C\frac{jv\beta}{a} K_v(Wa) - D\omega\mu W\, K_v{}'(Wa)\right) = 0$$
$$H_{\emptyset 1} - H_{\emptyset 2} = -\frac{j}{U^2}\left(B\frac{jv\beta}{a} J_v(Ua) + A\,\omega\epsilon_1\, U\, J_v{}'(Ua)\right) + \frac{j}{W^2}\left(D\frac{jv\beta}{a} K_v(Wa) + C\omega\epsilon_1 W\, K_v{}'(Wa)\right) = 0$$

From these four equation, the characteristic / eigen value equation can be expressed as

$$\left(\frac{J_v{}'(Ua)}{UJ_v(Ua)} + \frac{K_v{}'(Wa)}{WK_v(Wa)}\right)\left(k_1{}^2\frac{J_v{}'(Ua)}{UJ_v(Ua)} + k_2{}^2\frac{K_v{}'(Wa)}{WK_v(Wa)}\right) = \left(\frac{\beta v}{a}\right)^2\left(\frac{1}{U^2} + \frac{1}{W^2}\right)^2$$

MODES IN STEP-INDEX FIBER

- For the dielectric fiber waveguide, all modes are hybrid modes except those for which $v = 0$.
- When $v = 0$,

$$\left(\frac{J_1(Ua)}{UJ_0(Ua)} + \frac{K_1(Wa)}{WK_0(Wa)}\right)\left({k_1}^2\frac{J_1(Ua)}{UJ_0(Ua)} + {k_2}^2\frac{K_1(Wa)}{WK_0(Wa)}\right) = 0$$

Since the derivatives of the Bessel and the Modified Bessel functions can be related as

$$J_0{}'(x) = -J_1(x)$$

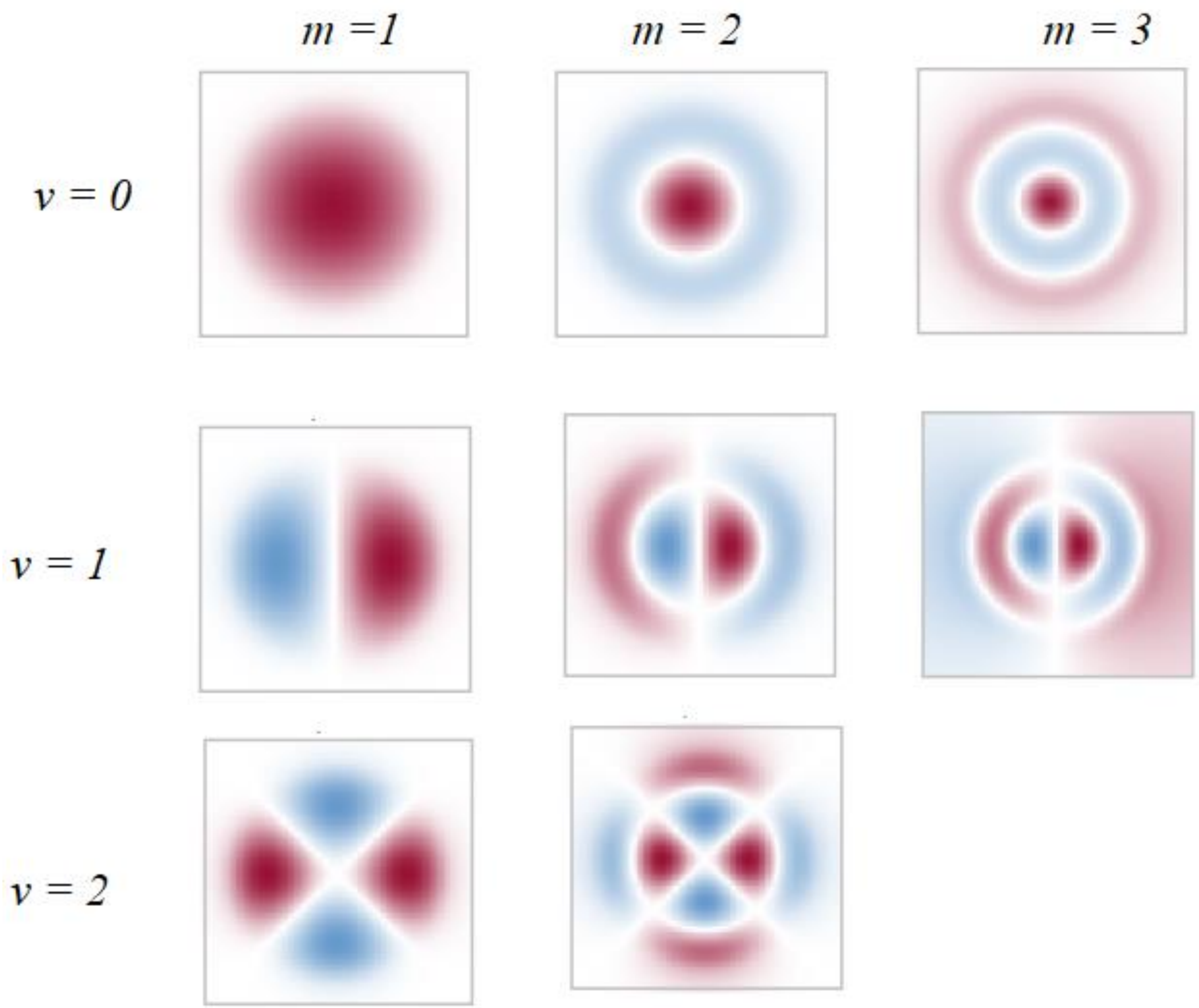
$$\frac{J_1(Ua)}{UJ_0(Ua)} + \frac{K_1(Wa)}{WK_0(Wa)} = 0; \qquad TE\ mode$$

$$ {k_1}^2\frac{J_1(Ua)}{UJ_0(Ua)} + {k_2}^2\frac{K_1(Wa)}{WK_0(Wa)} = 0; \qquad TM\ mode$$

MODES IN STEP-INDEX FIBER: IDENTIFICATION OF THE FIELD PATTERN FOR ORDER (v, m)

- To help describe the modes, first examine the behavior of the J-type Bessel functions. Because of the oscillatory behavior of Bessel function J_v, there will be ***m* roots** for a given ***v* value**. These roots will be designated by β_{vm},
- The combination (v,m) helps us to identify a particular mode and its corresponding light intensity pattern and the corresponding modes are either TE_{vm}, TM_{vm}, EH_{vm}, or HE_{vm}
- The index v of the combination (v,m) represents the number of complete cycles of the field in the azimuthal plane (indicates the behavior of the field in the azimuthal plane, i.e. the variation of the field with respect to ϕ)
- the index 'm' represents the number of zero crossings in the azimuthal direction (maxima and minima in the azimuthal plane)
- For example TE_{02} would result in an intensity pattern that would be circularly symmetric about the axis with maximum intensity at the center of the fiber and there would be two concentric dark rings around the axis.

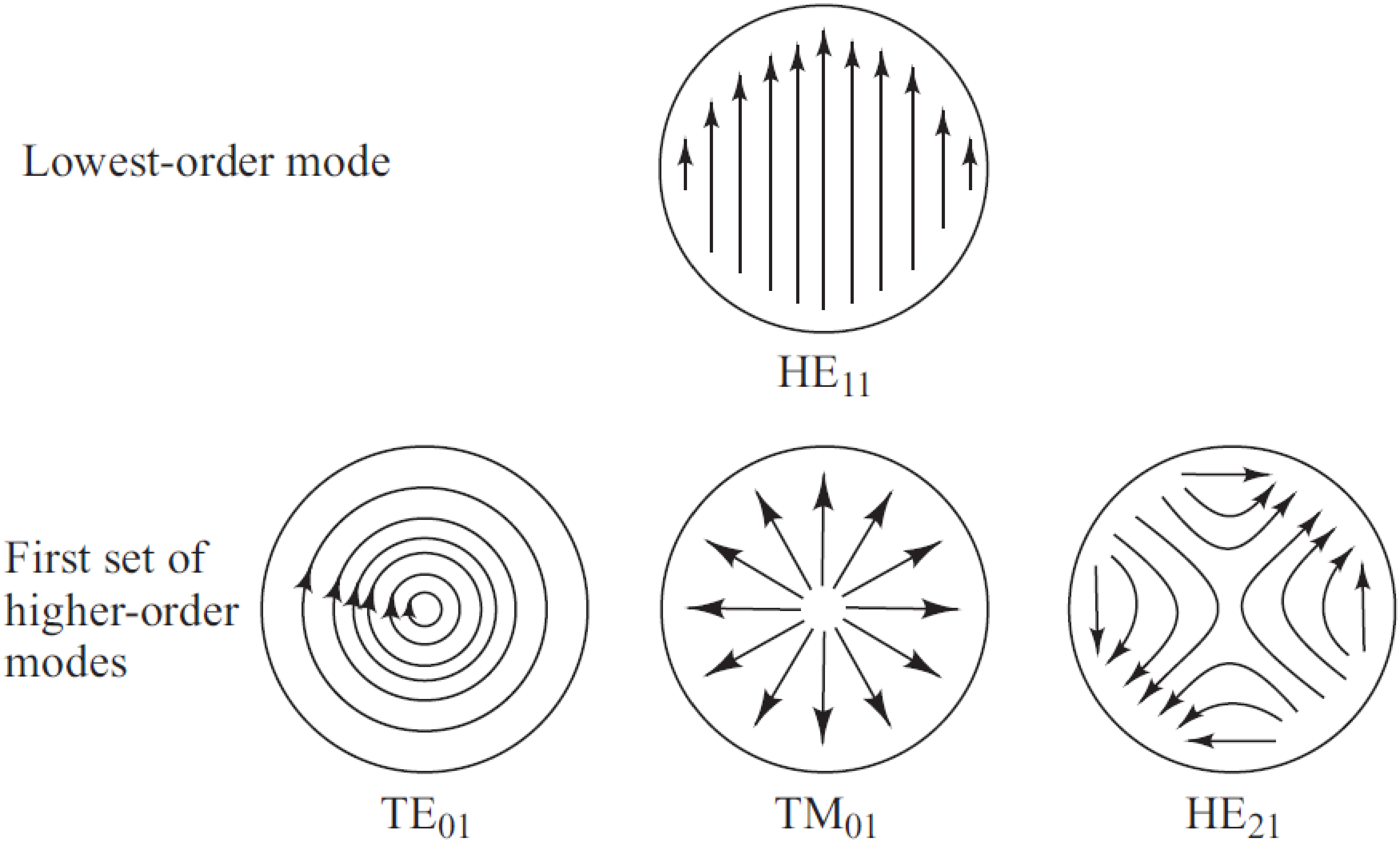
Mode pattern



Meridional Rays

Skew Rays

Lowest-order modes in a step-index fiber



Mode cut off

- A mode is referred to as being cut off when it is no longer bound to the core of the fiber, so that its field no longer decays on the outside of the core.
- The propagation constant β for the guided mode has to be nearer to k_1 and larger than k_2 for the light energy of the mode to remain confined inside the core of the optical fiber. (i.e., $kn_2 < \beta < kn_1$)- indicative of the amount of energy in the mode that lies in the core and the cladding.
- when $\beta = kn_2$, then the mode phase velocity is equal to the velocity of light in the cladding and the mode is no longer properly guided. In this case the mode is said to be cut off and the value $W = 0$
- Unguided or radiation modes have frequencies below cutoff where $\beta < kn_2$, and hence W is imaginary (these called leaky modes)
- As β is increased above n_2k, less power is propagated in the cladding until at $\beta = n_1k$ all the power is confined to the fiber core.

Cutoff conditions for some lower-order modes

ν	Mode	Cutoff condition
0	TE_{0m}, TM_{0m}	$J_0(ua) = 0$
1	HE_{1m}, EH_{1m}	$J_1(ua) = 0$
≥ 2	$EH_{\nu m}$	$J_\nu(ua) = 0$
	$HE_{\nu m}$	$\left(\dfrac{n_1^2}{n_2^2} + 1\right) J_{\nu-1}(ua) = \dfrac{ua}{\nu - 1} J_\nu(ua)$

NORMALIZED FREQUENCY OR V-NUMBER OF OPTICAL FIBER

- Which is defined as

$$V^2 = a^2(U^2 + W^2) = \left(\frac{2\pi a}{\lambda}\right)^2 ({n_1}^2 - {n_2}^2)$$

$$V = \frac{2\pi a}{\lambda}\sqrt{{n_1}^2 - {n_2}^2} = \frac{2\pi a}{\lambda} NA$$

- which is a dimensionless number that determines how many modes a fiber can support.
- The total number of modes M entering the fiber

$$M = \frac{V^2}{2}; \qquad \text{for step index fiber}$$

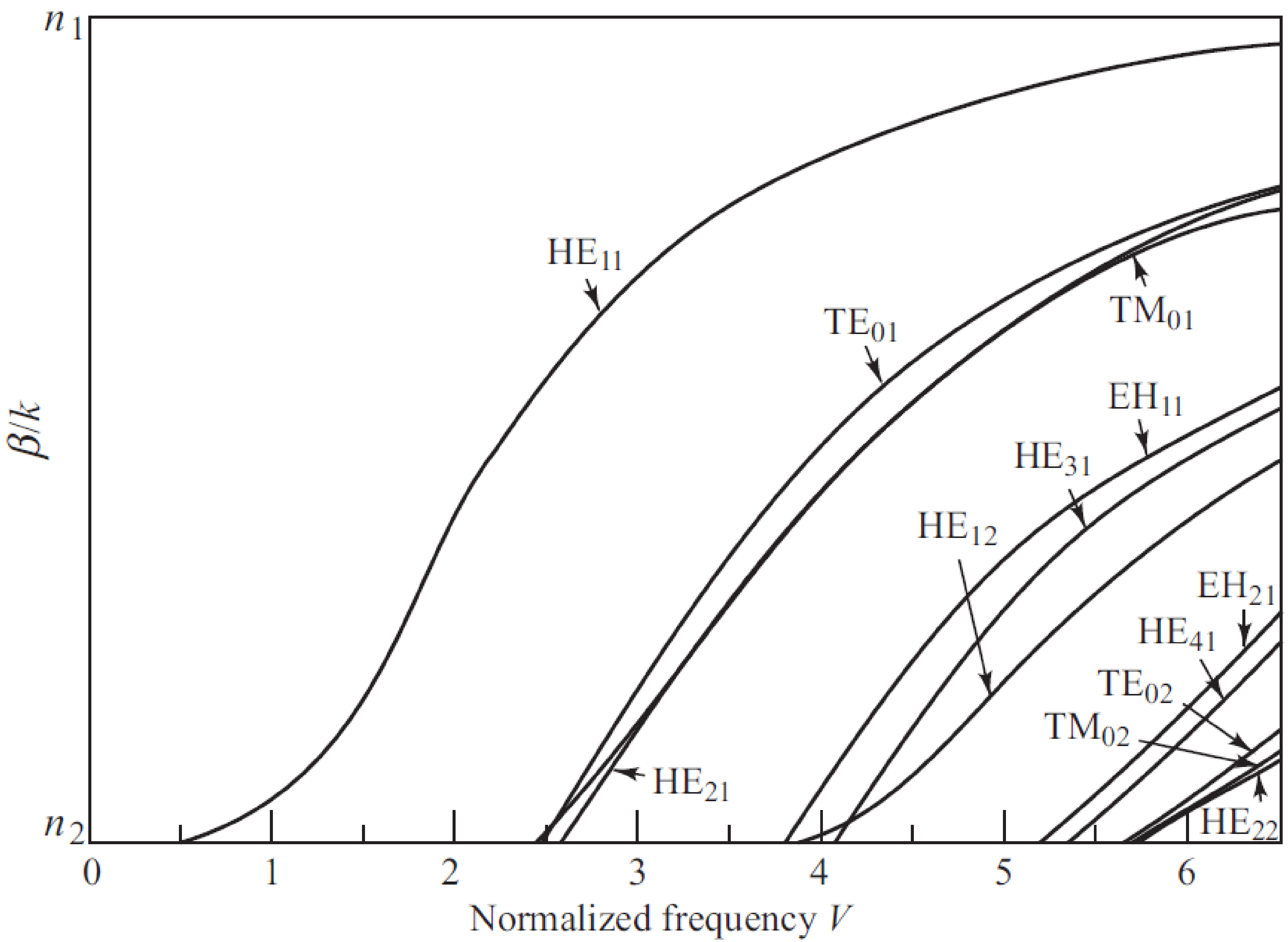
$$M = \frac{\alpha}{\alpha + 2}\frac{V^2}{2}; \qquad \text{for graded index fiber}$$

NORMALIZED PROPAGATION CONSTANT

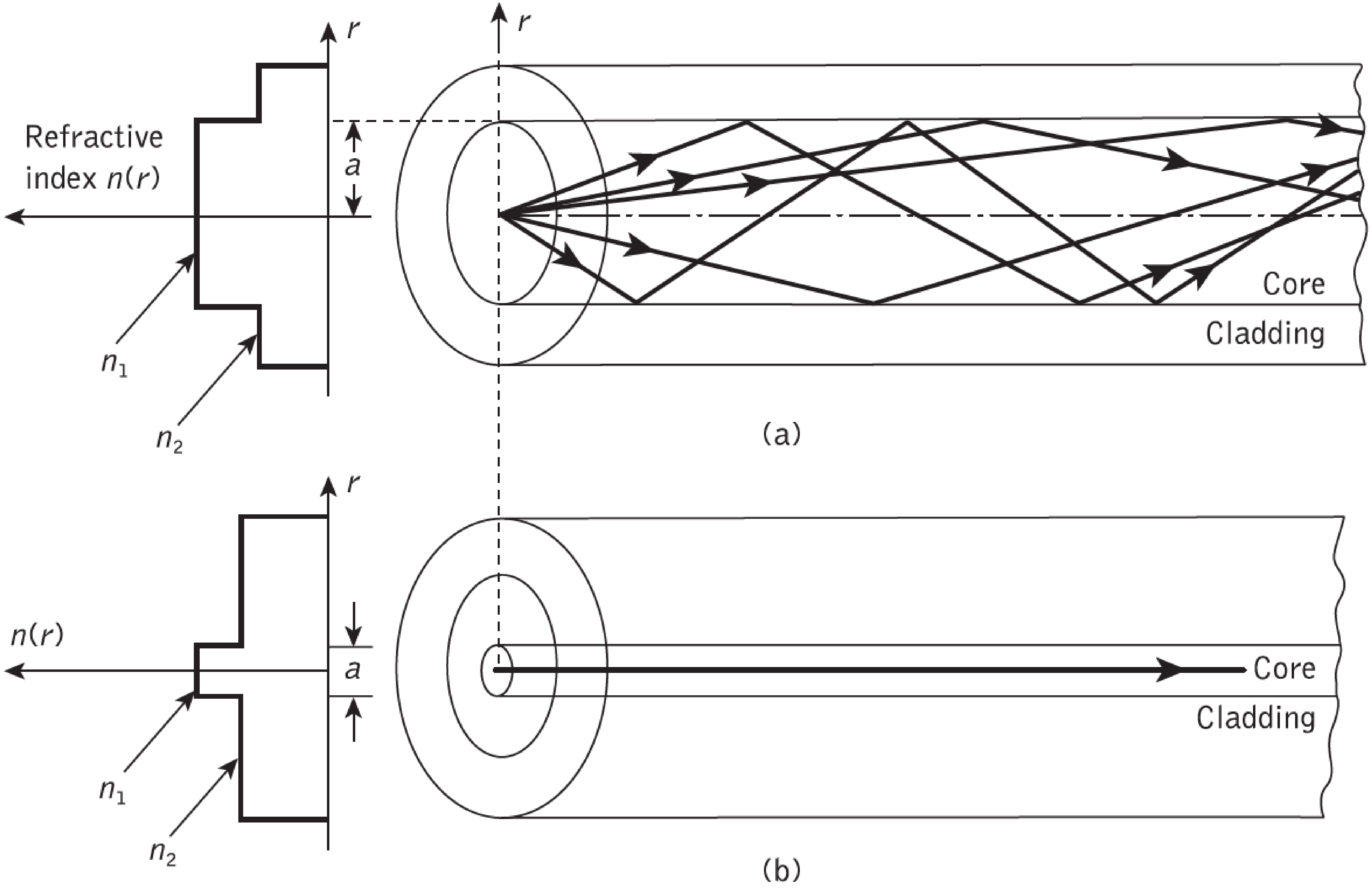
- The number of modes that can exist in a waveguide as a function of V may be conveniently represented in terms of a normalized propagation constant b defined

$$b = \frac{a^2 W^2}{V^2} = \frac{\left(\frac{\beta}{k}\right)^2 - {n_2}^2}{{n_1}^2 - {n_2}^2}$$

- The curve between $\frac{\beta}{k}$ and the normalized frequency V shows that for a particular mode to propagate, the V-number of the fiber corresponding to that mode must be greater than certain value which is the cut-off value for the mode.
- The HE_{11} mode has no cutoff and ceases to exist only when the core diameter is zero. This is the principle on which the single-mode fiber is based.
- For a fiber to be single mode: $V \leq 2.405$



n_1
n_2
β/k
HE11
TE01
TM01
EH11
HE31
HE12
HE21
EH21
HE41
TE02
TM02
HE22
0
1
2
3
4
5
6
Normalized frequency V

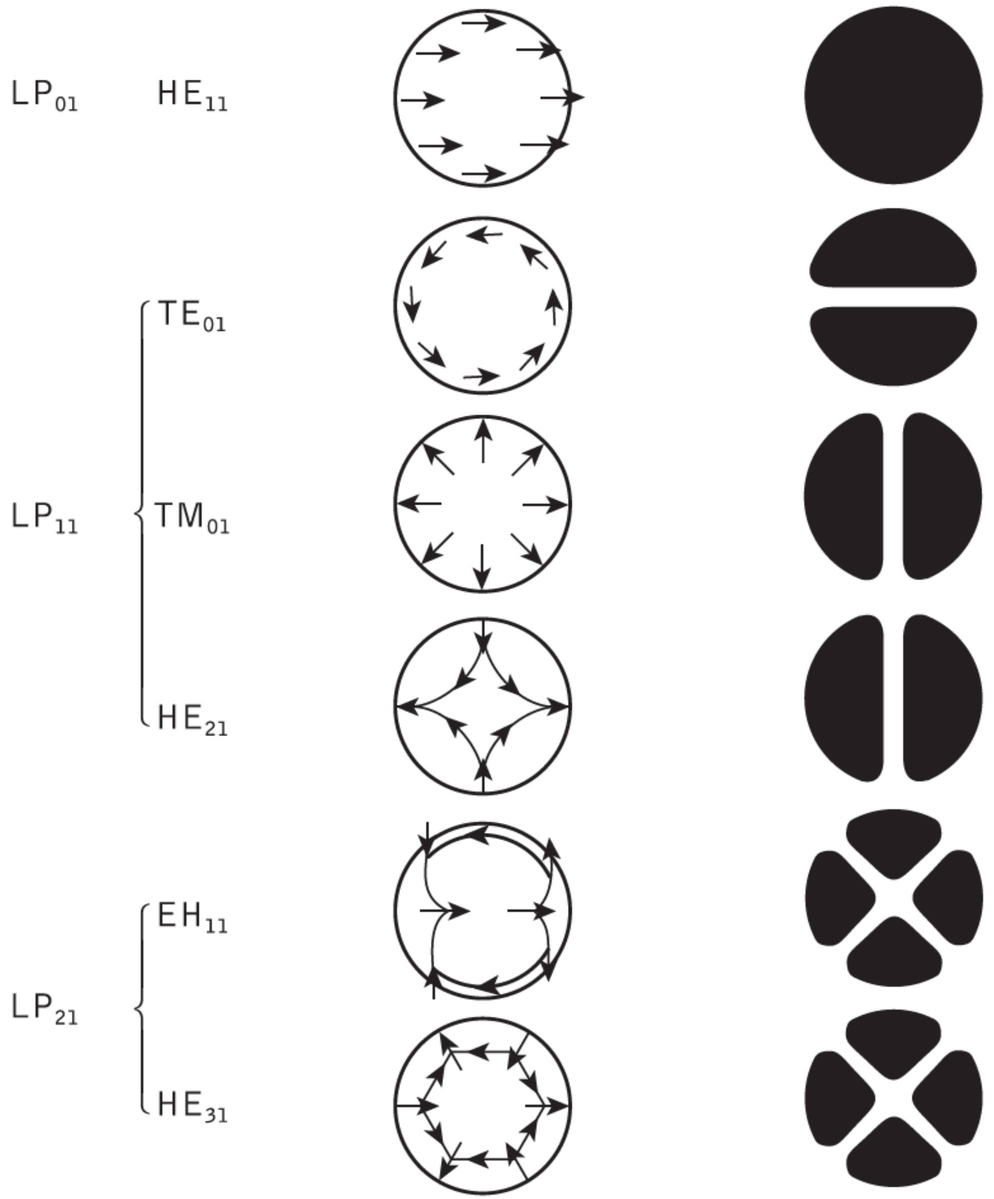


(a) multimode step index fiber; (b) single-mode step index fiber

LINEAR POLARIZED (LP) MODES:

- Consider the weakly guiding approximation where the relative index difference $\Delta << 1$.
- For very small relative refractive index difference, the HE–EH mode pairs have almost identical propagation constants. Such modes are said to be degenerate. Such degenerate modes are called linearly polarized (LP) modes, and are designated LP_{jm} modes
- The superpositions of these degenerating modes characterized by a common propagation constant correspond to particular LP modes regardless of their HE, EH, TE or TM field configurations.
  - Each LP_{0m} mode is derived from an HE_{1m} mode.
  - Each LP_{1m} mode comes from TE_{0m}, TM_{0m}, and HE_{2m} modes.
  - Each $LP_{\nu m}$ mode ($\nu \geq 2$) is from an $HE_{\nu+1,\, m}$ and an $EH_{\nu-1,\, m}$ mode.

Linear polarized (LP) modes



Problems

- A multimode step index fiber with a core diameter of 80 μm and a relative index difference of 1.5% is operating at a wavelength of 0.85 μm. If the core refractive index is 1.48, estimate: (a) the normalized frequency for the fiber; (b) the number of guided modes. **(Ans: (a) 75.8, (b) 2873)**
- A manufacturing engineer wants to make an optical fiber that has a core index of 1.480 and a cladding index of 1.478. What should the core size be for single-mode operation at 1550 nm? **(Ans: 7.7 μm)**
- An applications engineer has an optical fiber that has a 3.0 μm core radius and a numerical aperture of 0.1. Will this fiber exhibit single-mode operation at 800 nm? **(Ans: Yes, V=2.356)**
- Suppose we have a 50 μm diameter graded-index fiber that has a parabolic refractive index profile ($\alpha = 2$). If the fiber has a numerical aperture NA = 0.22, what is the total number of guided modes at a wavelength of 1310 nm? **(Ans: 174)**

PROBLEMS

- A graded index fiber with a parabolic index profile supports the propagation of 742 guided modes. The fiber has a numerical aperture in air of 0.3 and a core diameter of 70 μm. Determine the wavelength of the light propagating in the fiber. Further estimate the maximum diameter of the fiber which gives single-mode operation at the same wavelength. **(Ans: 1.2 μm, 4.4 μm)**
- A single-mode step index fiber which is designed for operation at a wavelength of 1.3 μm has core and cladding refractive indices of 1.447 and 1.442 respectively. When the core diameter is 7.2 μm, confirm that the fiber will permit single-mode transmission and estimate the range of wavelengths over which this will occur. **(Ans: <1139 nm)**

TEXT BOOKS

- Gerd Keiser, Optical Fiber Communications, TMH India, Fourth Edition, 2010.
- Senior John M., Optical Fiber Communications, Pearson Education India, Third Edition, 2009.
- R.P. Khare, *Fiber optics and optoelectronics, Oxford University Press 2004*

COURSE: *OPTICAL COMMUNICATION* (EC317)

UNIT-II

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DISTORTION IN OPTICAL FIBERS

- When an optical signal is transmitted on an optical fiber, the signal is distorted due to two phenomena: dispersion and attenuation.

Distortion in optical fiber

Attenuation

Material attenuation
- Absorption
- Scattering

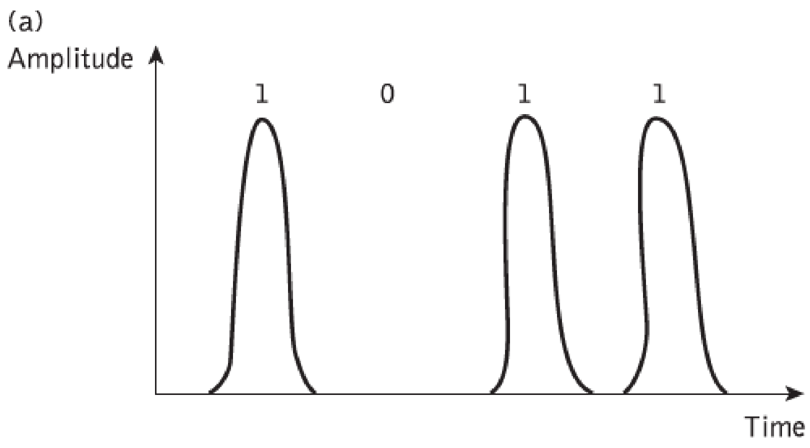
Bending loss

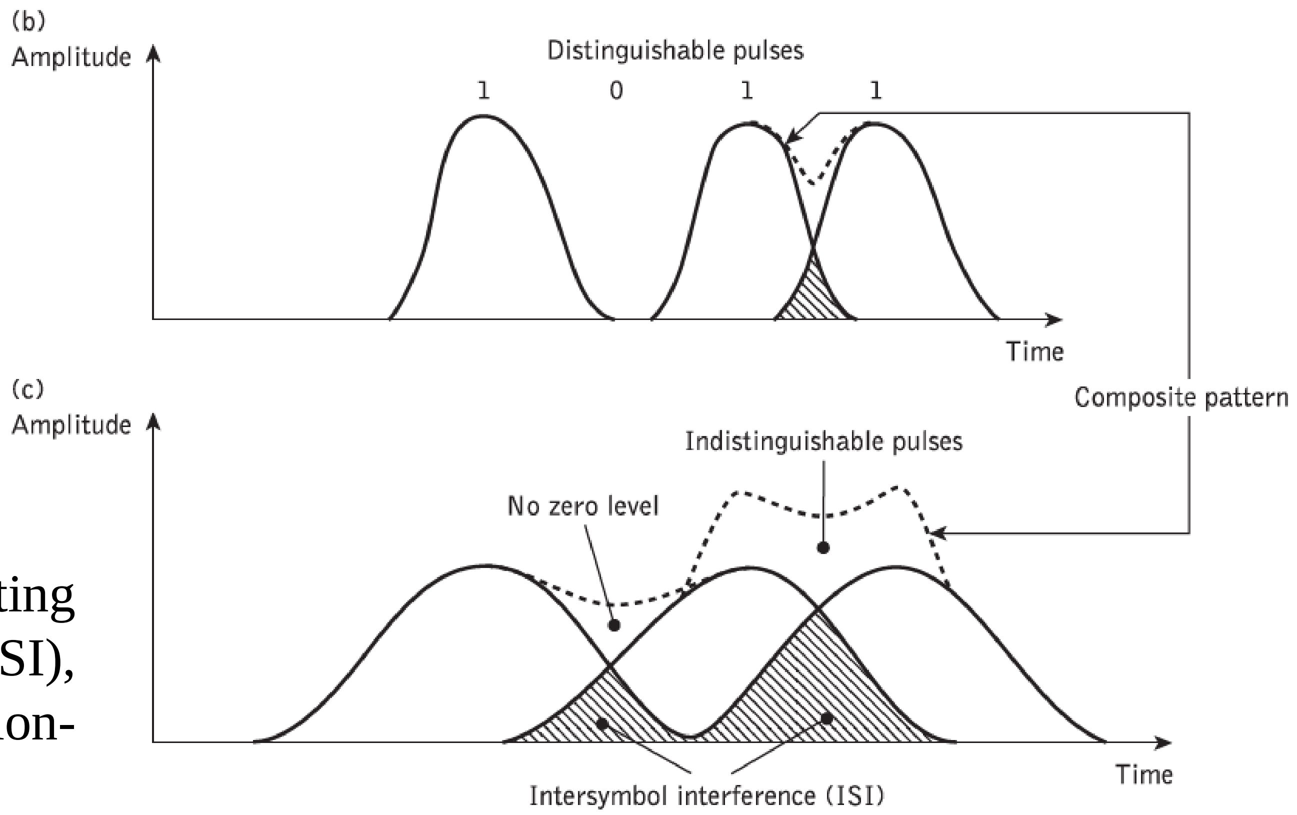
Radiation

Dispersion
- Intramodal dispersion
  - Material dispersion
  - Waveguide dispersion
- Inter modal dispersion

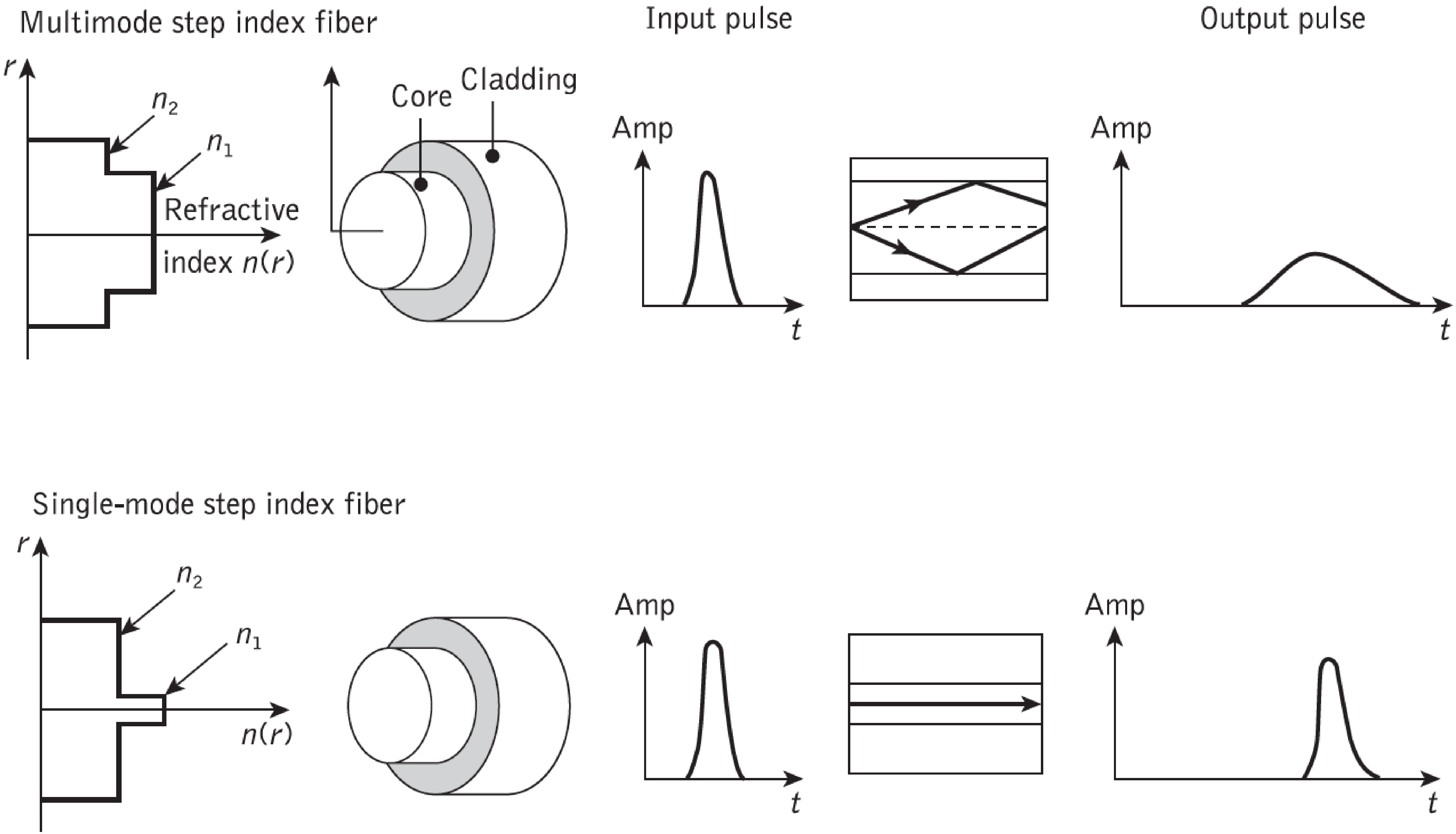
DISPERSION

- When light is launched into an optical fiber in the form of a light pulse to transmit the information
- The broadening of the transmitted light pulses as they travel along the fiber is known as dispersion.





- the overlap between adjacent pulses, creating errors in the receiver output (i.e., ISI), resulting in the limitation of information-carrying capacity of a fiber.


Multimode step index fiber
Input pulse
Output pulse
r
n_2
n_1
Refractive
index $n(r)$
Core
Cladding
Amp
t
Amp
t
Single-mode step index fiber
r
n_2
n_1
$n(r)$
Amp
t
Amp
t

CHROMATIC OR INTRAMODAL DISPERSION

- This type of dispersion results from the finite spectral linewidth of the optical source. Since optical sources do not emit just a single frequency but a band of frequencies
- There may be propagation delay differences between the different spectral components of the transmitted signal. This causes broadening of each transmitted mode and hence intramodal dispersion (group velocity dispersion).
- The delay differences may be caused by the dispersive properties of the **waveguide material (material dispersion)** and also guidance effects within the **fiber structure (waveguide dispersion)**.

MATERIAL DISPERSION

- This arises due to the variations of the refractive index of the core material as a function of wavelength.
- This refractive index property causes a wavelength dependence of the group velocity of a given mode; that is, pulse spreading occurs when different wavelengths follow the same path.
- The group velocity is given by $v_g = \frac{d\omega}{d\beta}$; where the propagation constant $\beta = \frac{2\pi n_1(\lambda)}{\lambda}$ and $\omega = \frac{2\pi c}{\lambda}$
- A time delay or group delay in the direction of the propagation $t_g = \frac{L}{v_g}$

$$t_g = \frac{L}{v_g} = L\frac{d\beta}{d\omega} \; or \; \frac{L}{c}\frac{d\beta}{dk}$$

Material dispersion

$$\frac{d\beta}{d\lambda} = -\frac{2\pi}{\lambda^2}\left(n_1 - \lambda\frac{dn_1}{d\lambda}\right) \qquad and \qquad \frac{d\omega}{d\lambda} = -\frac{2\pi c}{\lambda^2}$$

- Therefore

$$t_g = L\frac{d\beta/d\lambda}{d\omega/d\lambda} = \frac{L}{c}\left(n_1 - \lambda\frac{dn_1}{d\lambda}\right)$$

- If the spectral width of the optical source is not too wide, then the delay difference per unit wavelength along the propagation path is approximately $\frac{dt_g}{d\lambda}$.
- For spectral components which are $\delta\lambda$ apart, symmetrical around center wavelength, the total delay difference $\delta\tau$ over a distance L is:

$$\delta\tau = \left|\frac{dt_g}{d\lambda}\right|\delta\lambda = \frac{L}{c}\lambda\left|\frac{d^2 n_1}{d\lambda^2}\right|\delta\lambda$$

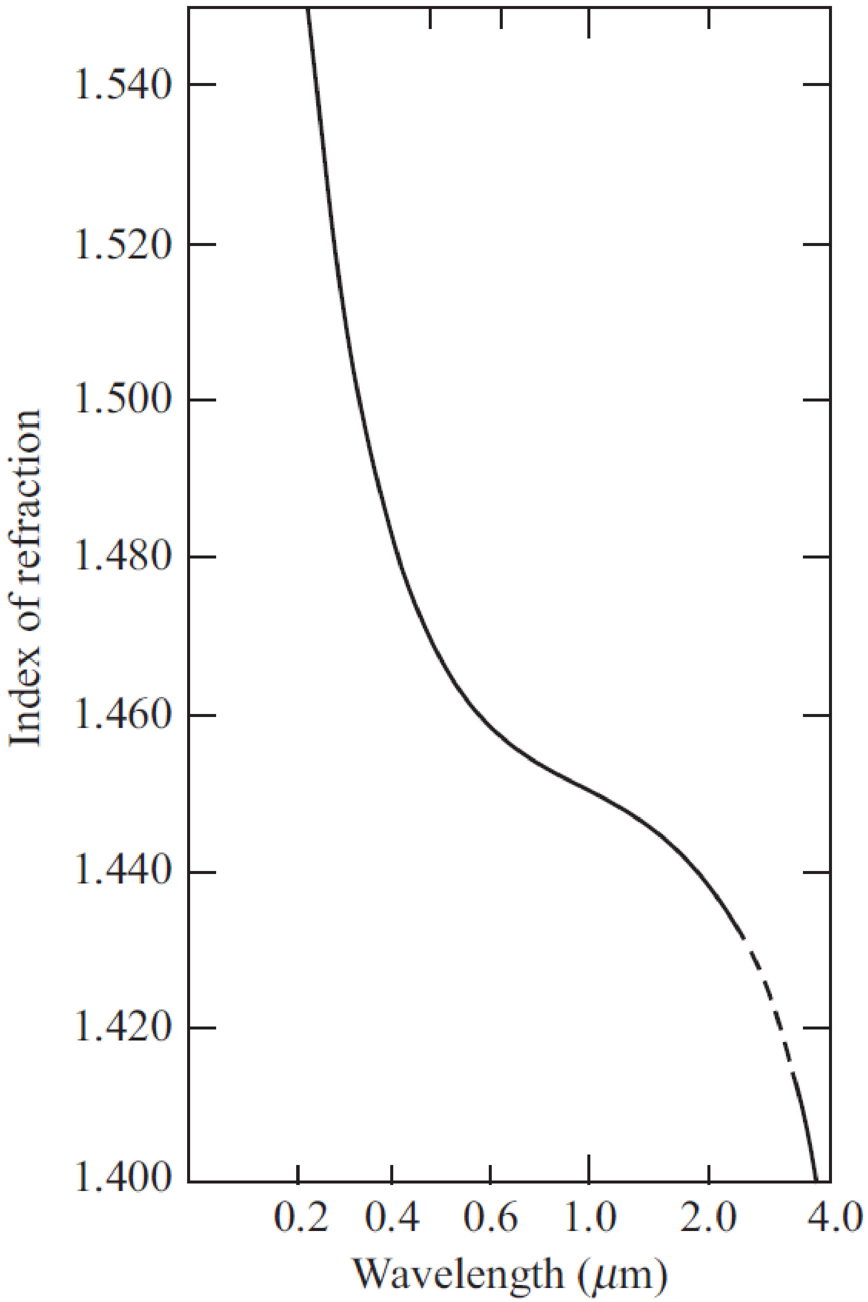
- The material dispersion of optical fibers is quoted in terms of the material dispersion parameter D_{mat} given by

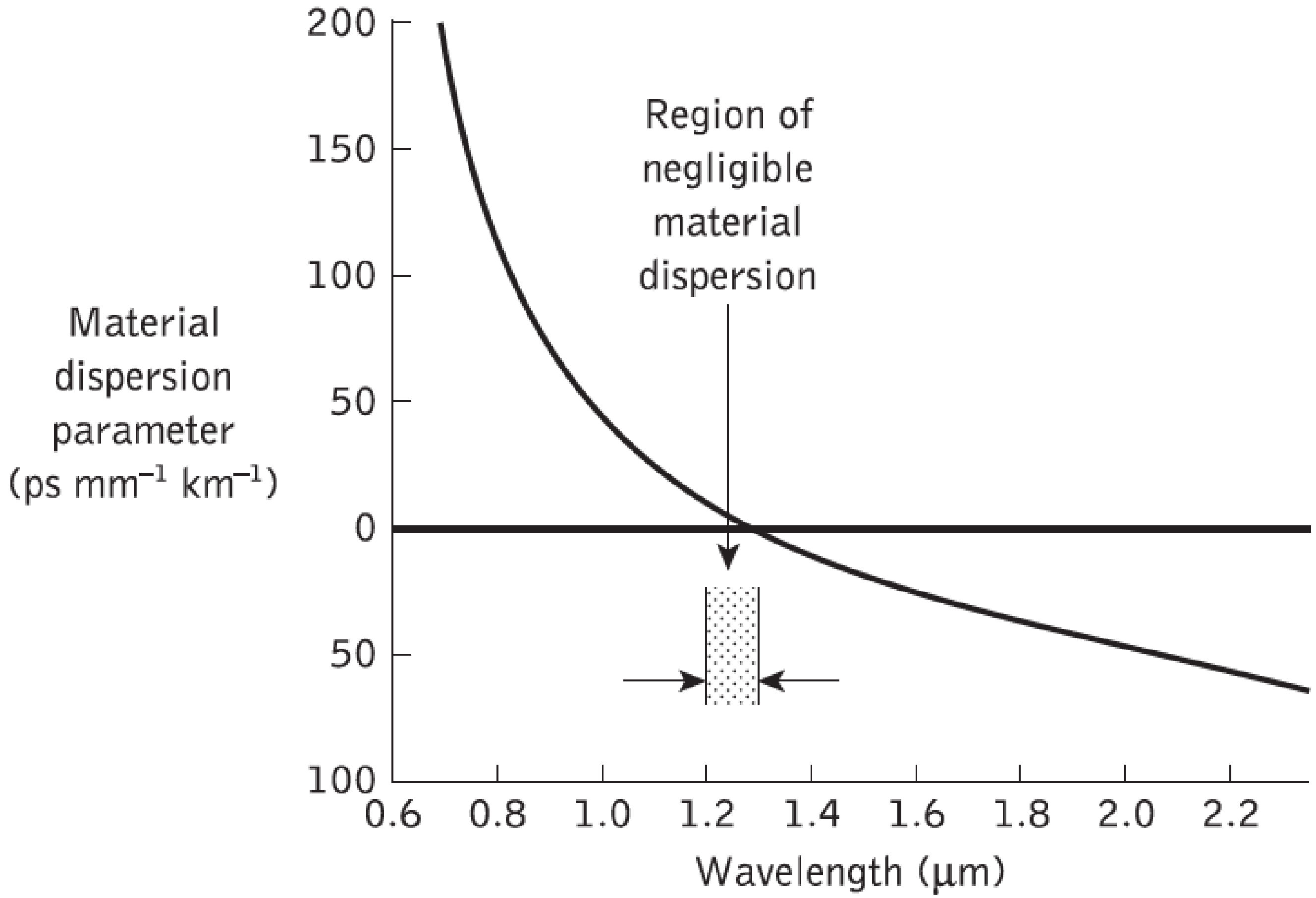
$$D_{mat} = \frac{1}{L}\frac{\delta\tau}{\delta\lambda} = \frac{\lambda}{c}\left|\frac{d^2 n_1}{d\lambda^2}\right|$$

D_{mat} has the units of ps nm^{-1} km^{-1}.

- In the case of optical pulse, if the spectral width of the optical source is characterized by its rms value of the Gaussian pulse σ_λ, the pulse spreading over the length of L, σ_m can be well approximated by:

$$\sigma_{mat} = \left|\frac{dt_g}{d\lambda}\right| \sigma_\lambda = LD_{mat}\sigma_\lambda$$


1.540
1.520
1.500
1.480
1.460
1.440
1.420
1.400
Index of refraction
0.2
0.4
0.6
1.0
2.0
4.0
Wavelength (μm)


Material
dispersion
parameter
(ps mm⁻¹ km⁻¹)
200
150
100
50
0
50
100
Region of
negligible
material
dispersion
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
Wavelength (μm)

WAVEGUIDE DISPERSION

- The degree of waveguide dispersion depends on the fiber design.
- Waveguide dispersion usually can be ignored in multimode fibers, but its effect is significant in single-mode fibers.
- This dispersion arises because the difference in core-cladding spatial power distributions, together with the speed variations of the various wavelengths, causes a change in propagation velocity for each spectral component.
- Waveguide dispersion is due to the dependency of the group velocity of the fundamental mode as well as other modes on the *V* number.
- In order to calculate waveguide dispersion, we consider that *n* is not dependent on wavelength. Defining the normalized propagation constant *b* as:

$$b = \frac{\left(\frac{\beta}{k}\right)^2 - {n_2}^2}{{n_1}^2 - {n_2}^2}$$

Waveguide dispersion

For small values of the index difference $\Delta = (n_1 - n_2)/n_1$, can be approximated by

$$b \approx \frac{\frac{\beta}{k} - n_2}{n_1 - n_2} \quad \Rightarrow \; \beta \approx kn_2(b\Delta + 1)$$

the group delay t_{wg} arising from waveguide dispersion is $t_g = \frac{L}{v_g} = \frac{L}{c}\frac{d\beta}{dk}$

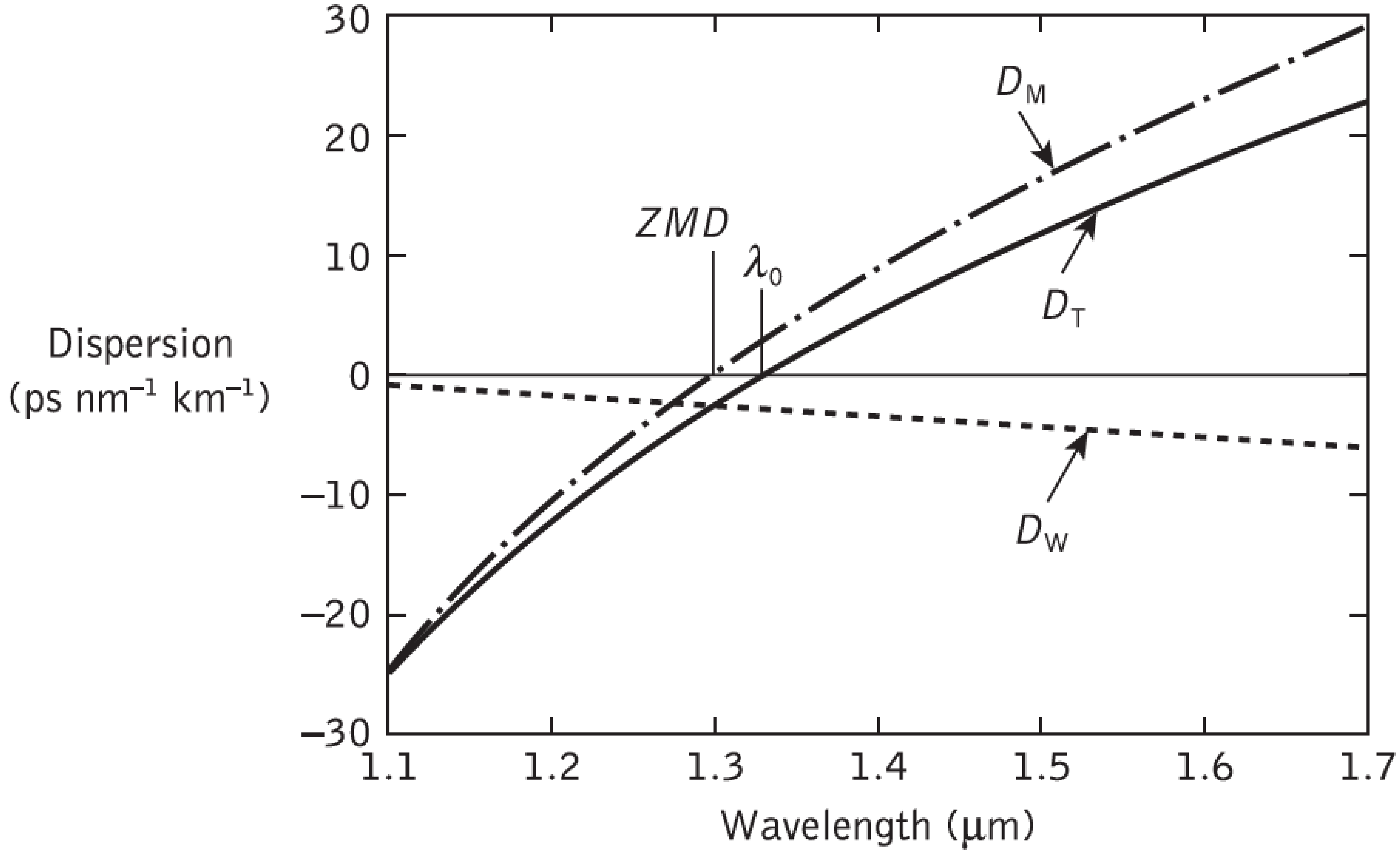
$$t_g = \frac{L}{c}n_2\left(1 + \Delta\frac{d(kb)}{dk}\right) = \frac{L}{c}n_2\left(1 + \Delta\left(b + k\frac{db}{dk}\right)\right) = \frac{L}{c}n_2\left(1 + \Delta\left(b + k\frac{db}{dV}\frac{dV}{dk}\right)\right)$$

$$V = kan_1\sqrt{2\Delta} \quad \Rightarrow \frac{dV}{dk} = an_1\sqrt{2\Delta} = \frac{V}{k}$$

$$t_g = \frac{L}{c}n_2\left(1 + \Delta\frac{d(bV)}{dV}\right)$$

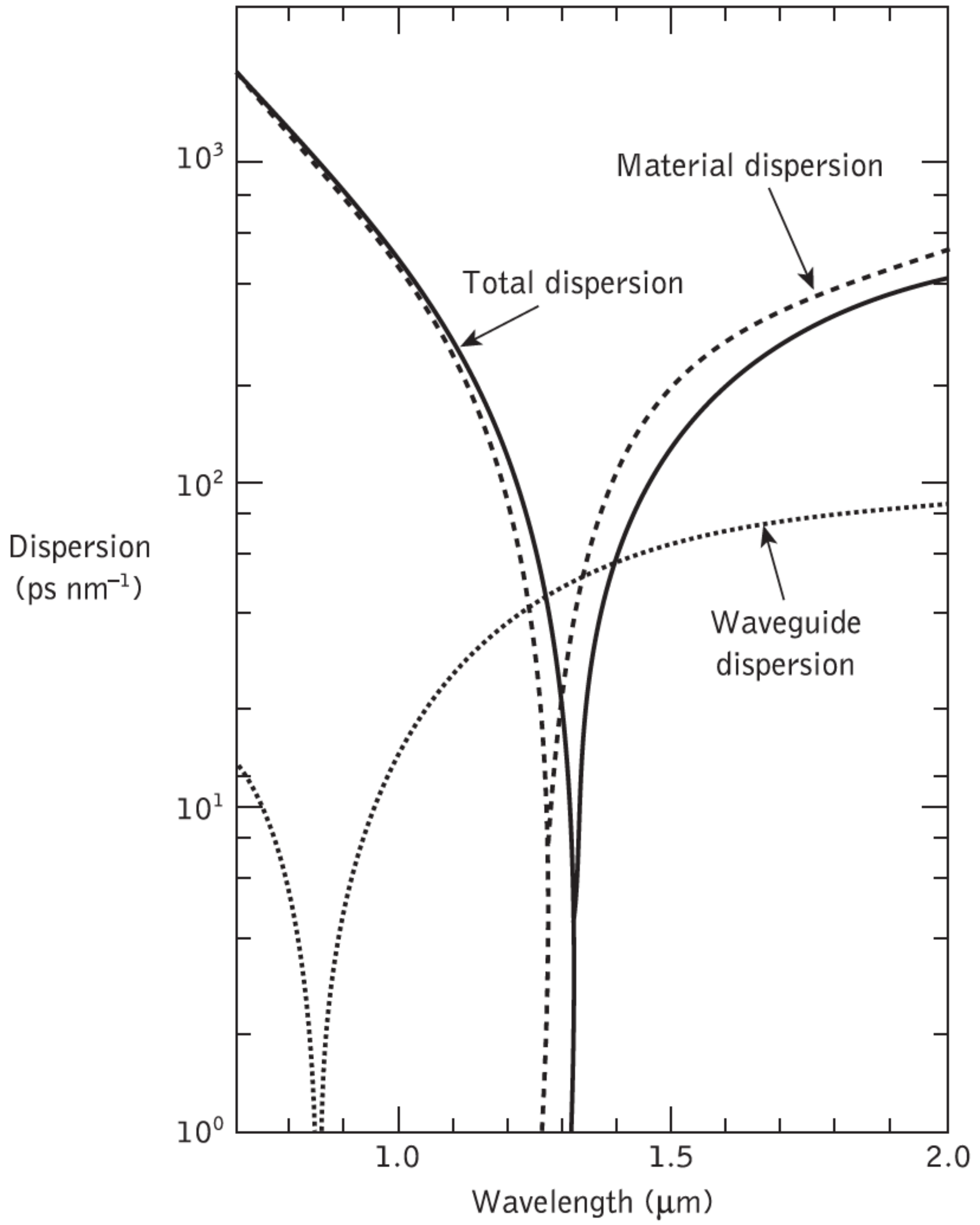
The waveguide dispersion is

$$D_{wg} = \frac{1}{L}\left|\frac{dt_g}{d\lambda}\right| = \frac{n_2\Delta}{c}\frac{d}{d\lambda}\left(\frac{d(bV)}{dV}\right)\frac{dV}{dV} = \frac{n_2\Delta}{c}\frac{V}{\lambda}\left(\frac{d^2(bV)}{dV^2}\right)$$



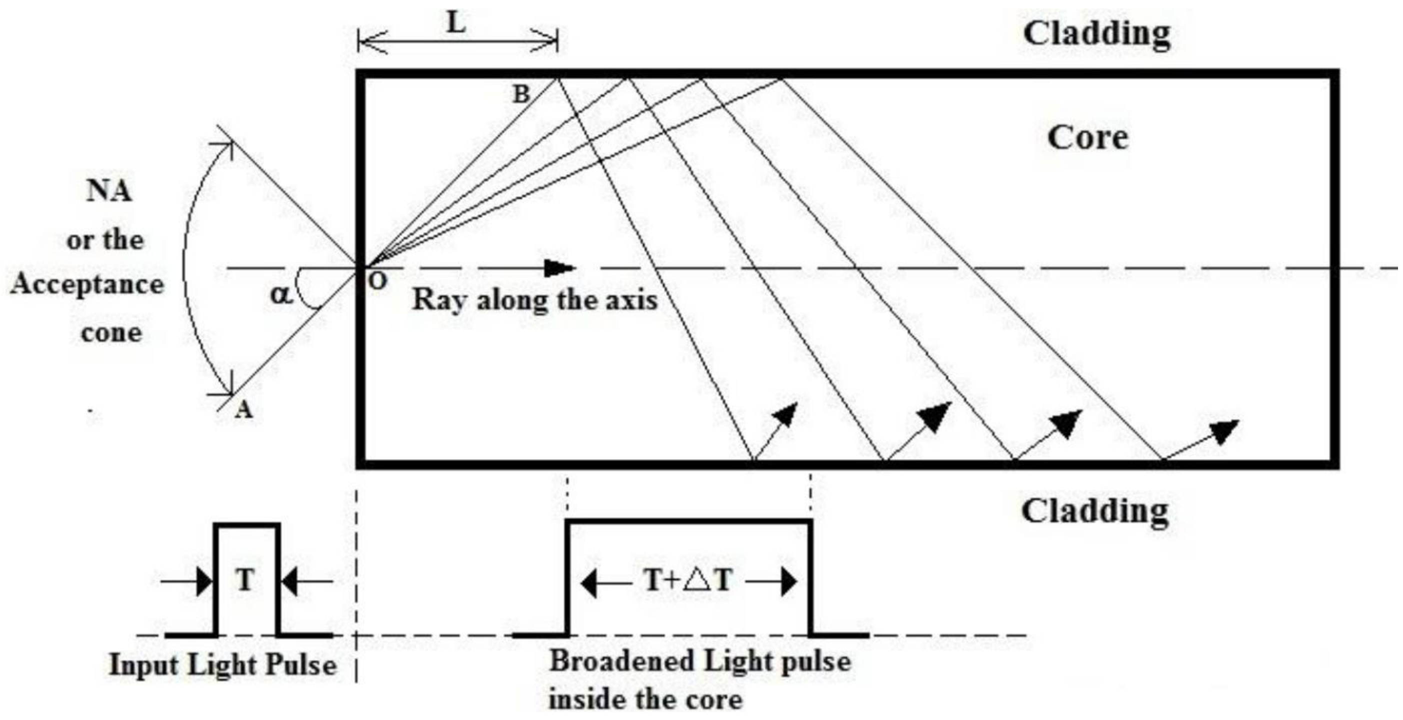
Dispersion (ps nm⁻¹ km⁻¹)
30
20
10
0
−10
−20
−30
1.1
1.2
1.3
1.4
1.5
1.6
1.7
Wavelength (μm)
ZMD
λ_0
D_M
D_T
D_W

- The wavelength at which the first-order dispersion is zero λ_0 may be extended to wavelengths of 1.55 μm and beyond by a combination of three techniques. These are:
  - lowering the normalized frequency (*V*) for the fiber;
  - increasing the relative refractive index difference Δ for the fiber;
  - suitable doping of the silica with germanium.



INTER-MODAL DISPERSION

- The light rays travel different paths inside the core of an optical fiber because different light rays are incident on the tip of the optical fiber at different angles within the acceptance cone and lead to the broadening of the actual time-width of the pulse. This phenomenon is called as inter-modal dispersion
- Intermodal dispersion or modal delay appears only in multimode fibers.



INTER-MODAL DISPERSION

- This broadening is simply obtained from ray tracing and for a fiber of length L is given by

$$\Delta T = T_{max} - T_{min}$$

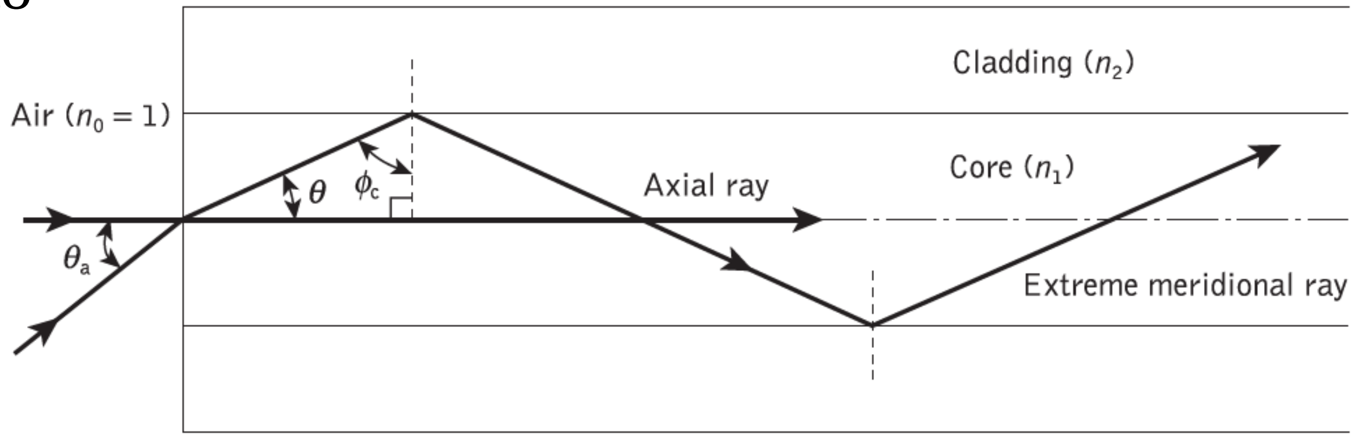
$$T_{min} = \frac{L}{c} n_1 \qquad and \qquad T_{max} = \frac{L}{c\cos\theta} n_1$$

$$\sin\phi_c = \cos\theta = \frac{n_2}{n_1}$$

$$\Delta T = \frac{L}{c} n_1 \left(\frac{n_1}{n_2} - 1\right) \approx \frac{L}{c} n_1 \Delta$$

The rms pulse broadening due to intermodal dispersion

$$\sigma_s \simeq \frac{L n_1 \Delta}{2\sqrt{3}c} \simeq \frac{L(NA)^2}{4\sqrt{3}n_1 c}$$



PROBLEMS

A 6 km optical link consists of multimode step index fiber with a core refractive index of 1.5 and a relative refractive index difference of 1%. Estimate:

(a) the delay difference between the slowest and fastest modes at the fiber output;

(b) the rms pulse broadening due to intermodal dispersion on the link;

(c) the maximum bit rate that may be obtained without substantial errors on the link assuming only intermodal dispersion

Sol:

(a) The delay difference

$$\Delta T = \frac{L}{c} n_1 \Delta = 6 \times 1.5 \times \frac{0.01}{3 \times 10^5} = 300\ ns$$

(b) The rms pulse broadening due to intermodal dispersion

$$\sigma_s = \frac{L}{2\sqrt{3}c} n_1 \Delta = 86.7\ ns$$

(c) The maximum bit rate may be estimated in two ways:

$B_{T,max} = \frac{1}{2\Delta T} = 1.7\ Mbps$ or $B_{T,max} = \frac{0.2}{\sigma_s} = 2.3\ Mbps$

PROBLEMS

- A glass fiber exhibits material dispersion given by $|\lambda^2(d^2n_1/d\lambda^2)|$ of 0.025. Determine the material dispersion parameter at a wavelength of 0.85 μm, and estimate the rms pulse broadening per km for a good LED source with an rms spectral width of 20 nm at this wavelength.

Sol:

Given that $\left|\lambda^2 \frac{d^2n_1}{d\lambda^2}\right| = 0.025$

Operating wavelength $\lambda = 850$ nm

RMS spectral width $\sigma_\lambda = 20\ nm$

The material dispersion

$$D_{mat} = \frac{\lambda}{c}\left|\frac{d^2n_1}{d\lambda^2}\right| = \frac{1}{c\lambda}\left|\lambda^2 \frac{d^2n_1}{d\lambda^2}\right| = \frac{0.025}{3\times 10^5 \times 850} = 98.04 \text{ ps nm}^{-1}\text{ km}^{-1}$$

The rms pulse broadening per km

$$\frac{\sigma_{mat}}{L} = D_{mat}\sigma_\lambda = 1.96\ ns/km$$

PROBLEMS

- A manufacturer's data sheet lists the material dispersion D_{mat} of a GeO_2-doped fiber to be 110 ps/(nm-km) at a wavelength of 860 nm. Find the rms pulse broadening per km due to material dispersion if the optical source is a GaAlAs LED that has a spectral width of 40 nm at an output wavelength of 860 nm.

ATTENUATION

- Signal attenuation (fiber loss) largely determines the maximum repeaterless separation between optical transmitter & receiver (i.e., maximum transmission distance between a transmitter and a receiver)
- Signal attenuation is usually expressed in the logarithmic unit of the decibel.
- The decibel, which is used for comparing two power levels, may be defined as the ratio of the input (transmitted) optical power P_i into a fiber to the output (received) optical power P_o from the fiber

$$Power\ ration\ in\ dBs = -10\log_{10}\left(\frac{P_o}{P_i}\right) = 10\log_{10}\left(\frac{P_i}{P_o}\right)$$

- In optical fiber communications the attenuation is usually expressed in decibels per unit length (i.e. dB/km)

$$\alpha = \frac{1}{L}10\log_{10}\left(\frac{P_i}{P_o}\right) \qquad in\ dB/km$$

Example

When the mean optical power launched into an 8 km length of fiber is 120 μW, the mean optical power at the fiber output is 3 μW. *Determine:*

(a) the overall signal attenuation or loss in decibels through the fiber assuming there are no connectors or splices;

(b) the signal attenuation per km for the fiber.

(c) the overall signal attenuation for a 10 km optical link using the same fiber with splices at 1 km intervals, each giving an attenuation of 1 dB;

Sol:

(a) The overall signal loss/attenuation

$$\alpha(dB) = 10\log_{10}\left(\frac{P_i}{P_o}\right) = 16\ dB$$

(b) The signal attenuation per km

$$\alpha(dB/km) = \frac{16}{8} = 2\ dB/km$$

(c) the link also has nine splices (at 1 km intervals) each with an attenuation of 1 dB. Therefore, the loss due to the splices is 9 dB. Hence, the overall signal attenuation for the link is: 29 dB

ATTENUATION IN FIBERS

- A number of mechanisms are responsible for the signal attenuation within optical fibers. These mechanisms are influenced by the **material composition, the preparation and purification technique, and the waveguide structure**.
- The basic attenuation mechanisms in a fiber are **material absorption, material scattering (linear and nonlinear scattering), curve and micro-bending losses**, mode coupling radiation losses and losses due to leaky modes. There are also losses at connectors and splices

MATERIAL ABSORPTION LOSS

- Material absorption is related to the **material composition and the fabrication process** for the fiber, which results in the dissipation of some of the transmitted optical power as heat in the waveguide.
- Absorption by **atomic defects** in the glass composition (i.e., imperfections in the atomic structure of the fiber material).
    - these defects include missing molecules, high-density clusters of atom groups, or oxygen defects in the glass structure
- Absorption is caused by the following mechanisms:
    - Intrinsic absorption
    - Extrinsic absorption

Intrinsic and Extrinsic absorption loss

- **Intrinsic absorption** caused by the interaction with one or more of the major components of the glass or fiber material.
  - electronic absorption bands (associated with the band gaps of the amorphous glass materials) in the ultra violet (UV) region and from atomic vibration bands in the near-infrared (IR) region
- The UV loss contribution in dB/km at any wave length (given in μm) can be expressed empirically (derived from observation or experiment) as a function of the mole fraction x

$$\alpha_{uv} = \frac{154.2x}{46.6x + 60} \times 10^{-2} \exp\left(\frac{4.63}{\lambda}\right)$$

- In the near-infrared region above 1.2 μm,

$$\alpha_{IR} = 7.81 \times 10^{11} \exp\left(\frac{-48.48}{\lambda}\right)$$

- **Extrinsic absorption** by impurity atoms in the glass material.

Impurity	*Loss due to 1 ppm of impurity (dB/km)*	*Absorption peak (nm)*
Iron: Fe^{2+}	0.68	1100
Iron: Fe^{3+}	0.15	400
Copper: Cu^{2+}	1.1	850
Chromium: Cr^{2+}	1.6	625
Vanadium: V^{4+}	2.7	725
Water: OH^{-}	1.0	950
Water: OH^{-}	2.0	1240
Water: OH^{-}	4.0	1380

SCATTERING LOSS

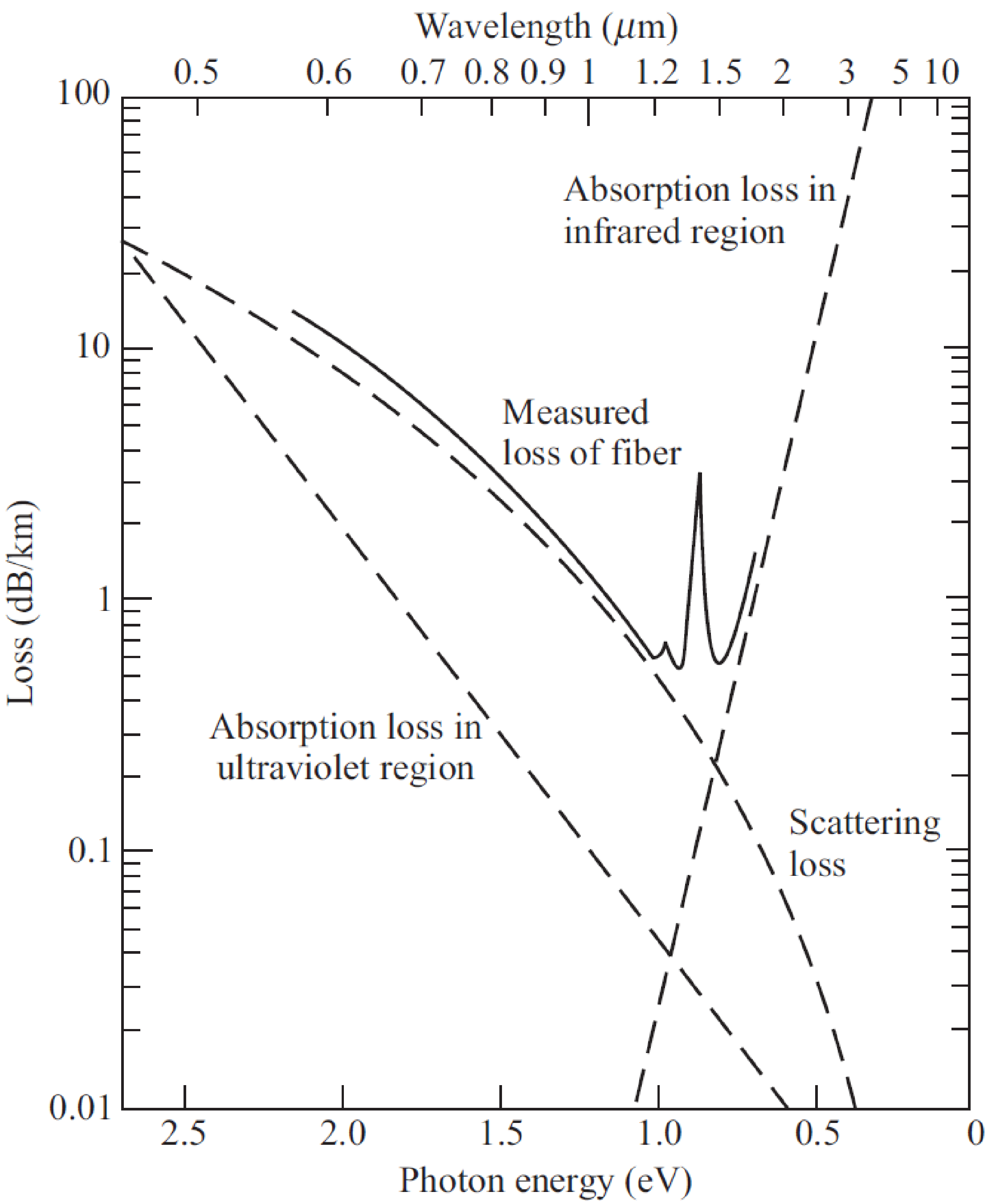
- Small (compared to wavelength) variation in material density, chemical composition, and structural inhomogeneity scatter light in other directions and absorb energy from guided optical wave.
- The essential mechanism is the Rayleigh scattering. Since the black body radiation classically is proportional to λ^{-4}, the attenuation coefficient due to Rayleigh scattering is approximately proportional to λ^{-4}.

$$\alpha_{\mathrm{scat}} = \frac{8\pi^3}{3\lambda^4}(n^2-1)^2 k_B T_f \beta_T \qquad \alpha_{\mathrm{scat}} = \frac{8\pi^3}{3\lambda^4} n^8 p^2 k_B T_f \beta_T$$

$$h = 6.626\times 10^{-34}\ \mathrm{Js},\quad k_B = 1.3806\times 10^{-23}\ \mathrm{JK}^{-1},\ T:\mathrm{Temperature}$$

where p is the photo-elastic coefficient

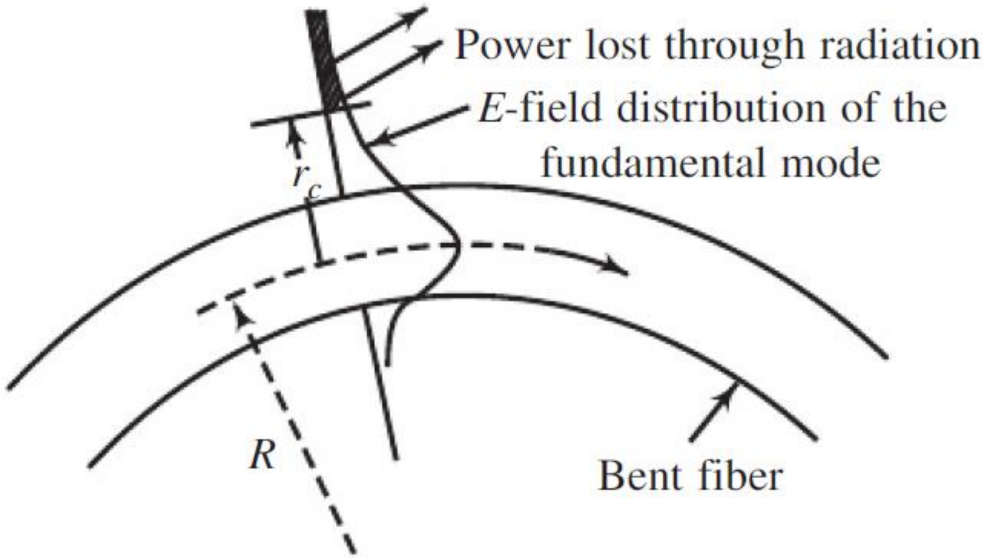
β_T is the isothermal compressibility of the material



Wavelength (μm)
0.5
0.6
0.7
0.8
0.9
1
1.2
1.5
2
3
5
10
100
10
1
0.1
0.01
Loss (dB/km)
Absorption loss in
infrared region
Measured
loss of fiber
Absorption loss in
ultraviolet region
Scattering
loss
2.5
2.0
1.5
1.0
0.5
0
Photon energy (eV)

Bending loss

- An optical fiber tends to radiate propagating power whenever it is bent. Two types of bends
  - macro-bends with radii much larger than the fiber diameter and
  - random micro-bends of the fiber axis that may arise because of faulty cabling.
- Every guided core mode has a modal electric-field distribution that has a tail extending into the cladding. This evanescent field decays exponentially with distance from the core.
- the optical energy in the tail beyond r_c is lost through radiation



$$M_{\mathrm{eff}} = M_{\infty}\left\{1 - \frac{\alpha+2}{2\alpha\Delta}\left[\frac{2a}{R} + \left(\frac{3}{2n_2kR}\right)^{2/3}\right]\right\}$$

- The amount of optical radiation from a bent fiber depends on the field strength at r_c and on the radius of curvature R.
- Since higher-order modes are bound less tightly to the fiber core than lower order modes, the higher-order modes will radiate out of the fiber first.

Example problem

- Consider a graded-index multimode fiber for which the index profile α = 2.0, the core index n_1 = 1.480, the core-cladding index difference Δ = 0.01, and the core radius a = 25 μm. If the radius of curvature of the fiber is R = 1.0 cm, what percentage of the modes remain in the fiber at a 1300-nm wavelength?

$$\frac{M_{\mathrm{eff}}}{M_\infty} = 1 - \frac{\alpha + 2}{2\alpha\Delta}\left[\frac{2a}{R} + \left(\frac{3}{2n_2 kR}\right)^{2/3}\right]$$

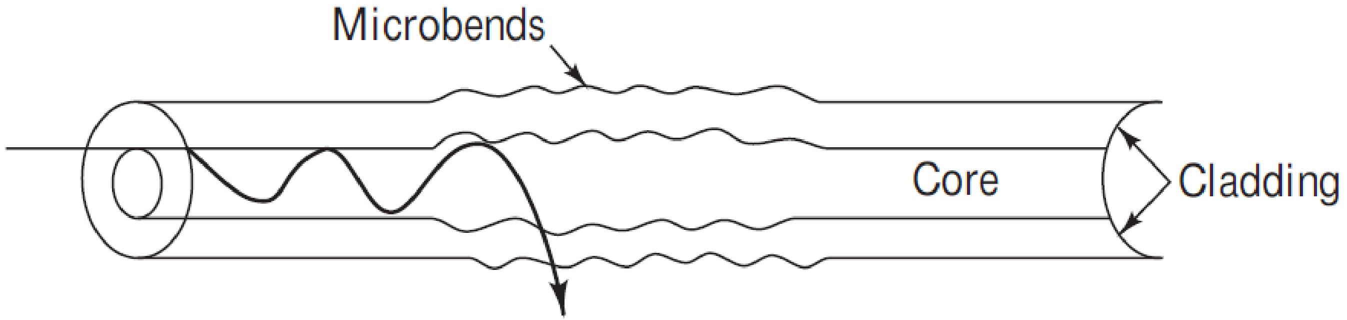
$$= 1 - \frac{1}{.01}\left[\frac{2(25)}{10000} + \left(\frac{3(1.3)}{2(1.465)2\pi(10000)}\right)^{2/3}\right]$$

$$= 0.42$$

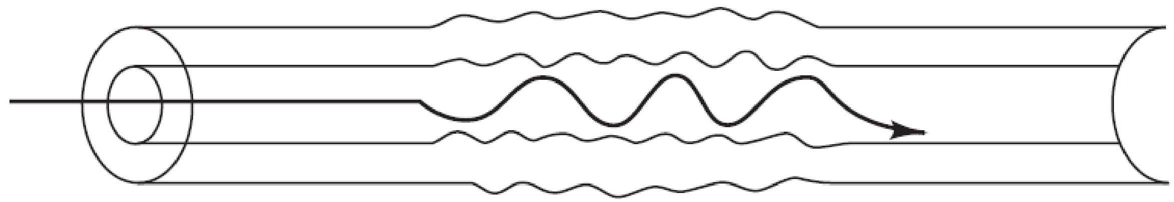
Thus 42 percent of the modes remain in this fiber at a 1.0-cm bend radius.

MICRO-BENDING LOSS

- The micro-bends are caused by manufacturing defects which are in the form of non-uniformities in the core radius or in the lateral pressure created by the cabling of the fiber. The effect of mode coupling in multimode fibers on pulse broadening can be significant for long fibers.
- Micro-bend losses in single-mode fibers can also be excessive if proper care is not taken to minimize them. One way to reduce such losses in single-mode fibers is to choose the V -value near the cut-off value of Vc (e.g., 2.405 for the step-index profile), so that the mode energy is confined mainly to the core.



Power loss from higher-order modes



Power coupling to higher-order modes

EXAMPLE

- A certain optical fiber has an attenuation of 0.6 dB/km at 1310 nm and 0.3 dB/km at 1550 nm. Suppose the following two optical signals are launched simultaneously into the fi ber: an optical power of 150 mW at 1310 nm and an optical power of 100 mW at 1550 nm. What are the power levels in mW of these two signals at (a) 8 km and (b) 20 km?

Sol:

EXAMPLE

A continuous 40-km-long optical fiber link has a loss of 0.4 dB/km.

(a) What is the minimum optical power level that must be launched into the fiber to maintain an optical power level of 2.0 mW at the receiving end?

(b) What is the required input power if the fiber has a loss of 0.6 dB/km?

Sol:

TEXT BOOKS

- Gerd Keiser, Optical Fiber Communications, TMH India, Fourth Edition, 2010.
- Senior John M., Optical Fiber Communications, Pearson Education India, Third Edition, 2009.
- R.P. Khare, Fiber optics and optoelectronics, Oxford University Press 2004

COURSE: *OPTICAL COMMUNICATION* (EC317)

UNIT-III OPTICAL SOURCES

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Detailed Syllabus

Unit-III

- **LED structures, light source materials, quantum efficiency and LED power, modulation of LED, exercise problems.**
- Laser diode, structure, modes and threshold conditions, single mode lasers, modulation of laser diodes, external modulation, linearity, exercise problems.
- Photo diode principles, Avalanche photodiode, photo detector noise, detector response time, structures for APD, exercise problems.

OPTICAL SOURCES: INTRODUCTION

- Fundamental function: To convert the electrical energy in the form current into optical energy (light) in an efficient manner
- Requirements:
  - The size and shape of the source should be compatible with the size of the fiber so that it can couple max. power into the fiber.
  - The response of the source should be linear. (track the electrical input signal to minimize distortion and noise)
  - It should emit monochromatic radiation at the wavelength where the fiber has low losses and low dispersion. (where the detectors are efficient)
  - It should provide sufficient optical power so that it overcomes the transmission losses down the link.
  - Should have a very narrow spectral width in order to minimize the dispersion.
  - Must be capable of maintaining a stable optical output which is unaffected by changes in ambient conditions.
  - comparatively cheap and highly reliable in order to compete with conventional transmission techniques

Optical sources

Light Emitting Diodes (LEDs)

- Monochromatic incoherent sources
- No optical cavity exists for wavelength selectivity
- The output radiation has a **broad spectral width** since the emitted photon energies range is 1 to $2k_BT$
- LEDs can only be coupled into multimode fibers.
- Some applications have used specially fabricated LEDs with SMFs for data transmission at bit rates up to 1.2Gb/s over several Km.

Injection LASER diodes

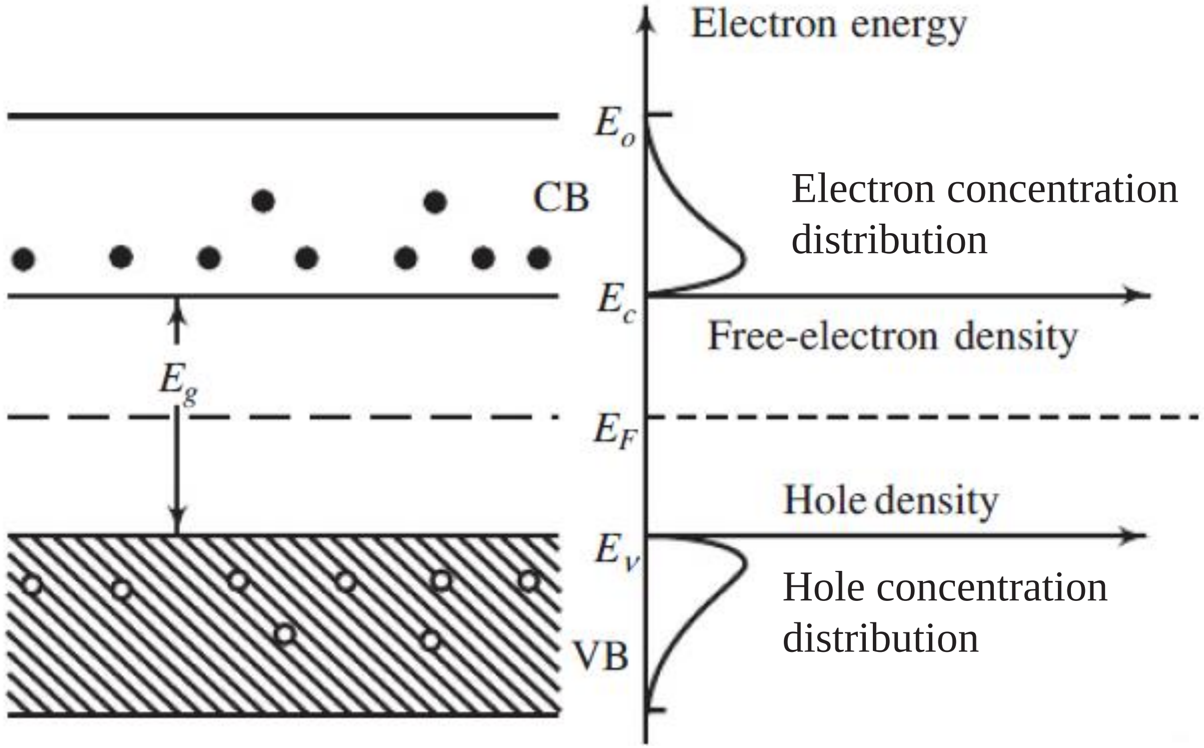
- Monochromatic coherent sources
- The optical energy is produced in optical resonant cavity
- It provides mono-chromatic highly **coherent radiation** and the output beam is very **directional**
- It can be coupled into either single mode or multimode fibers

In choosing an optical source compatible with the optical waveguide, various characteristics of the fiber, such as its **geometry**, its **attenuation** as a function of wavelength, its **group delay distortion** (bandwidth), and its **modal characteristics**, must be taken into account

Basic concepts

- To understand the basic operation of light sources, it is necessary to study about
  - Properties of semiconductor materials (Energy band structure of these materials (intrinsic and extrinsic))
  - *pn* junction
  - Emission of radiation by recombination
  - Direct and indirect band gaps semiconductors

Intrinsic semiconductors

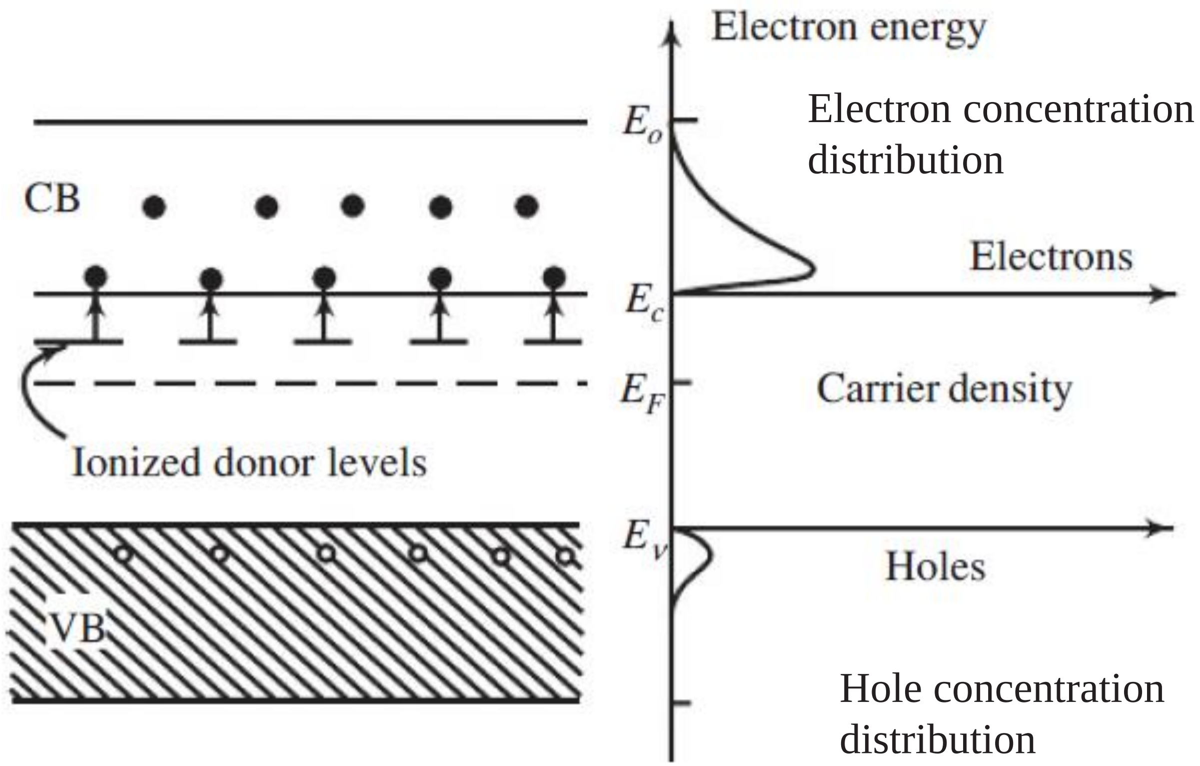


$$n = p = n_i \propto \exp(-\frac{E_g}{2k_B T})$$

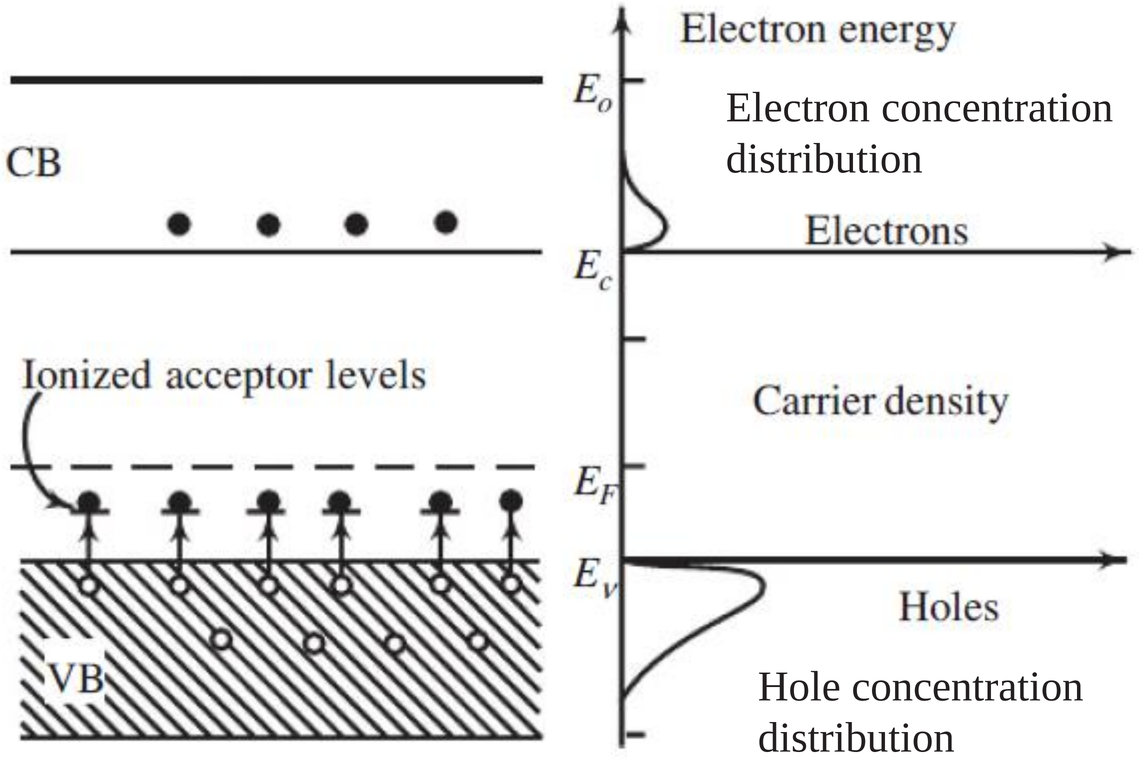
The distribution of electrons (or holes) in the conduction (or valence) band depends upon two main factors:

- The density of energy levels in the energy band
- Probability that a particular energy level has been occupied by an electron (or hole)

Extrinsic semiconductors: n-type

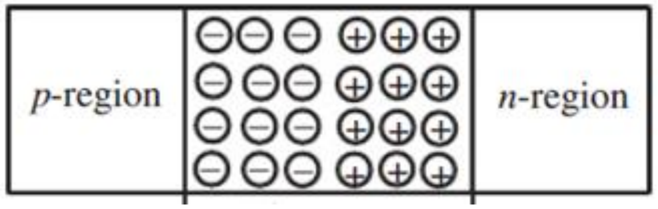


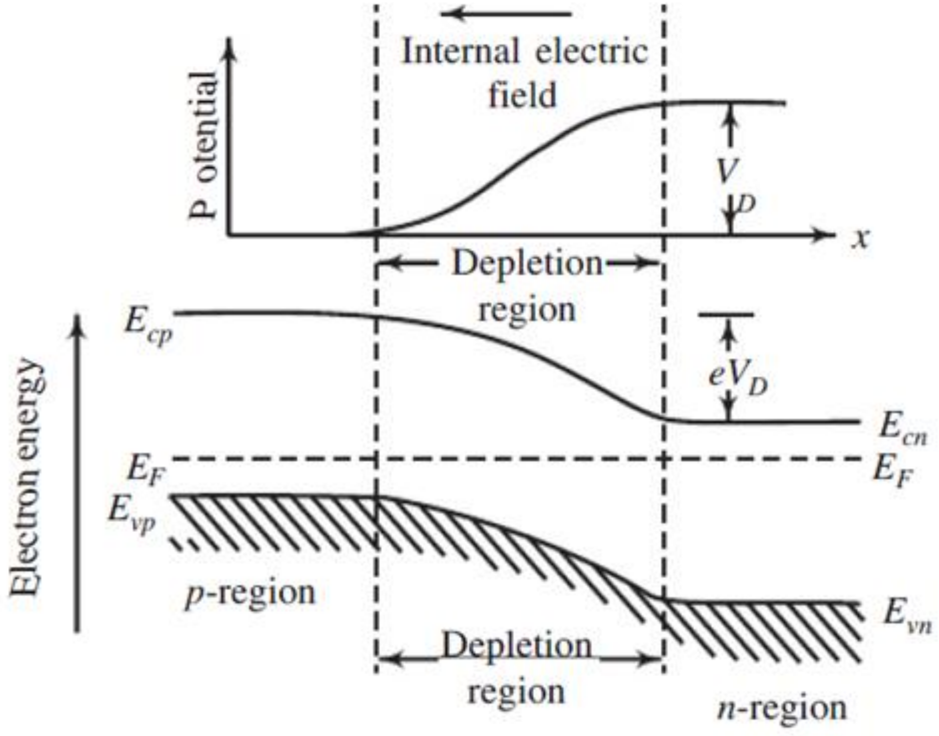
Extrinsic semiconductors: p-type



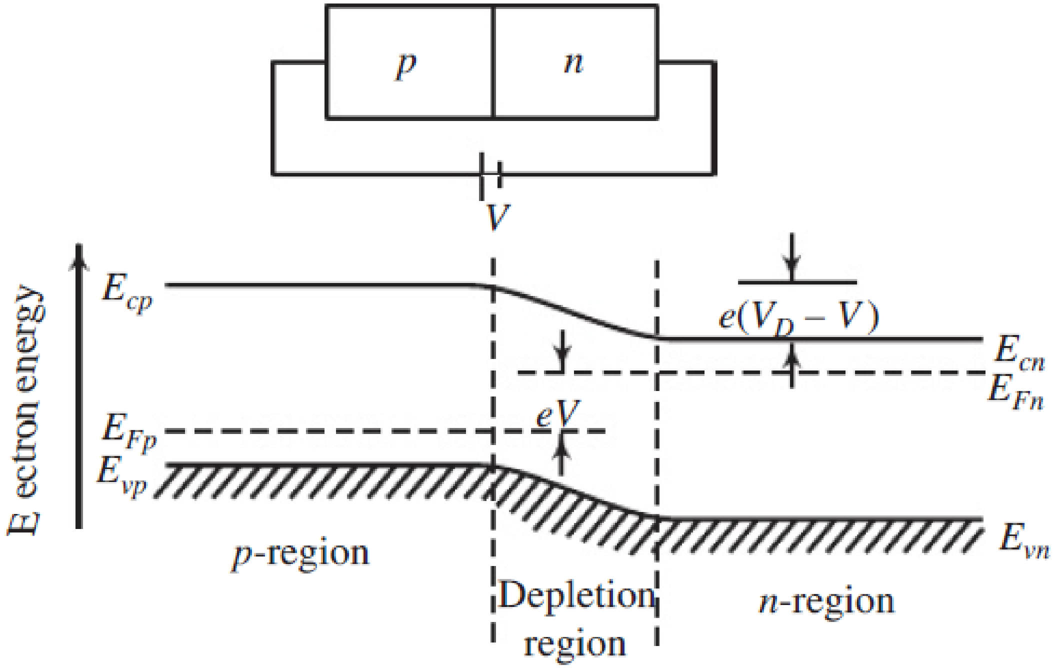
P-N JUNCTION

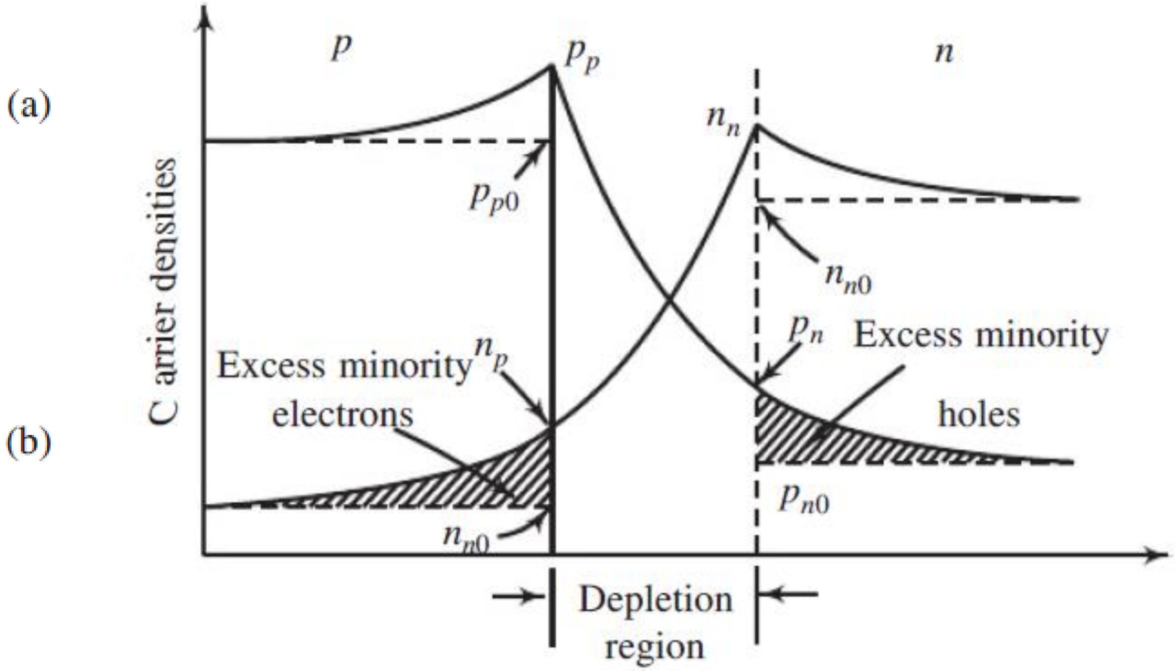
- The p-n junction is formed by adjoining the p and n type semiconductor layers
- A thin depletion region is formed at the junction through carrier recombination (diffusion of holes and electrons).
- The diffusion of holes from the p-region leaves behind ionized acceptors, thereby creating a negative space charge near the junction and the diffusion of electrons from the n-region creates a positive space charge near the junction.
- This establishes a potential barrier between the p and n type regions which restricts the diffusion of majority carriers.
- In the absence of an external applied voltage no current flows as the potential barrier prevents the net flow of carriers from one region to another.





P-N JUNCTION IN FORWARD BIAS





$$n_p = n_{n0}\exp[-e(V_D - V)/kT]$$
$$p_n = p_{p0}\exp[-e(V_D - V)/kT]$$

$$n_p = n_{p0}\exp(eV/kT)$$
$$p_n = p_{n0}\exp(eV/kT)$$

Mechanism behind photon emission in LEDs

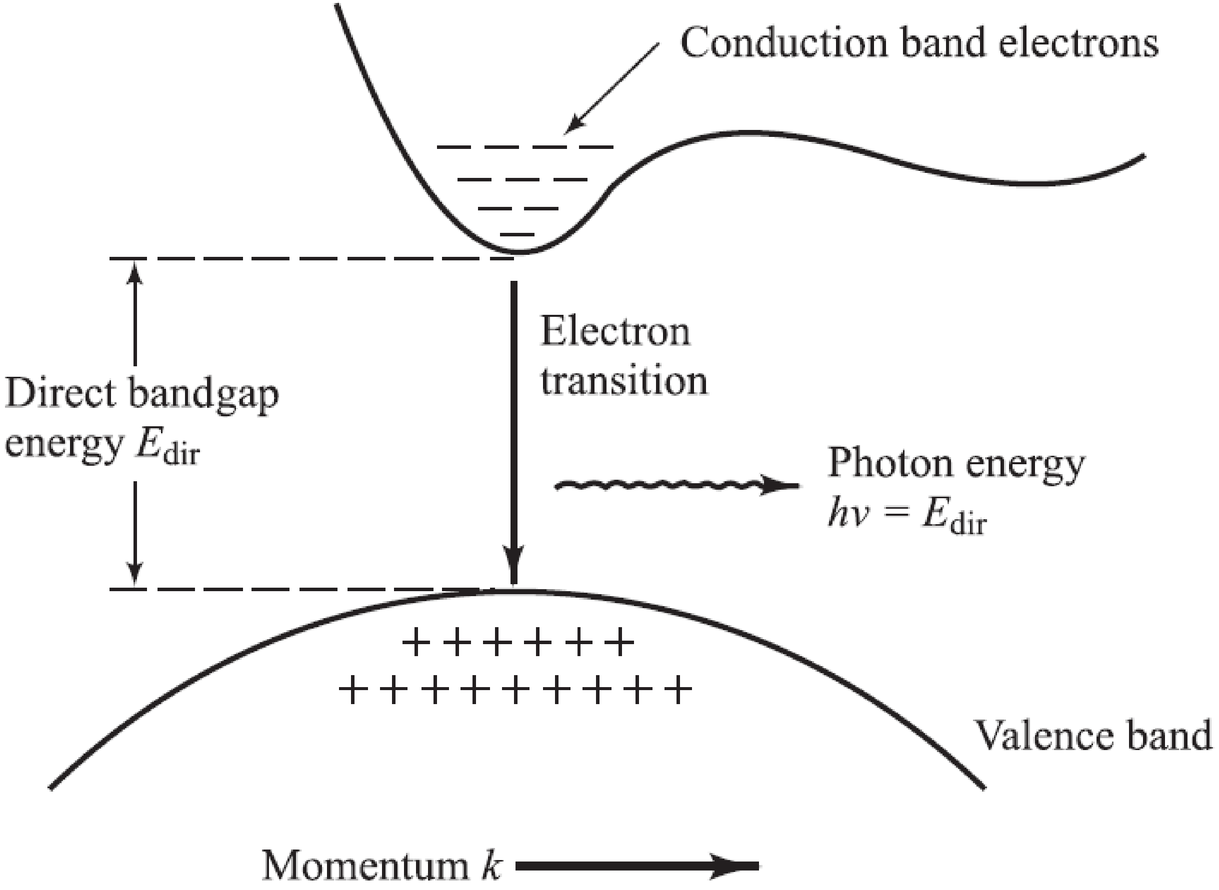
- If the p-n junction is forward biased, the majority carriers from both sides cross the junction and enter the opposite sides. This results in an increase in the minority carrier concentration on the two sides. This process is known as minority carrier injection.
- The injected carriers diffuse away from the junction, recombining with majority carriers. (This releases the energy which is equal to the initial difference in the energies of the two charged particles)
- This recombination of electrons and holes may be
    - Either radiatively (in which case a photon energy is emitted)
    - Or non-radiatively (where the recombination energy is dissipated in the form of heat)
- The phenomenon of emission of radiation (photon) by the recombination of injected minority carriers with majority carriers is called as injection luminescence or electroluminescence. This is the mechanism by which light is emitted in LED.

LIGHT SOURCE MATERIALS: DIRECT AND INDIRECT BAND GAP SEMICONDUCTORS

- A semiconductor material is classified into two types on the basis of its energy band shape as a function of energy-momentum space: **direct band gap** and **indirect band-gap** semiconductor materials.
- Electron transitions to or from the conduction band with the absorption or emission of a photon respectively. Here both energy and momentum must be conserved.

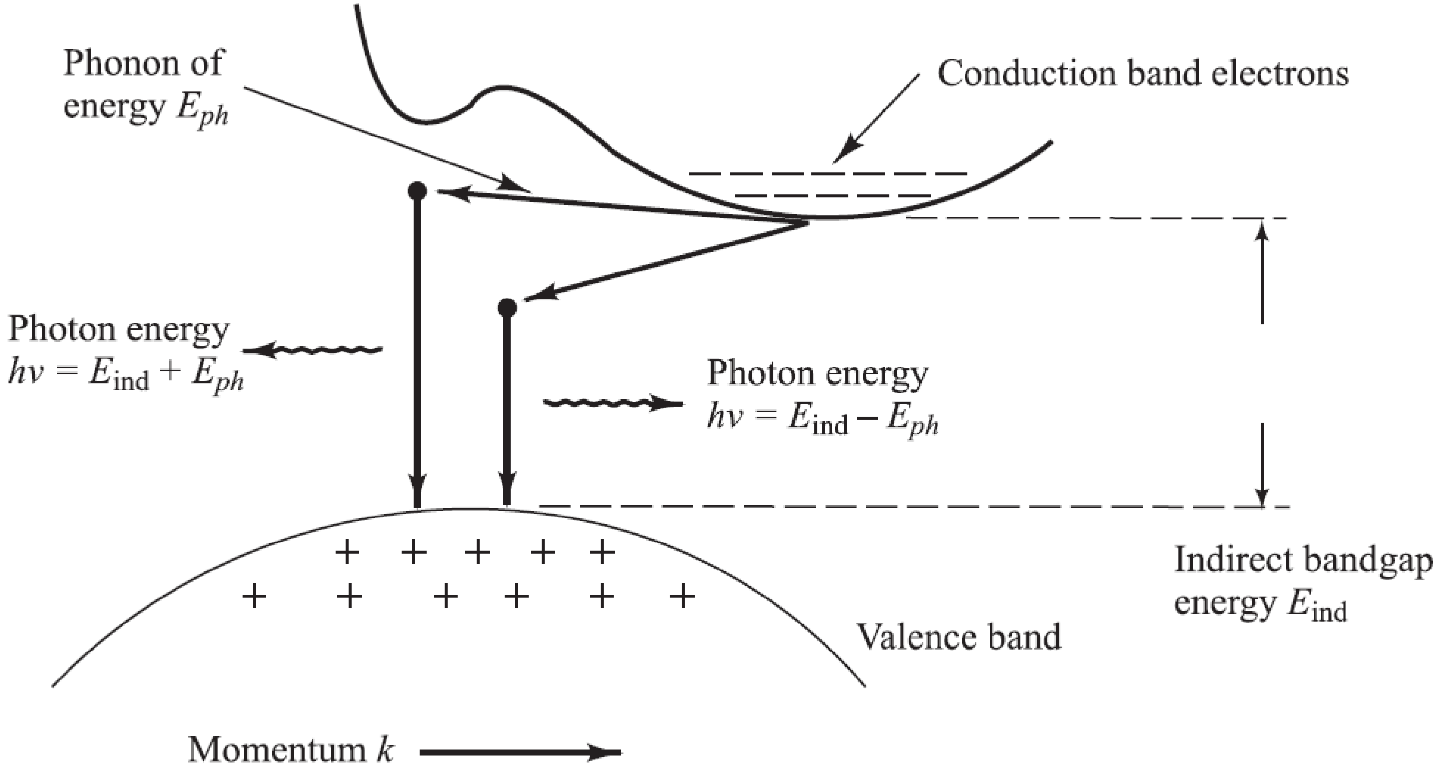
DIRECT BAND GAP MATERIALS

- For direct band gap materials, the minimum energy levels of conduction band and the maximum energy levels of valence band occur at same values of momentum
- The direct transition of an electron across the energy gap provides an efficient mechanism for photon emission
- Ex: GaAs, GaSb, InAs



INDIRECT BAND GAP MATERIALS

- For indirect band gap materials, the minimum conduction band and the maximum valence band energy levels occur at different values of momentum
- Here, the electron and hole recombination requires the simultaneous emission of a photon in order to conserve the momentum
- Ex: Si, Ge, GaP

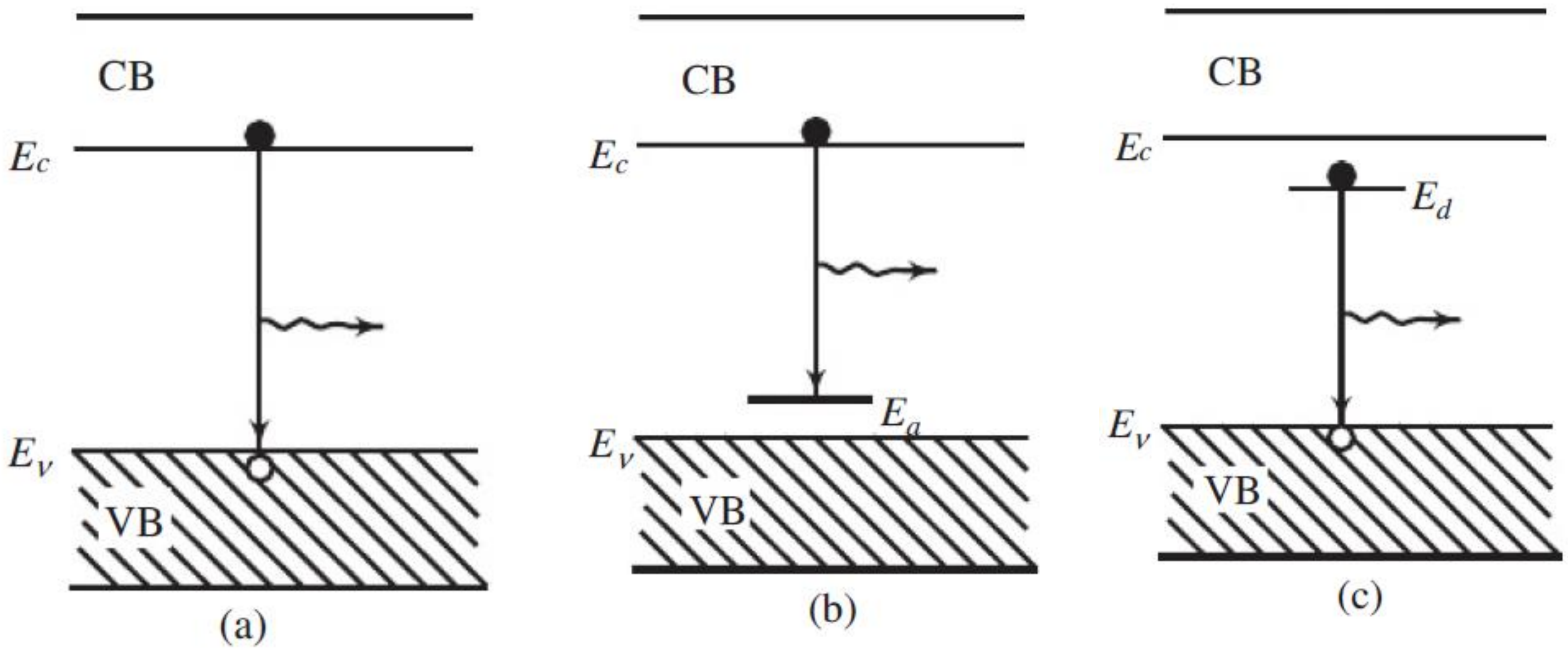


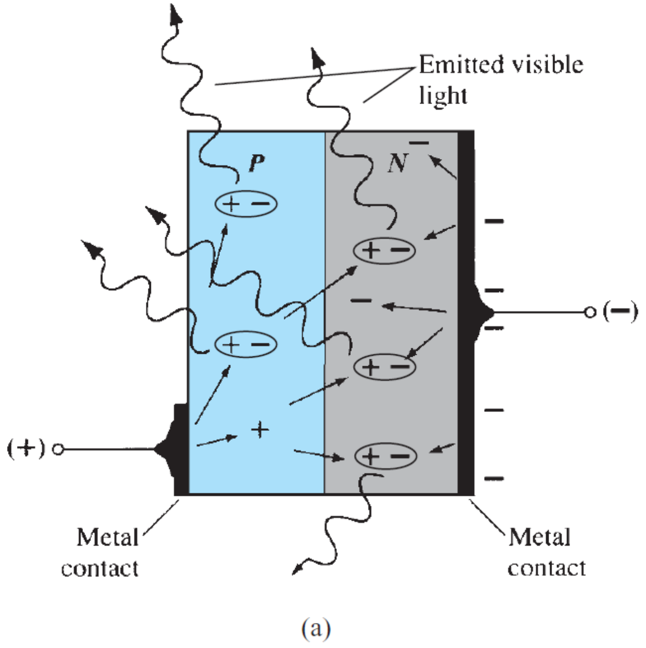
DIRECT BAND GAP (DBG) VERSUS INDIRECT BAND GAP (IBG) SEMICONDUCTOR MATERIALS

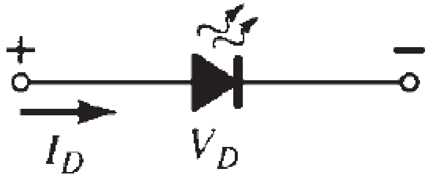
- In a DBG semiconductor, a direct recombination takes place with the **release of the energy equal to the energy difference between the recombining particles**. But in case of a IBG semiconductor, due to a relative difference in the momentum, first, the **momentum is conserved** by release of energy and only **after the both the momenta align themselves, a recombination occurs accompanied** with the release of energy.
- The probability of a radiative recombination, in case of IBG semiconductor is much less in comparison to that in case of DBG semiconductors. Hence, the **efficiency factor of a DBG semiconductor is much more than that of a IBG** semiconductor.
- The ratio of the number of radiative recombinations (photons produced within the structure) to the number of injected carriers is known as internal quantum efficiency.
- The most useful material for electroluminescence purpose (more internal quantum efficiency) are direct bad gap semiconductors

Other radiative recombination processes

- Energy levels may be introduced into the band gap by adding impurities, which may greatly increase the electron-hole recombination (effectively reduces the carrier life time)
- An indirect band gap semiconductors may be made into a more useful electroluminescence material by adding impurities, which will effectively convert it into a direct band gap materials.
- Types radiative recombination processes:
  - Conduction to valence band transition (band to band)
  - Conduction band to acceptor impurity transition
  - Donor impurity to valence band transition
  - Donor impurity to acceptor impurity transition







(a) the recombination of an electron in the CB with a hole in the VB (normally referred to as direct band-to-band transition)

(b) the downward transition of an electron in the CB to an empty acceptor level

(c) the transition of an electron from a filled donor level to a hole in the VB

- In Si and Ge, the greater percentage is given up in the form of heat and the emitted light is insignificant.
- In other materials, such as gallium arsenide phosphide (GaAsP) or gallium phosphide (GaP), the number of photons of light energy emitted is sufficient to create a very visible light source.
- Here the photon energy is equal to the energy of band gap

Color	Construction	Typical Forward Voltage (V)
Amber	AlInGaP	2.1
Blue	GaN	5.0
Green	GaP	2.2
Orange	GaAsP	2.0
Red	GaAsP	1.8
White	GaN	4.1
Yellow	AlInGaP	2.1

SPECTRUM OF EMISSION

- If the transition takes place from the electron level at the bottom of the CB to the hole level at the top of the VB, the emitted photon will have energy

$$E_{ph} = \frac{hc}{\lambda} = E_g = E_C - E_V$$

$$\lambda\ (in\ \mu m) = \frac{1.24}{E_g(eV)}$$

where h is Planck's constant c is the speed of light, and λ is the wavelength of emitted radiation.

- depending on the energy levels involved, there will be a range of photon energies that are emitted by the LED.

- The probability of existence of an electron in the conduction band of a n-type semiconductor material

$$F(E_2) = e^{-(E_2 - E_{Fn})/kT}$$

- Similarly, the probability of the existence of a hole in the valence band of a p-type semiconductor material

$$1 - F(E_1) = e^{(E_1 - E_{Fp})/kT}$$

- the total number of photons would, hence, correspond to the total number of electrons and holes available for recombination. This quantity would be proportional to the probability of existence of an electron-hole pair in the semiconductor material

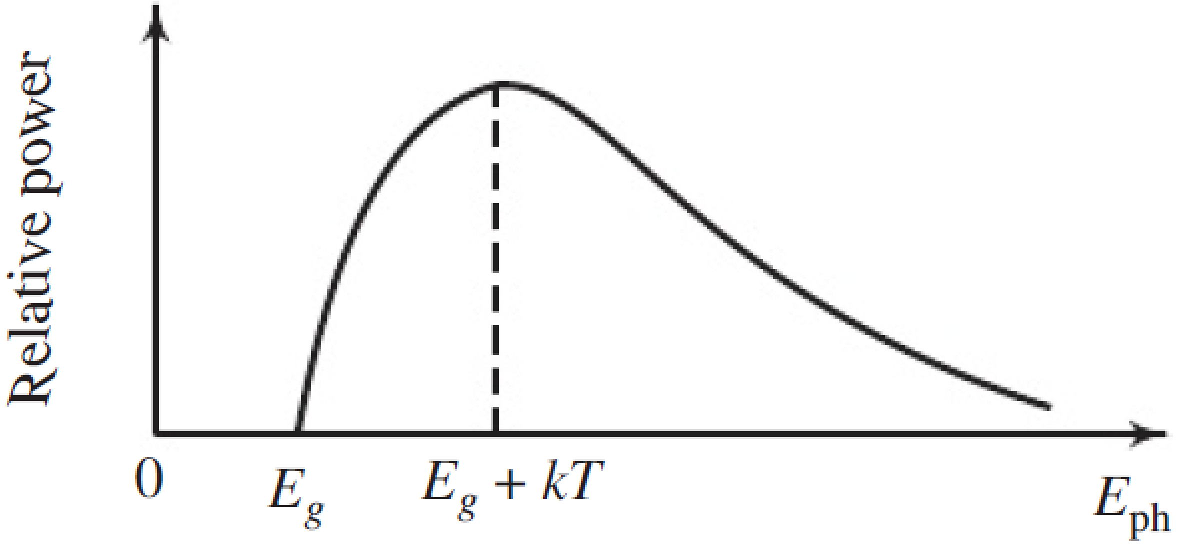
$$probability\ of\ photon \propto F(E_2)\big(1 - F(E_1)\big)$$
$$\propto e^{-(E_2 - E_1)/kT} e^{(E_{Fn} - E_{Fp})/kT}$$

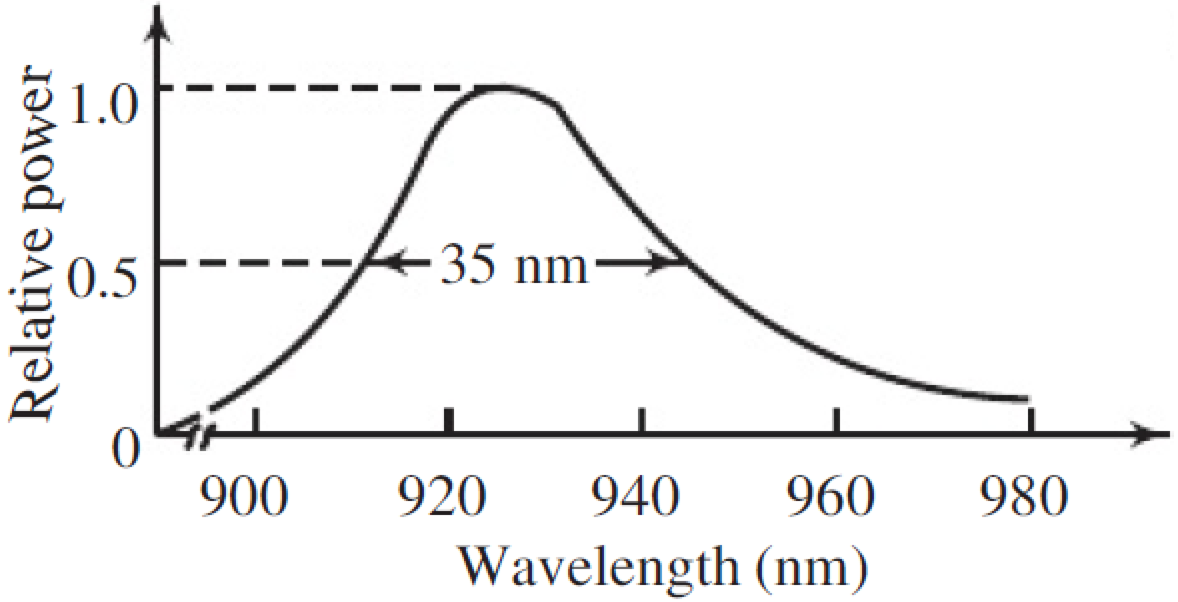
- The total number of photons

$$N_{ph} \propto \int_{E_C}^{E_V + E_{ph}} e^{-\frac{E_{ph}}{kT}}\, dE_2$$

$$\propto (E_{ph} - E_g) e^{-\frac{E_{ph}}{kT}}$$

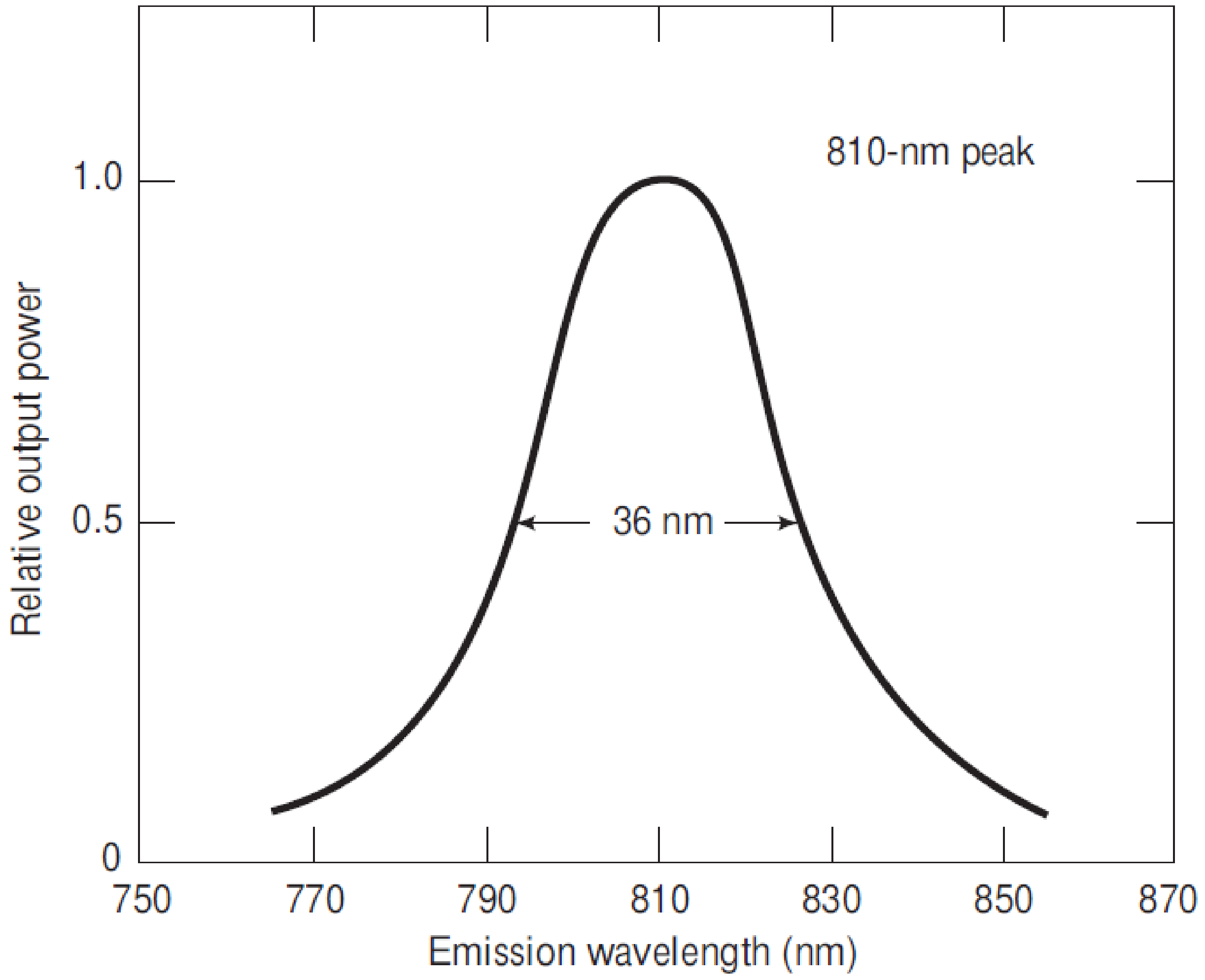
Where $E_g = E_C - E_V$ and $E_{ph} = E_2 - E_1$


Relative power
0
E_g
$E_g + kT$
E_{ph}


Relative power
1.0
0.5
0
35 nm
900
920
940
960
980
Wavelength (nm)

Examples for light source materials

- the principal material used for light sources is the ternary and quaternary types of alloy $\mathbf{Ga_{1-x}Al_xAs}$.
- The ratio x of aluminum arsenide to gallium arsenide determines the bandgap of the alloy and, correspondingly, the wavelength of the peak emitted radiation
- The energy gap in electron volts for values of x between zero and 0.37 (the direct band gap region) can be found from the empirical equation
  $E_g = 1.424 + 1.266\,x + 0.266\,x^2$
- For $In_{1-x}\,Ga_x\,As_y\,P_{1-y}$,
  $E_g(eV)=1.35-0.72y+0.12y2$,
  Where $y=2.2x;\ 0<x<0.47$



Calculated spectral width values of LEDs

λ_{max}(μm)	E_{ph}(eV)	Approx. $\Delta\lambda$ (nm)
0.85	1.455	36
1.30	0.952	85
1.55	0.798	120

LED Internal quantum efficiency

- Generally, the excess minority carrier density decays exponentially with time *t*

$$n(t) = n_0 e^{-t/\tau}$$

where n_0 is the initial injected excess electron density and τ represents the total carrier recombination lifetime.

$$internal\ quantum\ efficiency\ \eta_{int} = \frac{no.\,of\ radiative\ recombinations\ (photons)}{Total\ number\ of\ recombinations}$$

The rate of electron-hole recombination in a semiconductor material can be expressed as

$$-\frac{dn(t)}{dt} = \frac{n_0}{\tau} e^{-\frac{t}{\tau}} = \frac{n(t)}{\tau}$$

Here, 'n_0' is the initial charge carrier density in the semiconductor material and 'τ' is the average life-time of a carrier against recombination.

the total rate of recombination can be written as $\frac{n(t)}{\tau} = \frac{n(t)}{\tau_{rr}} + \frac{n(t)}{\tau_{nr}}$

Where 'τ_{rr}' be the life-time of a carrier against radiative recombination and 'τ_{nr}' be the life-time of a carrier against non-radiative recombination.

$$\eta_{int} = \frac{\frac{n(t)}{\tau_{rr}}}{\frac{n(t)}{\tau_{rr}} + \frac{n(t)}{\tau_{nr}}} = \frac{1}{1 + \frac{\tau_{rr}}{\tau_{nr}}}$$

LED POWER

The LED power can be defined as

$$P_{int} = \frac{\eta_{int} I}{q} E_{ph} = \frac{\eta_{int} I}{q} \frac{hc}{\lambda}$$

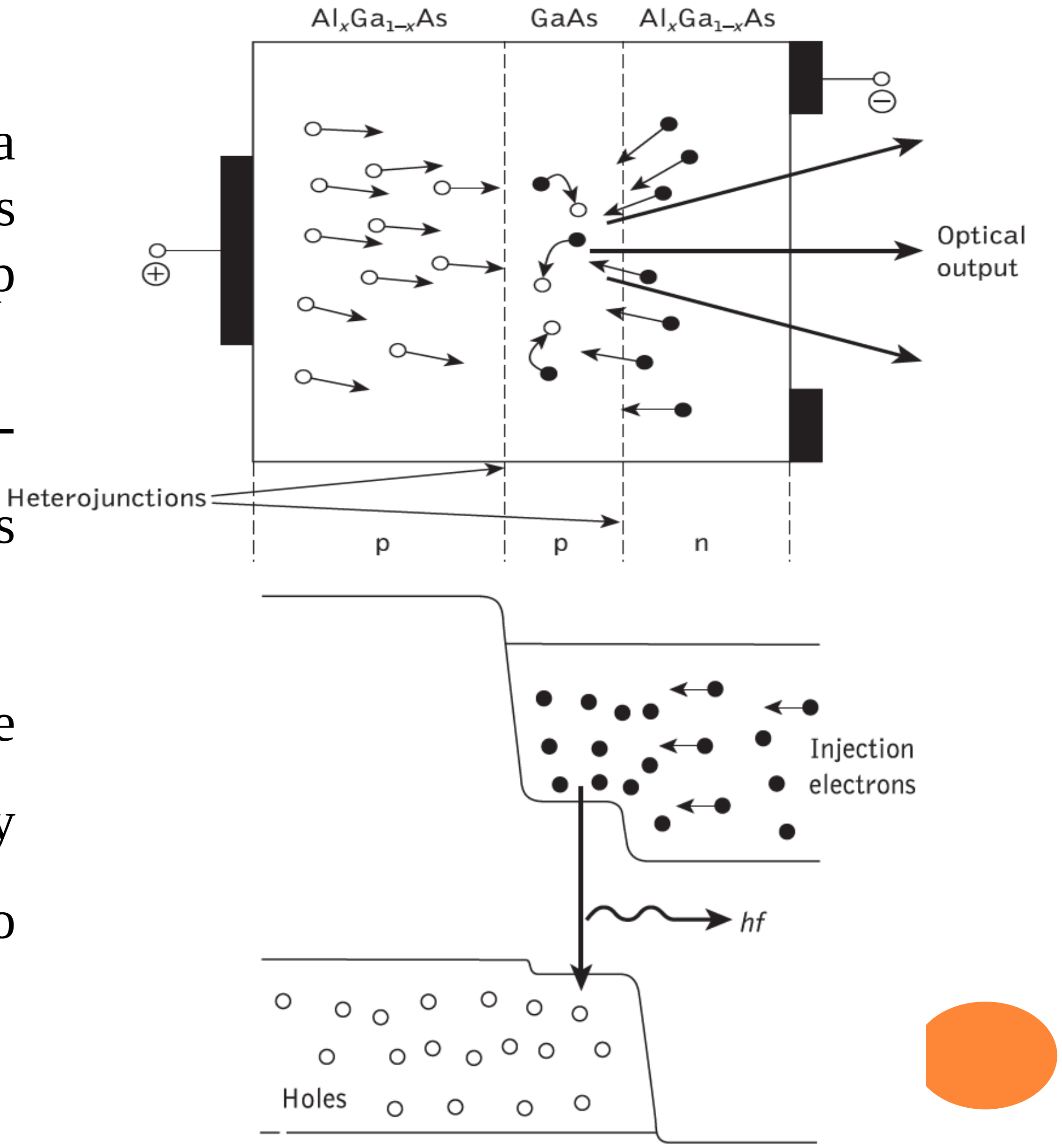
$$P_{int} = \frac{\eta_{int} I}{q} \frac{hc}{\lambda}$$

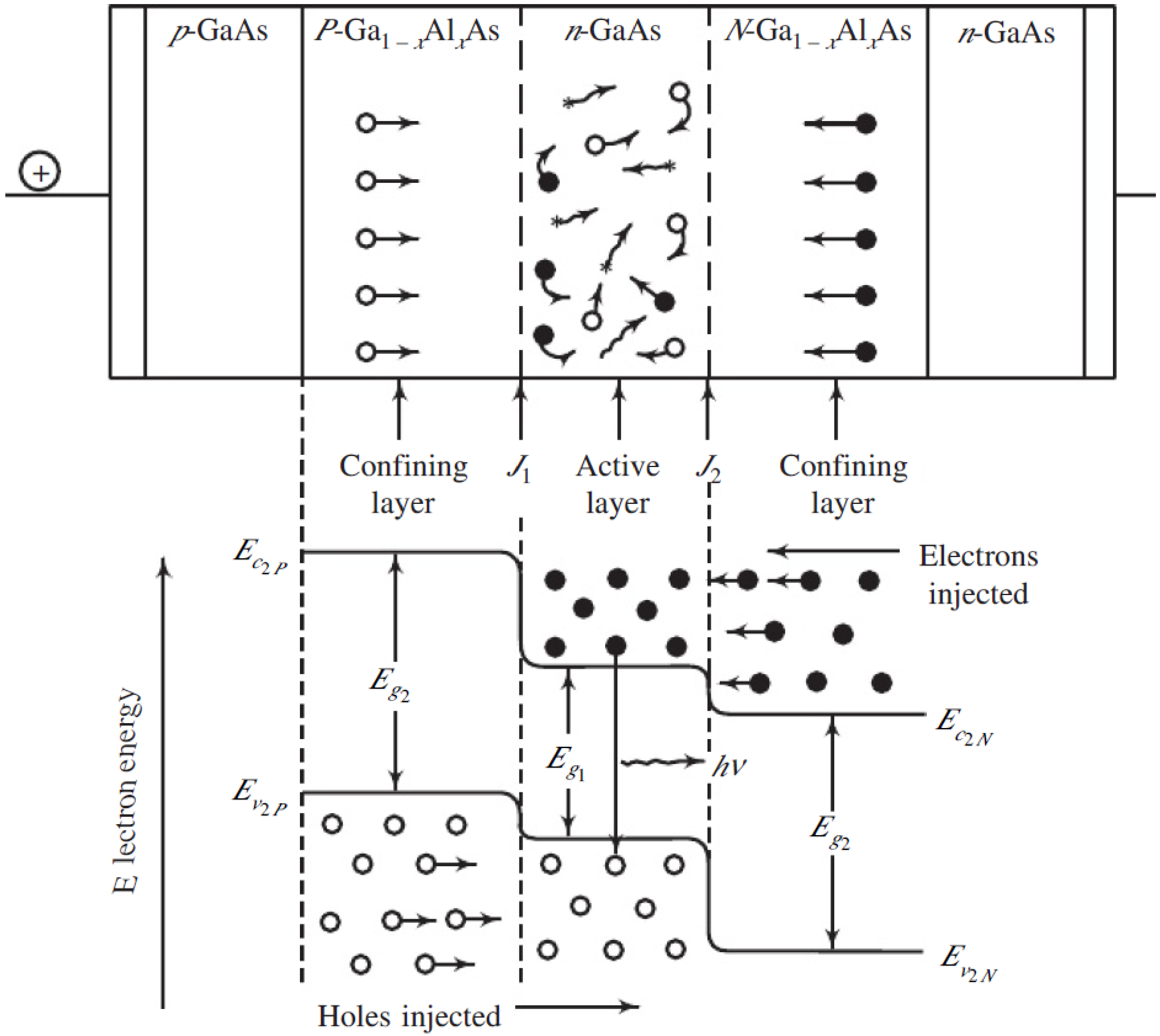
LIGHT EMITTING DIODE (LED) STRUCTURE

- In optical transmission applications, the source must have
  - high radiance output (to couple sufficient high optical power levels into the fiber)
  - fast emission response time (the time delay between the application of a current pulse and the onset of optical emission)
  - high quantum efficiency (related to the fraction of injected electron-hole pairs that recombine radiatively)
- To obtain the necessary high radiance and high quantum efficiency, LEDs may be fabricated with **double hetero structure**.

The double-heterojunction LED

- A **double hetero-structure** is formed when a layer of narrow band gap material (ex: GaAs) is sandwiched between the layers of wide band gap materials (ex:GaAl As).
- When forward bias is applied, the holes from p-GaAlAs are injected into p-GaAs and electrons from n-GaAlAs are injected into p-GaAs.
- A large number of carriers are confined in the central layer of p-GaAs (active layer), where they recombine and produced optical energy equal to band gap of n-GaAs.





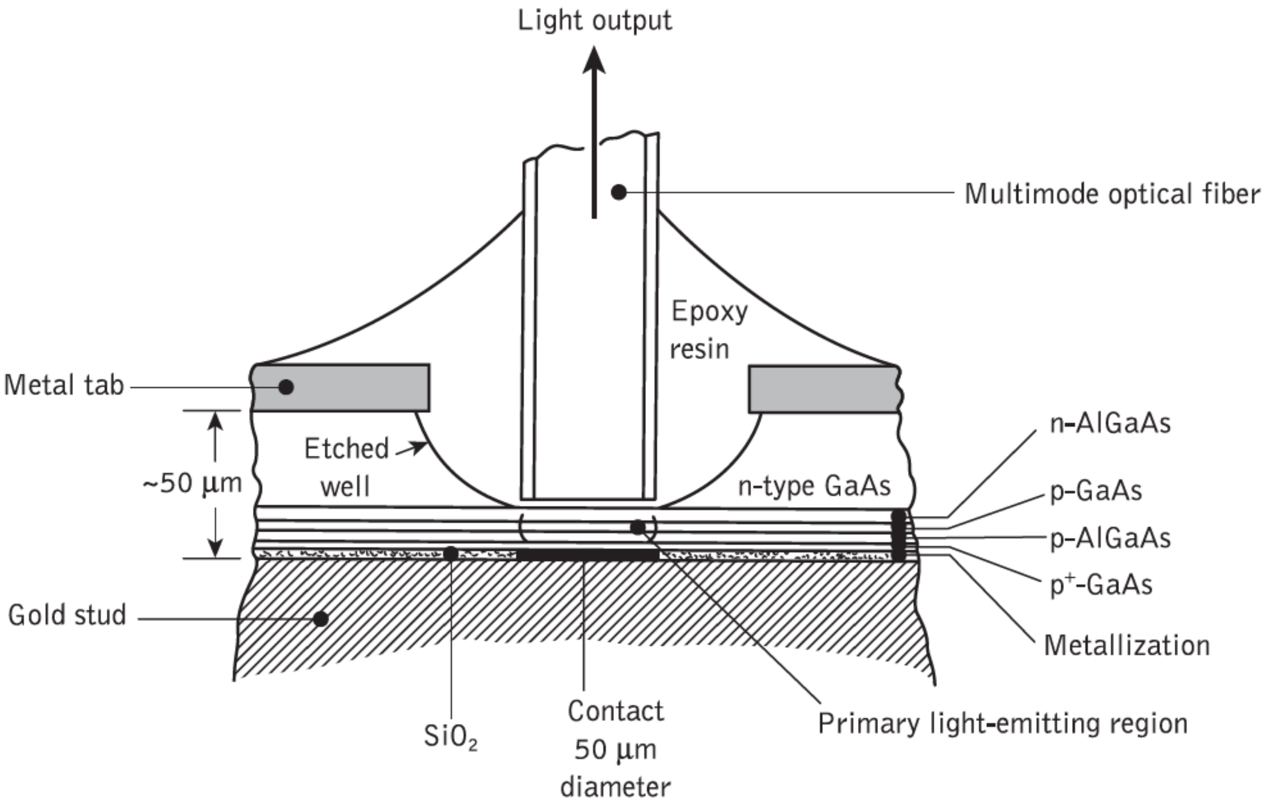
p-GaAs
P-$Ga_{1-x}Al_xAs$
n-GaAs
N-$Ga_{1-x}Al_xAs$
n-GaAs
+
Confining layer
J_1
Active layer
J_2
Confining layer
E_{c_2P}
E_{g_2}
E_{v_2P}
Electrons injected
E_{c_2N}
E_{g_1}
$h\nu$
E_{g_2}
E_{v_2N}
E lectron energy
Holes injected

LED STRUCTURE (CONT…)

- There are two basic LED structures
  - Surface (Burrus or front) emitting LED
  - Edge emitting LED

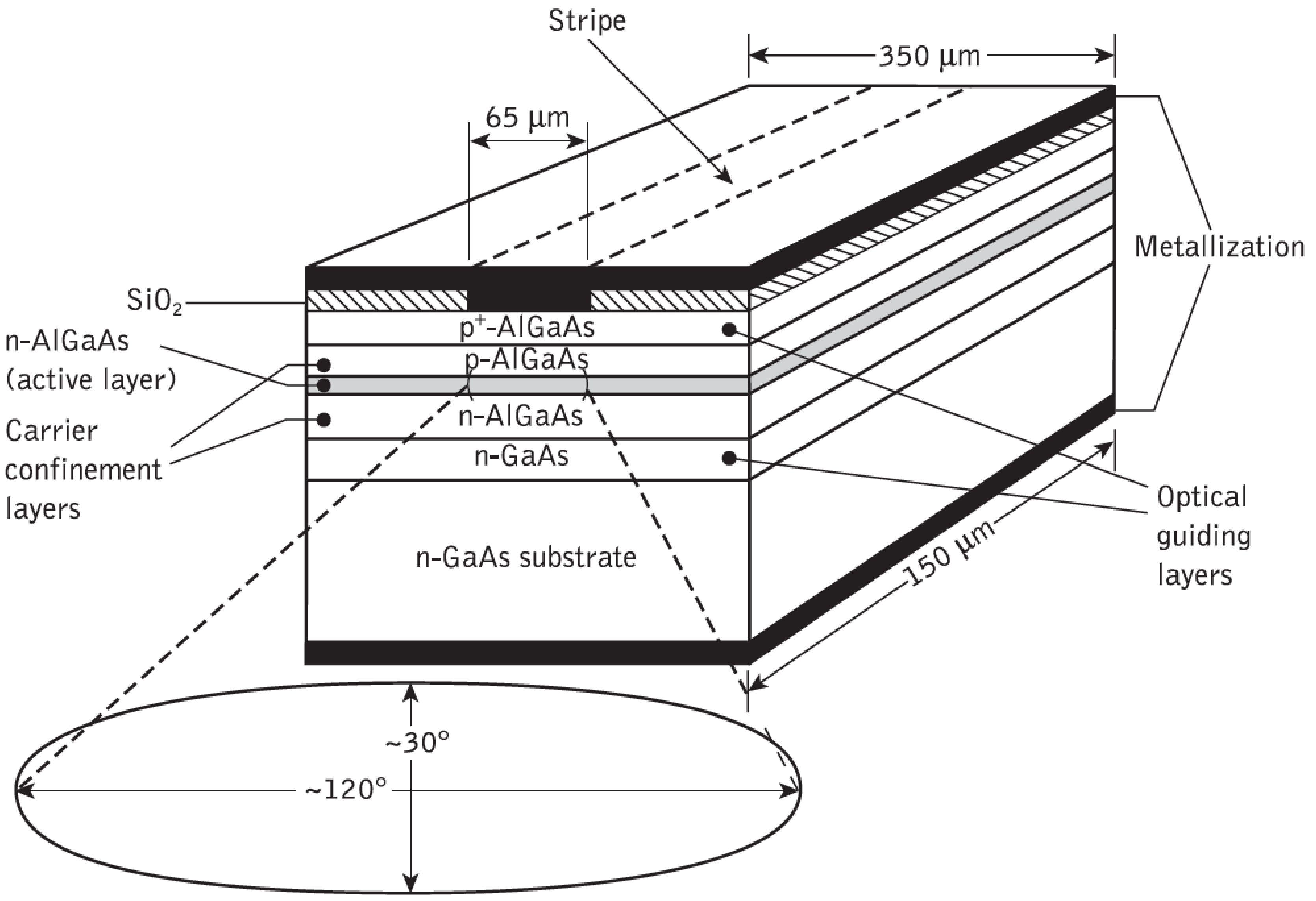
SURFACE EMITTING LED

- In surface emitting LED, the plane of the active light emitting region is oriented perpendicular to the axis of the fiber.
- A well is etched through the GaAs substrate of the device in order to prevent heavy absorption of the emitted radiation and physically to accommodate the fiber.
- These structures have a low thermal impedance in the active region allowing high current densities and giving high-radiance emission into the optical fiber.
- The emission pattern from active layer is essentially isotropic with a 120^0 half power beam width.
- The circular active region in practical surface emitting LEDs is 50µm and up to 2.5µm thick.



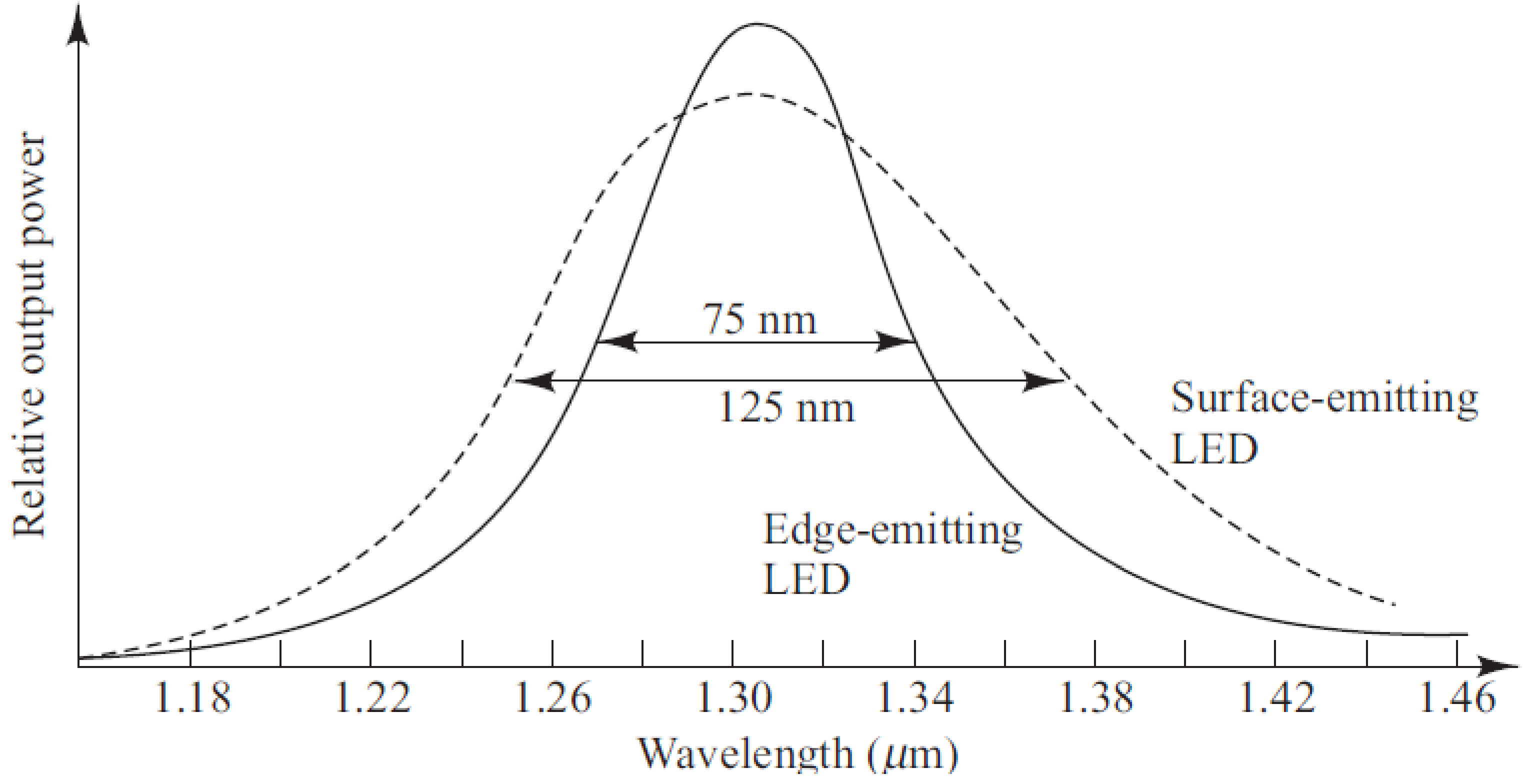
EDGE EMITTING LED

- It consists of an active junction region and two guiding layers, both have a refractive index less than that of the active region, but higher than the index of the surrounding material.
- This structure forms a waveguide channel that directs the optical radiation towards the fiber core.
- To match the typical fiber core diameters, the contact strips are 50-70µm.
- Range of length of the active regions is usually from 100 to 150µm
- The emission pattern is more directional than that of surface emitters.
- In the plane parallel to the junction the emitted beam is Lambertian with half power width of 120^0, in perpendicular to the junction the half power beam width is $25\text{-}35^0$



Schematic diagram of an edge-emitting double hetero-junction LED

Spectral width of LED types

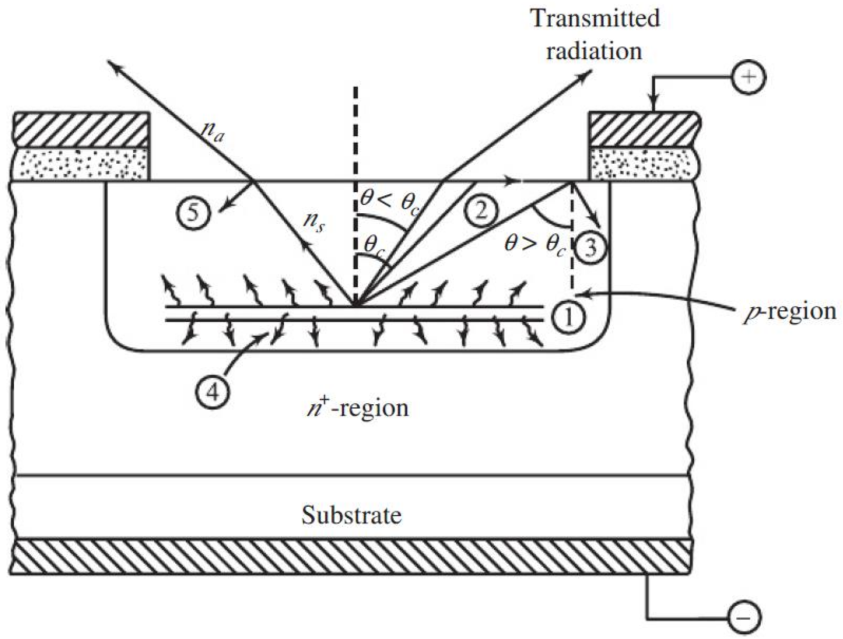


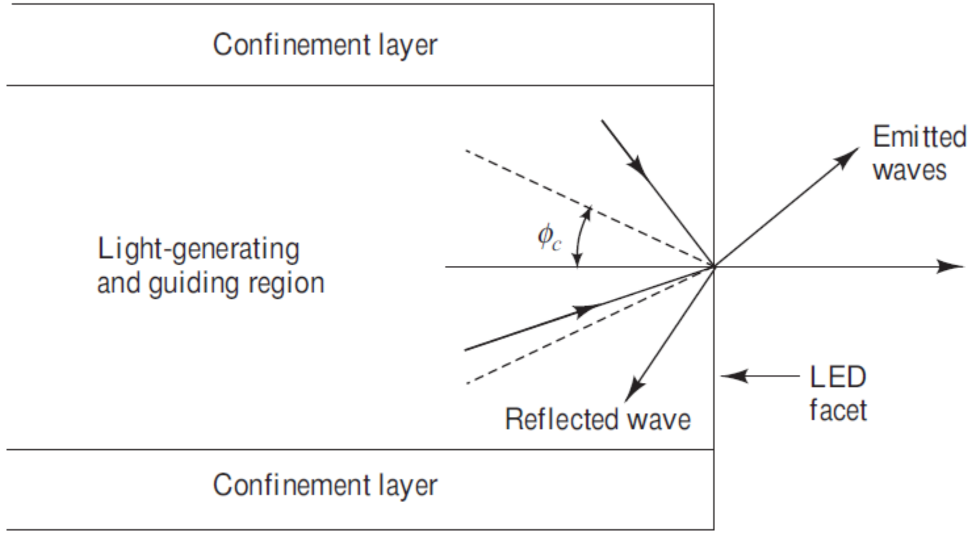
EXTERNAL QUANTUM EFFICIENCY

- It is defined as the ratio of the number of photons guided in the fiber to the number of internally generated photons

$$\eta_{ext} = \frac{\text{number of photons guided to the fiber}}{\text{number of internally generated photons}}$$

- In order to calculate the external quantum efficiency, we need to consider the reflection effects at the surface of the LED.
- If we consider the LED structure as a simple 2D slab waveguide, only light falling within a cone defined by critical angle will be emitted from an LED.





$$\eta_{\text{ext}} = \frac{1}{4\pi}\int_0^{\phi_c} T(\phi)(2\pi \sin\phi)\,d\phi$$

$$T(\phi): \text{Fresnel Transmission Coefficient} \approx T(0) = \frac{4n_s n_a}{(n_s + n_a)^2}$$

$$\text{If } n_a = 1 \Rightarrow \eta_{\text{ext}} \approx \frac{1}{n_s(n_s+1)^2}$$

$$\text{LED emitted optical powr, } P = \eta_{\text{ext}} P_{\text{int}} \approx \frac{P_{\text{int}}}{n_s(n_s+1)^2}$$

Modulation of an LED

- The frequency response of an LED depends on the following factors:
  - Doping level in the active region
  - Injected carrier life time in the recombination region τ_i
  - parasitic capacitance of the LED
- If the drive current of an LED is modulated at a frequency of ω, the output optical power of the device will vary as:

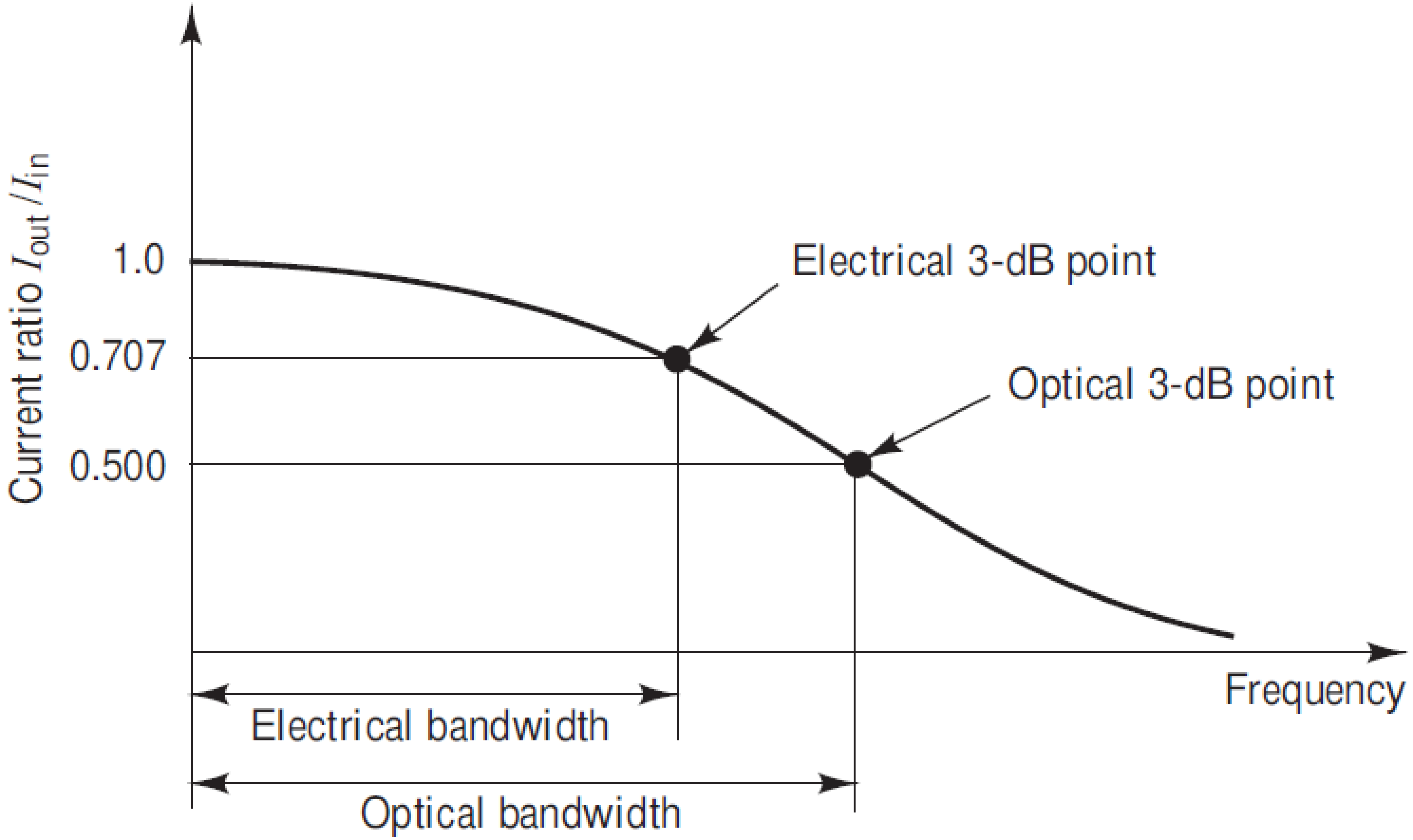
$$P(\omega) = \frac{P_0}{\sqrt{1 + (\omega \tau_i)^2}}$$

- Electrical current is directly proportional to the optical power, thus we can define electrical bandwidth and optical bandwidth, separately.

$$\text{Electrical BW} = 10\log\left[\frac{p(\omega)}{p(0)}\right] = 20\log\left[\frac{I(\omega)}{I(0)}\right]$$

p : electrical power, I : electrical current

$$\text{Optical BW} = 10\log\left[\frac{P(\omega)}{P(0)}\right] = 10\log\left[\frac{I(\omega)}{I(0)}\right]$$



Current ratio I_{out}/I_{in}
1.0
0.707
0.500
Electrical 3-dB point
Optical 3-dB point
Frequency
Electrical bandwidth
Optical bandwidth

TEXT BOOKS

- Gerd Keiser, Optical Fiber Communications, TMH India, Fourth Edition, 2010.
- Senior John M., Optical Fiber Communications, Pearson Education India, Third Edition, 2009.
- R.P. Khare, *Fiber optics and optoelectronics, Oxford University Press 2004*