Department of Electronics & Communication Engg.

Course : Optical Communication Engg-10EC64. **Sem.: 7th (2017-18)**

Course Coordinator:

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Chapter 1

Overview of Photonic Communications

Optics

- Optics is an old subject involving the generation, propagation & detection of light.
- Three major developments are responsible for rejuvenation of optics & its application in modern technology:

1- Invention of Laser

2- Fabrication of low-loss optical Fiber

3- Development of Semiconductor Optical Device

As a result, new disciplines have emerged & new terms describing them have come into use, such as:

- **Electro-Optics**: is generally reserved for optical devices in which electrical effects play a role, such as lasers, electro-optic modulators & switches.

Photonics

- **Optoelectronics**: refers to devices & systems that are essentially electronics but involve lights, such as LED, liquid crystal displays & array photodetectors.
- **Quantum Electronics**: is used in connection with devices & systems that rely on the interaction of light with matter, such as lasers & nonlinear optical devices.
- **Quantum Optics**: Studies quantum & coherence properties of light.
- **Lightwave Technology**: describes systems & devices that are used in optical communication & signal processing.
- **Photonics**: in analogy with electronics, involves the control of photons in free space and matter.

Photonic Communications

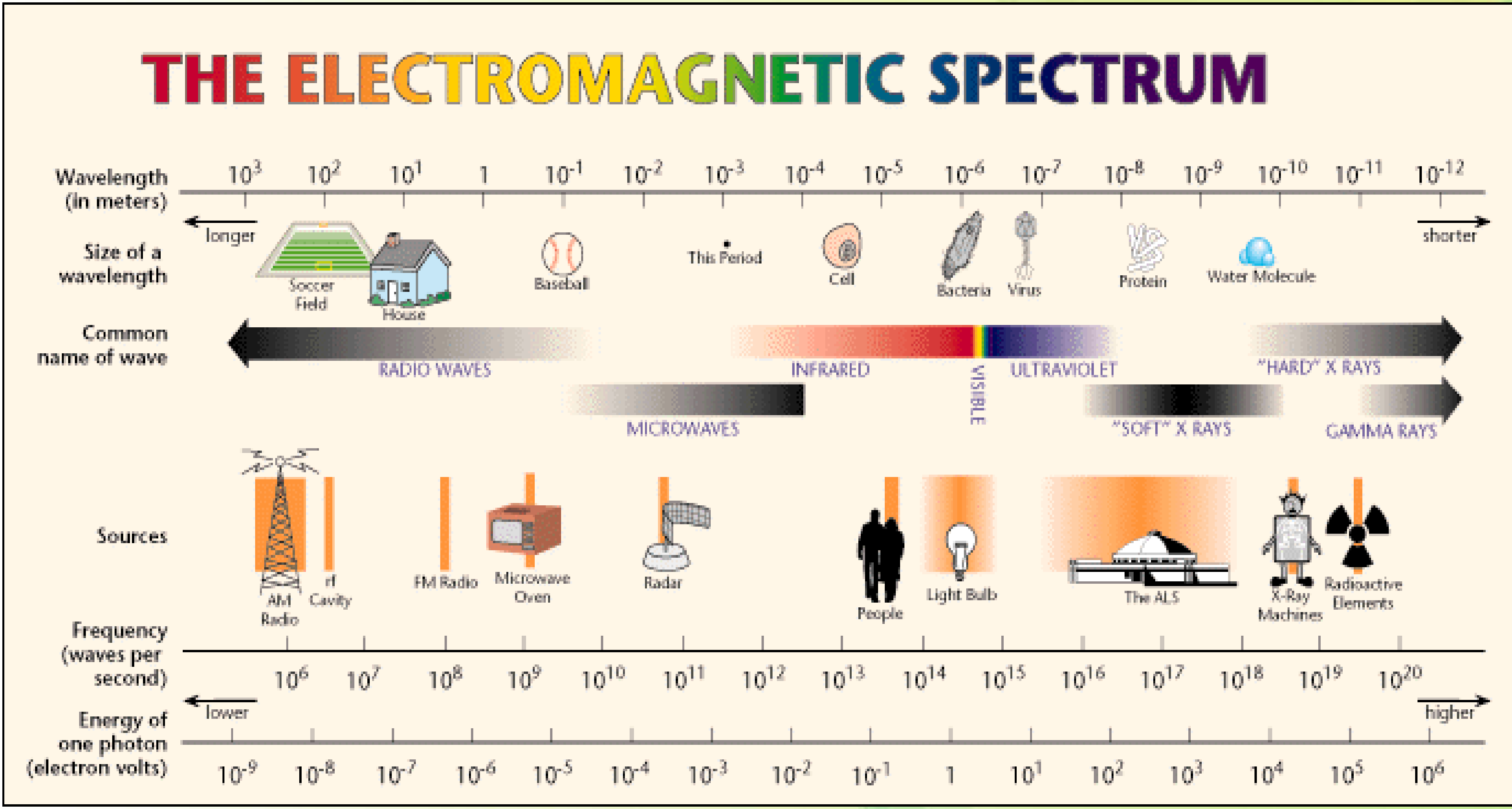
- Photonics reflects the importance of the photon nature of light. Photonics & electronics clearly overlap since electrons often control the flow of photons & conversely, photons control the flow of electrons.
- The scope of Photonics:

  1- Generation of Light (coherent & incoherent)

  2- Transmission of Light (through free space, fibers, imaging systems, waveguides, …)

  3- Processing of Light Signals (modulation, switching, amplification, frequency conversion, …)

  4- Detection of Light (coherent & incoherent)
- **Photonic Communications**: describes the applications of photonic technology in communication devices & systems, such as transmitters, transmission media, receivers & signal processors.


THE ELECTROMAGNETIC SPECTRUM
Wavelength (in meters)
10^3 10^2 10^1 1 10^-1 10^-2 10^-3 10^-4 10^-5 10^-6 10^-7 10^-8 10^-9 10^-10 10^-11 10^-12
longer
shorter
Size of a wavelength
Soccer Field
House
Baseball
This Period
Cell
Bacteria
Virus
Protein
Water Molecule
Common name of wave
RADIO WAVES
INFRARED
VISIBLE
ULTRAVIOLET
"HARD" X RAYS
MICROWAVES
"SOFT" X RAYS
GAMMA RAYS
Sources
AM Radio
rf Cavity
FM Radio
Microwave Oven
Radar
People
Light Bulb
The ALS
X-Ray Machines
Radioactive Elements
Frequency (waves per second)
10^6 10^7 10^8 10^9 10^10 10^11 10^12 10^13 10^14 10^15 10^16 10^17 10^18 10^19 10^20
lower
higher
Energy of one photon (electron volts)
10^-9 10^-8 10^-7 10^-6 10^-5 10^-4 10^-3 10^-2 10^-1 1 10^1 10^2 10^3 10^4 10^5 10^6

Why Photonic Communications?

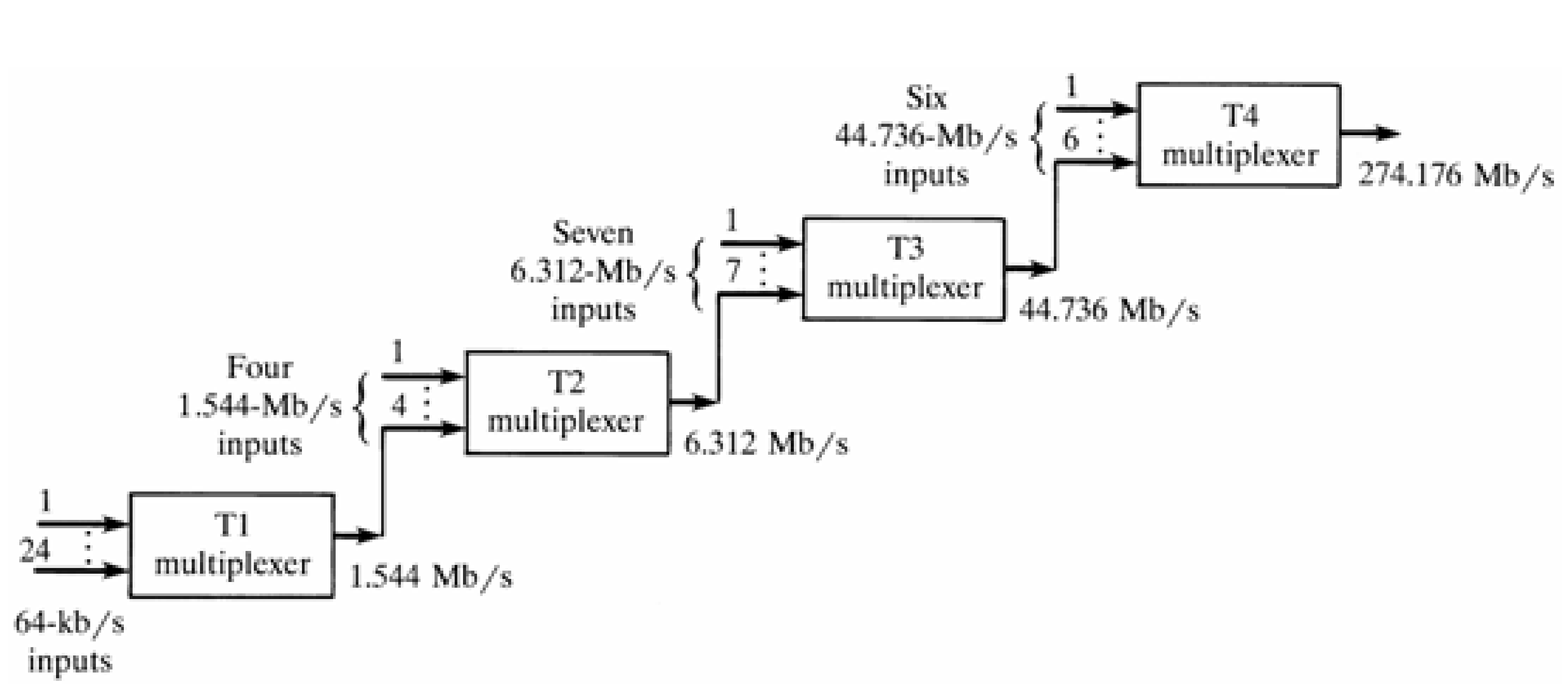
- Extremely wide bandwidth: high carrier frequency (a wavelength of 1552.5 nm corresponds to a center frequency of 193.1 THz!) & consequently orders of magnitude increase in available transmission bandwidth & larger information capacity.
- Optical Fibers have small size & light weight.
- Optical Fibers are immune to electromagnetic interference (high voltage transmission lines, radar systems, power electronic systems, airborne systems, …)
- Lack of EMI cross talk between channels
- Availability of very low loss Fibers (0.25 to 0.3 dB/km), high performance active & passive photonic components such as tunable lasers, very sensitive photodetectors, couplers, filters,
- Low cost systems for data rates in excess of Gbit/s.

BW demands in communication systems

Type & applications	Format	Uncompressed	Compressed
Voice, digital telegraphy	4 kHz voice	64 kbps	16-32 kbps
Audio	16-24 kHz	512-748 kbps	32-384 kbps (MPEG, MP3)
Video conferencing	176 144 or 352 288 frames @ 10-30 frames/s	2-35.6 Mbps	64 kbps-1.544 Mbps (H.261 coding)
Data transfer, E-commerce,Video entertainment			1-10 Mbps
Full-motion broadcast video	720 480frames @ 30 frames/s	249 Mbps	2-6Mbps (MPEG-2)
HDTV	1920 1080 frames@ 30 frames /s	1.6 Gbps	19-38 Mbps (MPEG-2)

Early application of fiber optic communication

- Digital link consisting of time-division-multiplexing (TDM) of 64 kbps voice channels (early 1980).



SONET & SDH Standards

- **SONET** (Synchronous Optical NETwork) is the network standard used in north America & **SDH** (Synchronous Digital Hierarchy) is used in other parts of the world. These define a synchronous frame structure for sending multiplexed digital traffic over fiber optic trunk lines.

- The basic building block of SONET is called **STS-1** (Synchronous Transport Signal) with 51.84 Mbps data rate. Higher-rate SONET signals are obtained by byte-interleaving *N* STS-1 frames, which are scramble & converted to an Optical Carrier Level *N* (**OC-N**) signal.

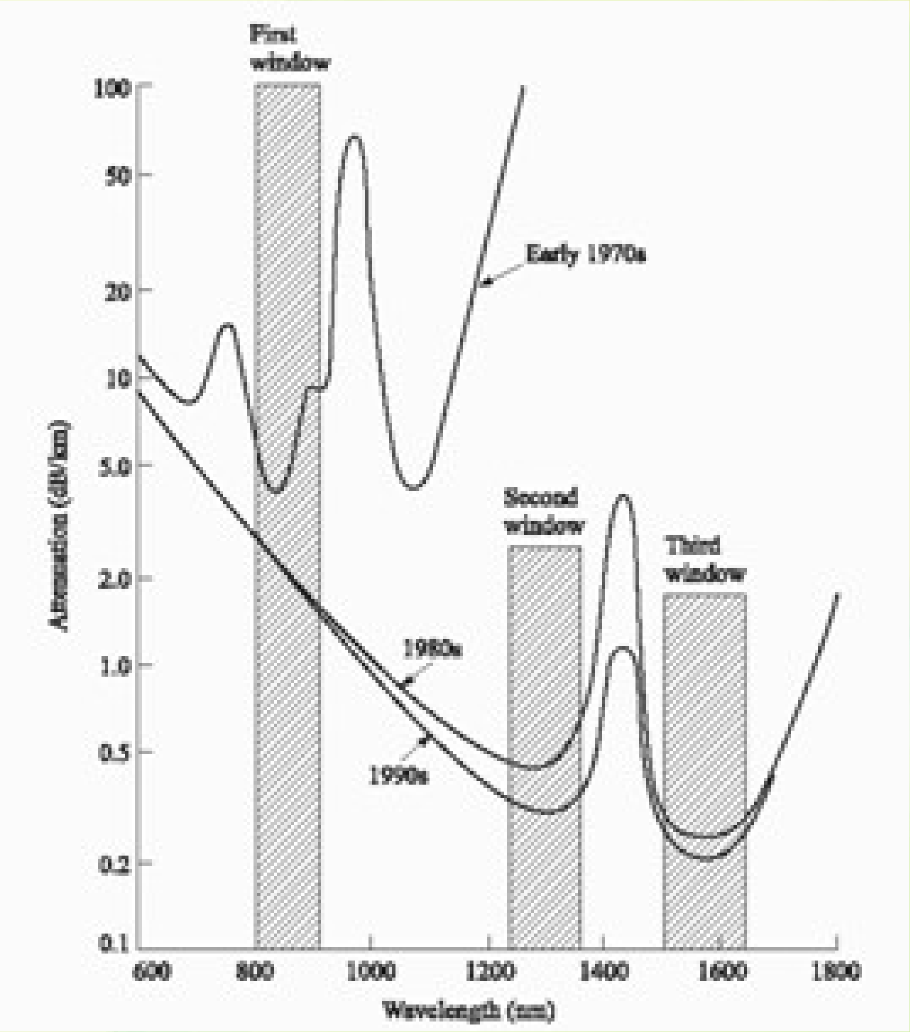
- The basic building block of SDH is called **STM-1** (Synchronous Transport Module) with 155.52 Mbps data rate. Higher-rate SDH signals are achieved by synchronously multiplexing *N* different STM-1 to form **STM-N** signal.

SONET & SDH transmission rates

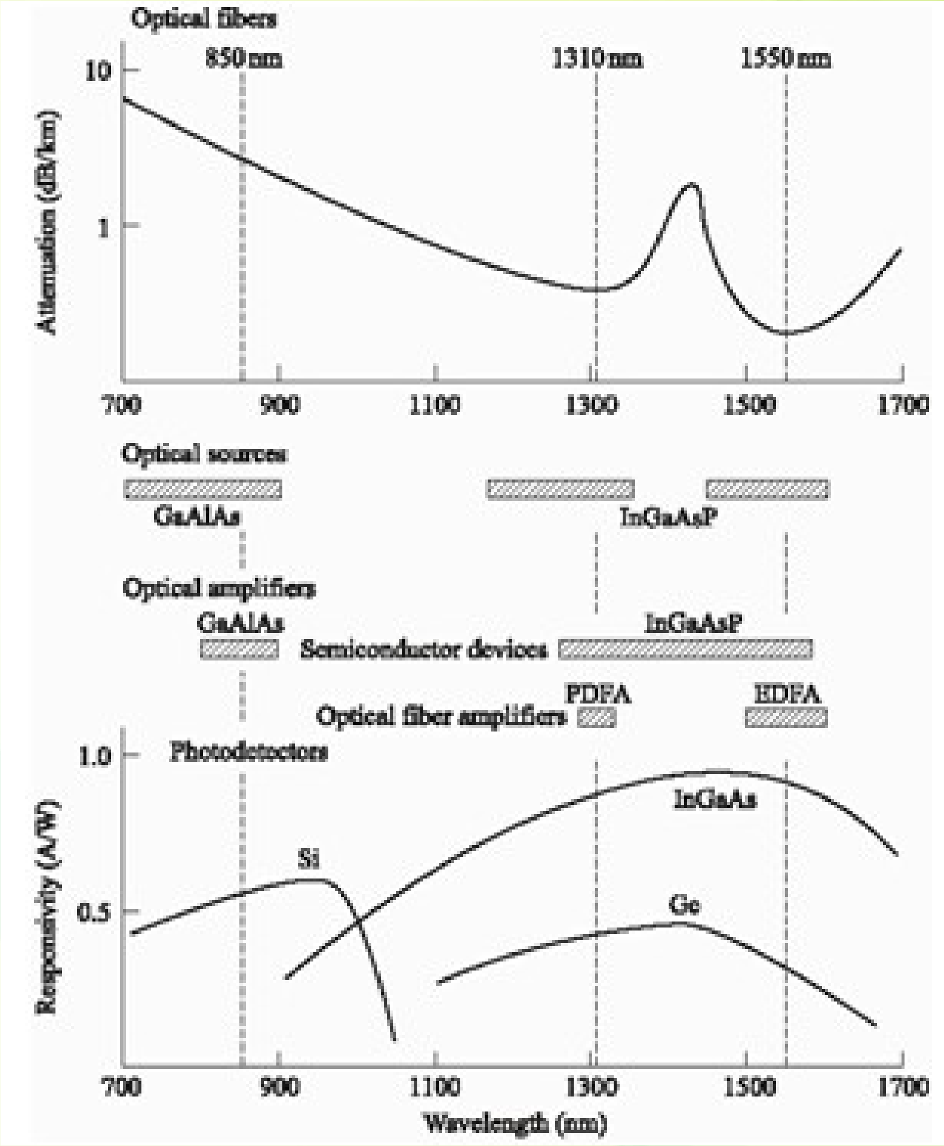
SONET level	Electrical level	Line rate (Mb/s)	SDH equivalent
OC-1	STS-1	51.84	-
OC-3	STS-3	155.52	STM-1
OC-12	STS-12	622.08	STM-4
OC-24	STS-24	1244.16	STM-8
OC-48	STS-48	2488.32	STM-16
OC-96	STS-96	4976.64	STM-32
OC-192	STS-192	9953.28	STM-64

Evolution of fiber optic systems

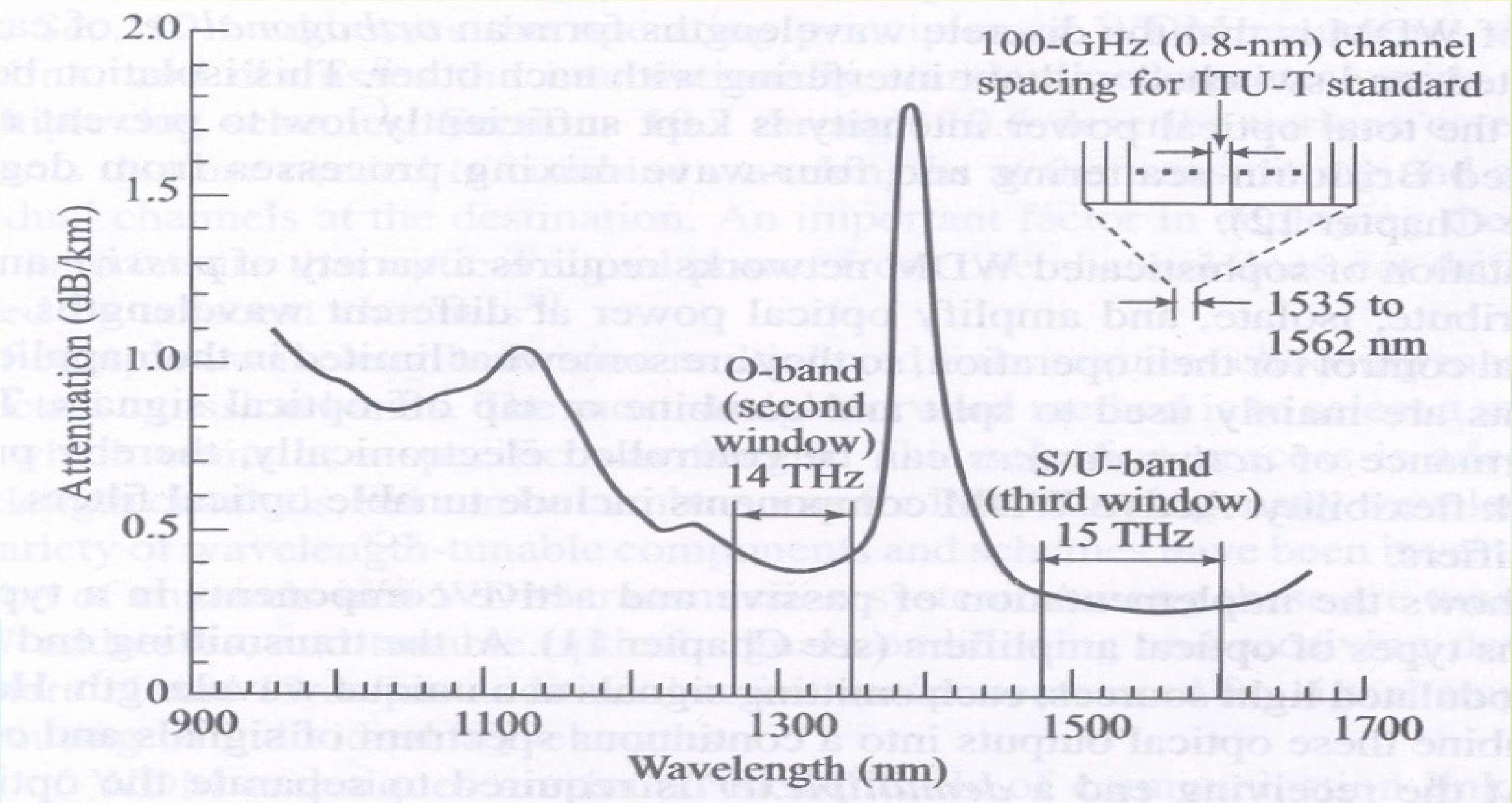
- 1950s:Imaging applications in medicine & non-destructive testing, lighting
- 1960s:Research on lowering the fiber loss for telecom. applications.
- 1970s:Development of low loss fibers, semiconductor light sources & photodetectors
- 1980s:single mode fibers (OC-3 to OC-48) over repeater sapcings of 40 km.
- 1990s:Optical amplifiers (e.g. EDFA), WDM (wavelength division multiplexing) toward dense-WDM.



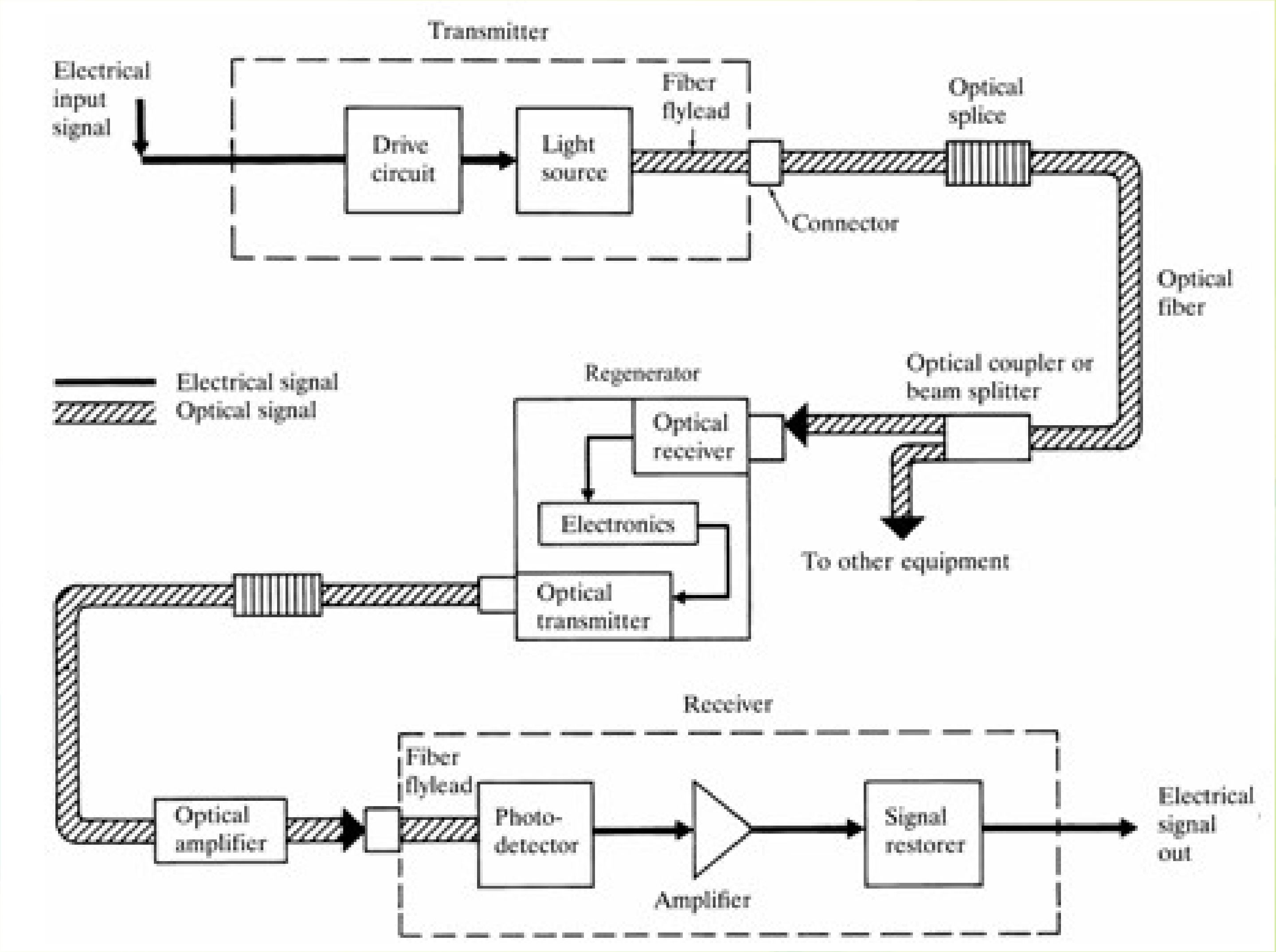
Operating range of 4 key components in the 3 different optical windows



Transmission windows and bandwidths



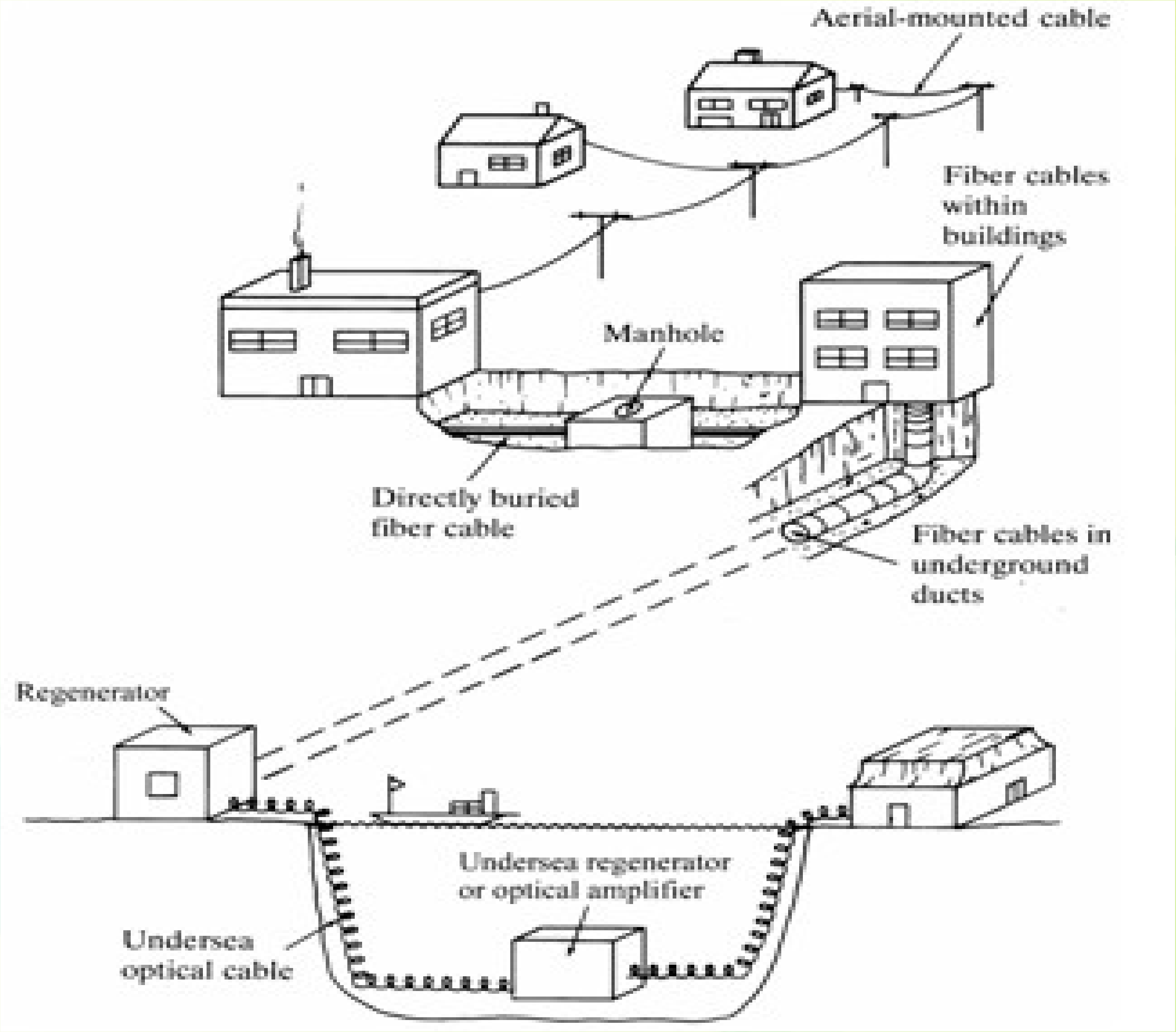
Major elements Of typical photonic comm link



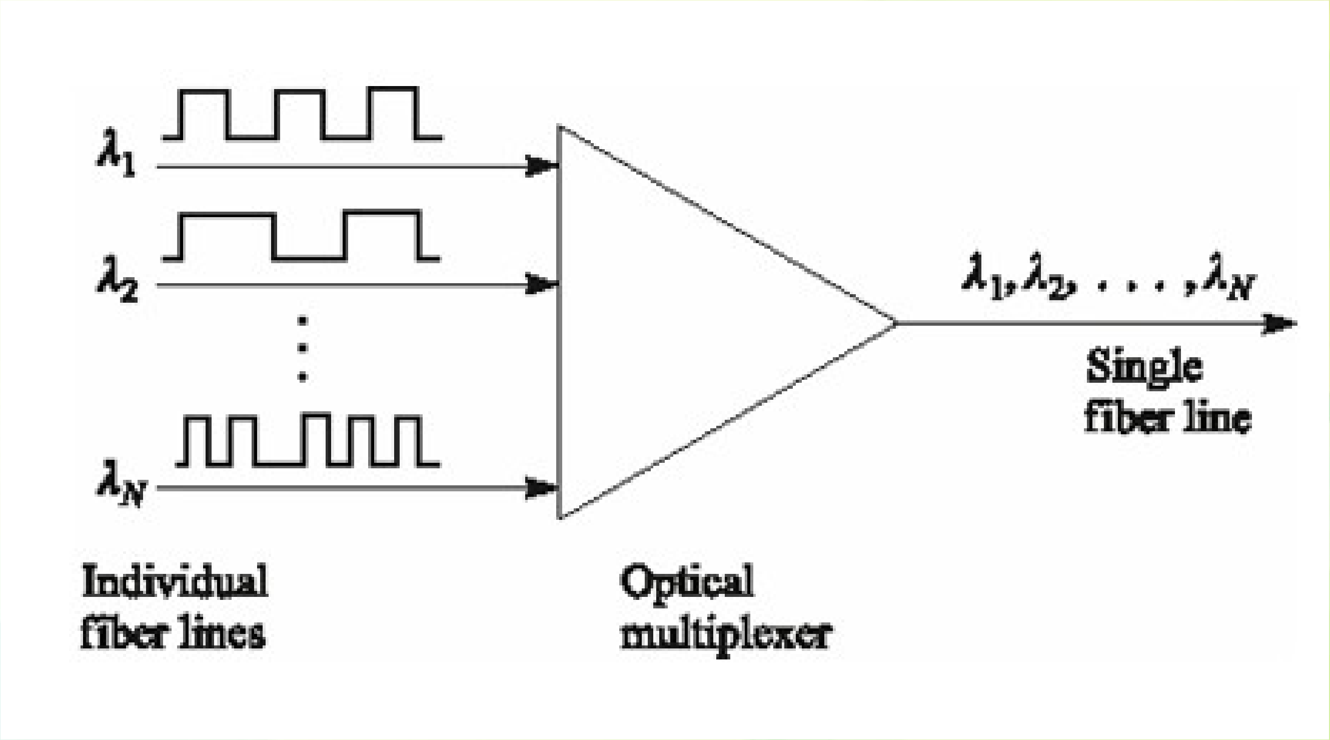
Fibre Optics

- Telecom applications
  - Primarily SMFs
- Networking applications
  - Mostly SMFs (FTTH)
- Fibre optic Sensing
  - SMF and MMF
- Medical applications
  - Mostly MMF, or bundle fibres (light pipes
- Industrial applications
  - Mostly MMF

Installation of Fiber optics



WDM Concept



λ_1
λ_2
λ_N
$\lambda_1, \lambda_2, \ldots, \lambda_N$
Single fiber line
Individual fiber lines
Optical multiplexer

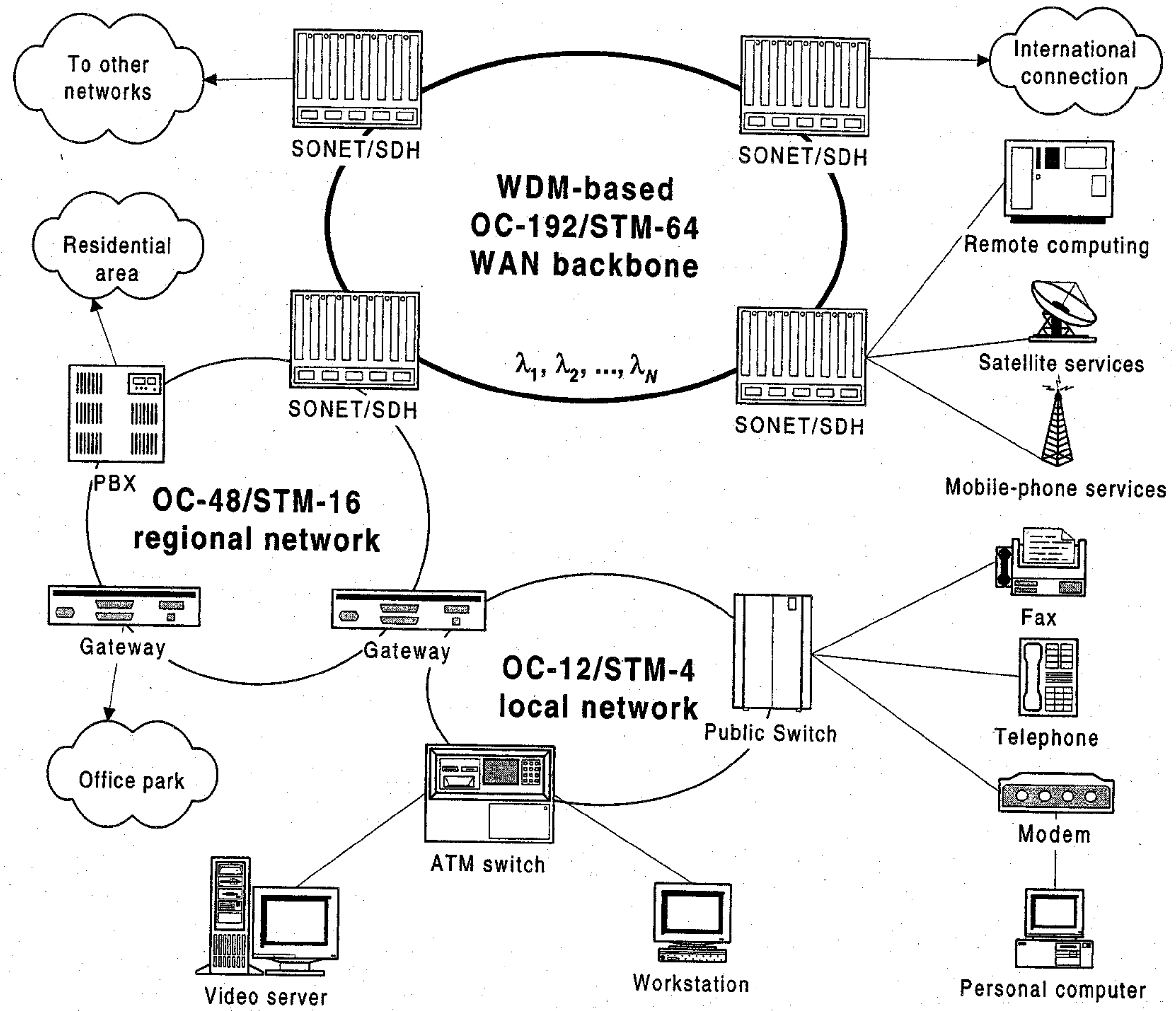


FIGURE 1-9
Conceptual SONET/SDH optical transport network connecting local, metropolitan, and wide-area communications elements.

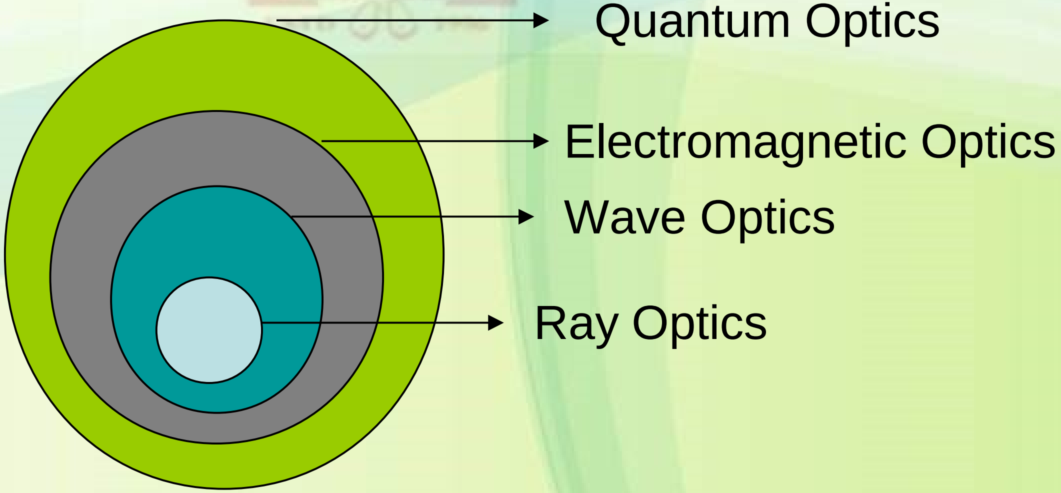
Chapter 2

Optical Fibers: Structures, Waveguiding & Fabrication

Theories of Optics

- Light is an electromagentic phenomenon described by the same theoretical principles that govern all forms of electromagnetic radiation. **Maxwell's equations** are in the hurt of electromagnetic theory & is fully successful in providing treatment of light propagation. **Electromagnetic optics** provides the most complete treatment of light phenomena in the context of **classical optics.**
- Turning to phenomena involving the interaction of **light & matter,** such as **emission** & **absorptio**n of light, **quantum theory** provides the successful explanation for light-matter interaction. These phenomena are described by quantum electrodynamics which is the marriage of electromagnetic theory with quantum theory. For optical phenomena, this theory also referred to as **quantum optics.** This theory provides an explanation of virtually all optical phenomena.

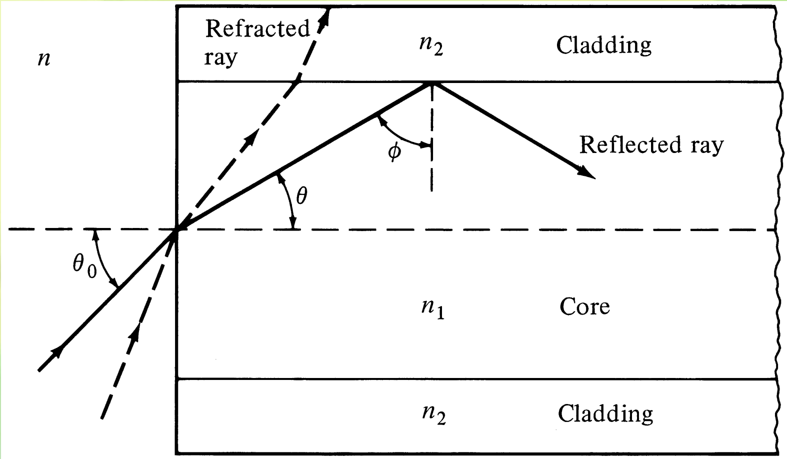
- In the context of classical optics, electromagentic radiation propagates in the form of two mutually coupled vector waves, an **electric field-wave** & **magnetic field wave**. It is possible to describe many optical phenomena such as diffraction, by **scalar** wave theory in which light is described by a single scalar wavefunction. This approximate theory is called scalar wave optics or simply **wave optics**. When light propagates through & around objects whose dimensions are much greater than the optical wavelength, the wave nature of light is not readily discerned, so that its behavior can be adequately described by rays obeying a set of geometrical rules. This theory is called **ray optics.** Ray optics is the limit of wave optics when the wavelength is very short.



Launching optical rays to slab waveguide

$\sin\phi_{\min} = \frac{n_2}{n_1}$; minimum angle that supports TIR

[2-21]



Maximum entrance angle, $\theta_{0\max}$ is found from the Snell's relation written at the fiber end face.

$$n\sin\theta_{0\max} = n_1\sin\theta_c = \sqrt{n_1^2 - n_2^2} \quad [2\text{-}22]$$

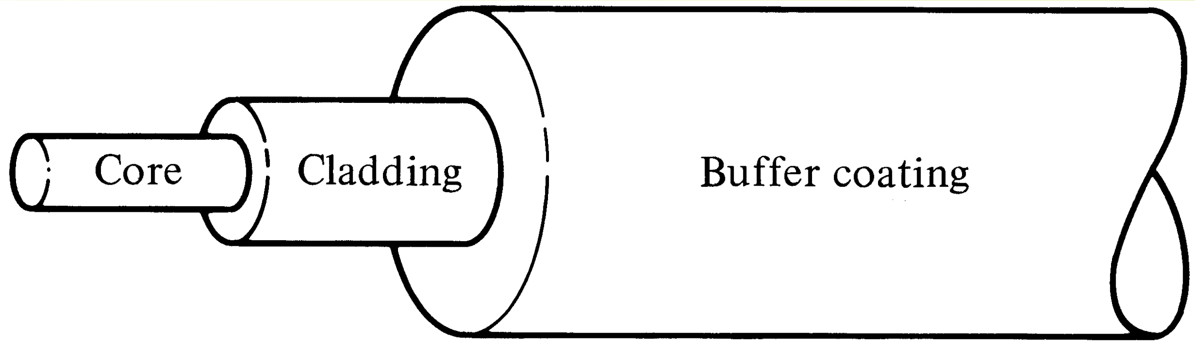
Numerical aperture:

$$\mathrm{NA} = n\sin\theta_{0\max} = \sqrt{n_1^2 - n_2^2} \approx n_1\sqrt{2\Delta} \quad [2\text{-}23]$$

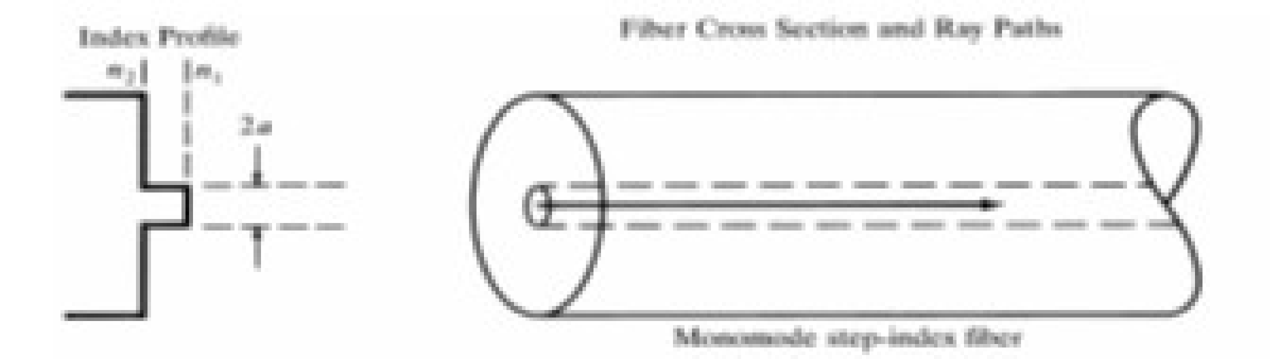
$$\Delta = \frac{n_1 - n_2}{n_1} \quad [2\text{-}24]$$

fppt.com

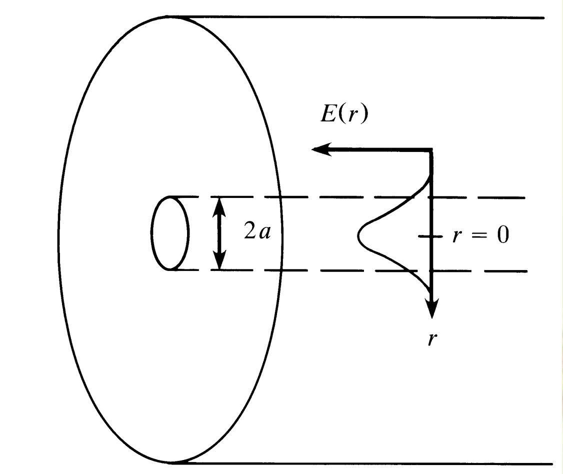
Optical Fibers: Modal Theory (Guided or Propagating modes) & Ray Optics Theory

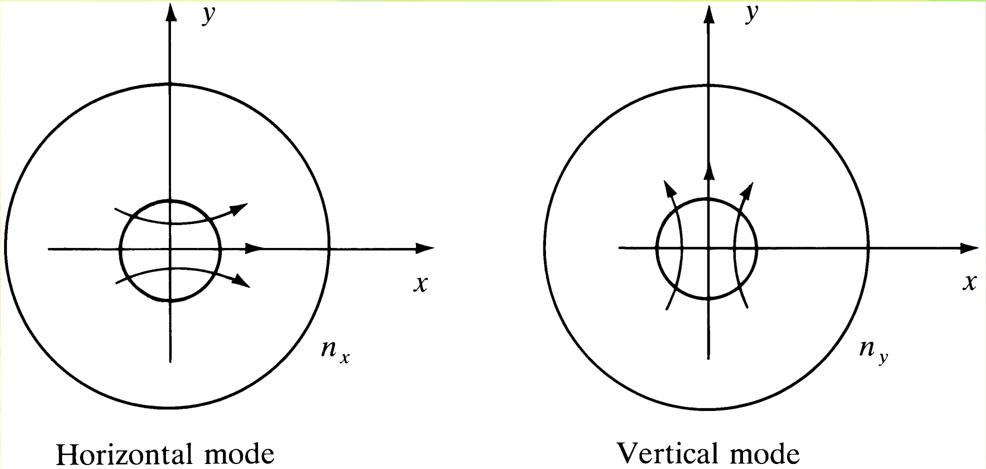


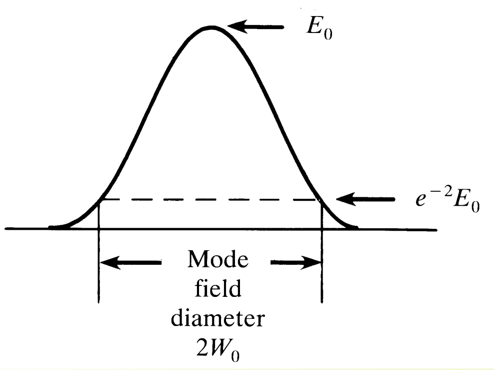
$$n_1 > n_2$$



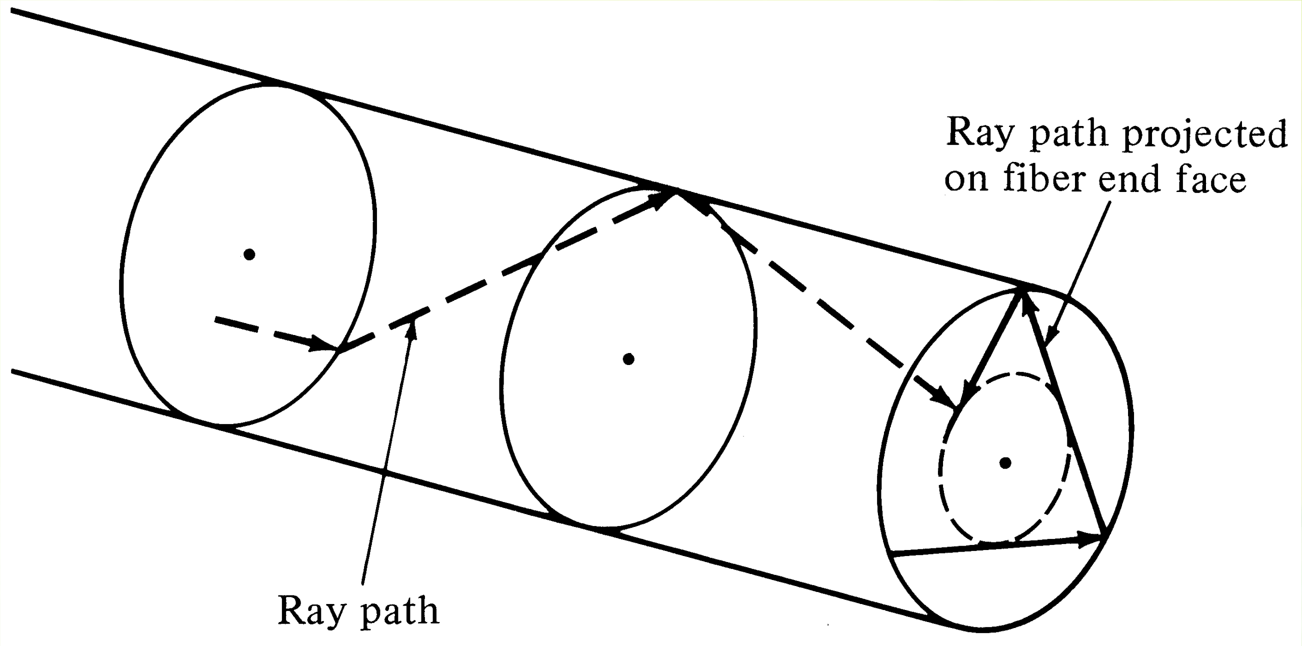
Fundamental Mode Field Distribution





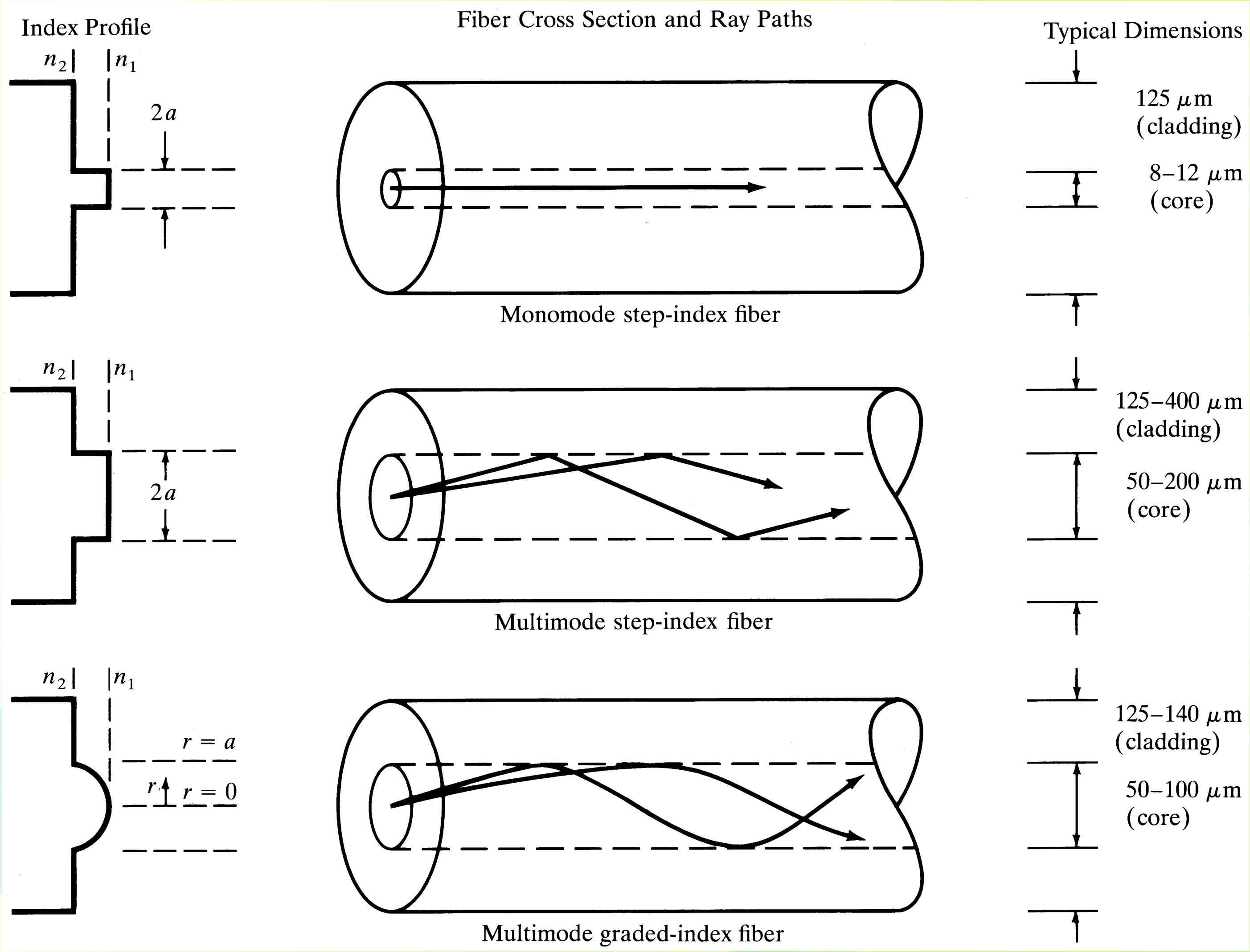


Ray Optics Theory (Step-Index Fiber)



Each particular guided mode in a fiber can be represented by a group of rays which Make the same angle with the axis of the fiber.

Different Structures of Optical Fiber



Mode propagation constant as a function of frequency

- Mode propagation constant, , is the most important transmission characteristic of an optical fiber, because the field distribution can be easily written in the form of eq. [2-27].
- In order to find a mode propagation constant and cut-off frequencies of various modes of the optical fiber, first we have to calculate the **normalized frequency**, *V*, defined by:

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

a: radius of the core, is the optical free space wavelength,

n_1 & n_2 are the refractive indices of the core & cladding.

Single mode Operation

- The cut-off wavelength or frequency for each mode is obtained from:

$$\beta_{lm}(\omega_c) = n_2 k = \frac{2\pi n_2}{\lambda_c} = \frac{\omega_c n_2}{c}$$

- **Single mode operation** is possible (Single mode fiber) when:

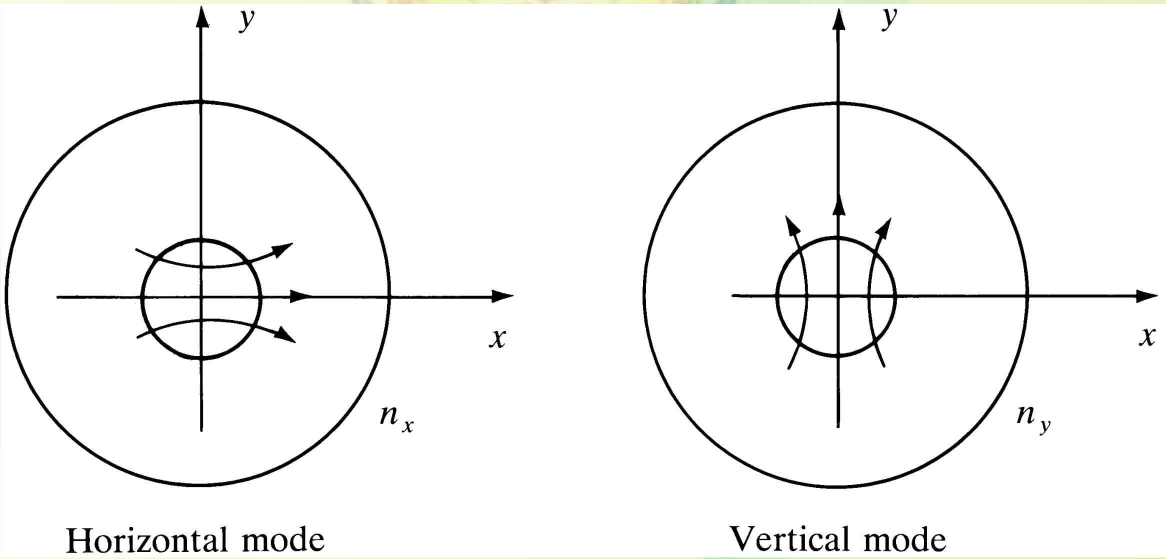
$$V \leq 2.405$$

Only HE_{11} can propagate faithfully along optical fiber

Birefringence in single-mode fibers

- Because of asymmetries the refractive indices for the two degenerate modes (vertical & horizontal polarizations) are different. This difference is referred to as **birefringence**, :

$$B_f = n_y - n_x$$



Fiber Beat Length

- In general, a linearly polarized mode is a combination of both of the degenerate modes. As the modal wave travels along the fiber, the difference in the refractive indices would change the phase difference between these two components & thereby the state of the polarization of the mode. However after certain length referred to as **fiber beat length,** the modal wave will produce its original state of polarization. This length is simply given by:

$$L_p = \frac{2\pi}{kB_f}$$

Multi-Mode Operation

- Total number of modes, *M*, supported by a multi-mode fiber is approximately (When *V* is large) given by:

$$M \approx \frac{V^2}{2}$$

- **Power distribution in the core & the cladding:** Another quantity of interest is the ratio of the mode power in the cladding, to the total optical power in the fiber, *P*, which at the wavelengths (or frequencies) far from the cut-off is given by:

$$\frac{P_{clad}}{P} \approx \frac{4}{3\sqrt{M}}$$

2.7 Fiber Fabrication

Fiber Material

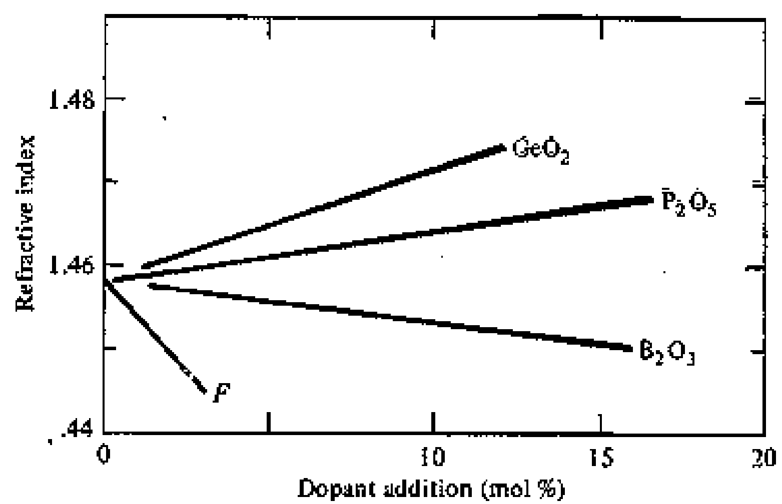
- Low loss
- Possibility of controlling refractive index

1.458

<u>Glass fibers (Silica-based)</u> [SiO_2, n=1.485 @ 850 nm]

1. Core: $GeO_2 - SiO_2$; Cladding: SiO_2
2. Core: $P_2O_5 - SiO_2$; Cladding: SiO_2
3. Core: SiO_2; Cladding: $B_2O_3 - SiO_2$
4. Core: $GeO_2 - B_2O_3 - SiO_2$; Cladding: SiO_2

Low loss, resistant to thermal shock, chemical durability



[*Optical Fiber Communications*, 3rd Edition, by Gerd Keiser, Mc Graw-Hill, 2000]

<u>Active glass fibers</u> (Erbium doped) are used for lasers and optical amplifiers

Plastic fibers

TABLE 2-4
Sample characteristics of PMMA and PFP polymer optical fibers

	PMMA POF	PFP POF
Core diameter	0.4 mm	0.125–0.30 mm
Cladding diameter	1.0 mm	0.25–0.60 mm
Numerical aperture	0.25	0.20
Attenuation	150 dB/km at 650 nm	60–80 dB/km at 650–1300 nm
Bandwidth	2.5 Gb/s over 100 m	2.5 Gb/s over 300 m

[*Optical Fiber Communications*, 3rd Edition, by Gerd Keiser, Mc Graw-Hill, 2000]

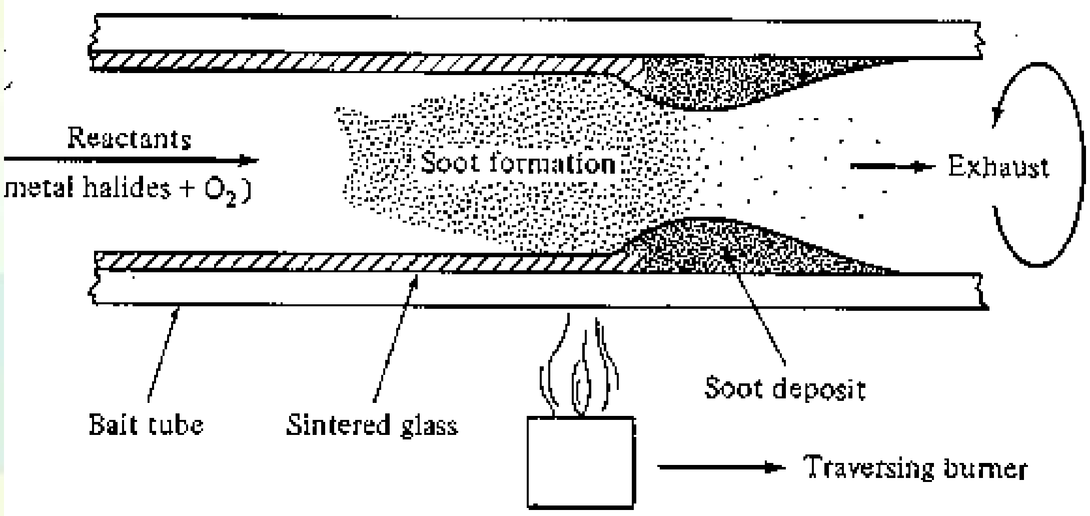
Fiber Fabrication

1. **Vapor phase oxidation processes (*preform* fabrication and fiber-drawing)**
2. **Direct-melt methods**

Vapor-Phase Oxidation Methods (OVPO, VAD, MCVD, PCVD)

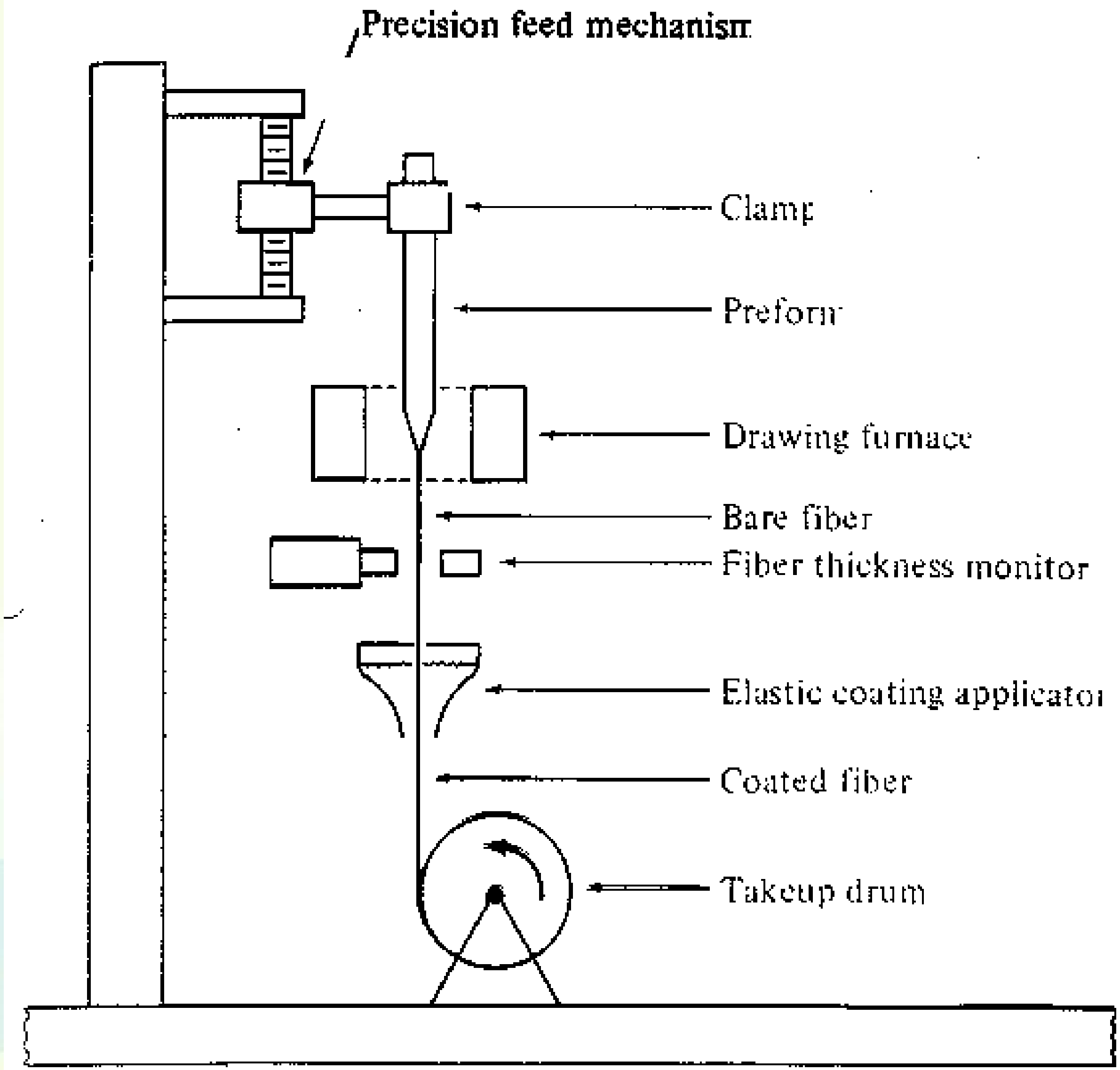
- Preform fabrication
- Fiber-drawing

<u>Prefrom fabrication using MCVD</u>



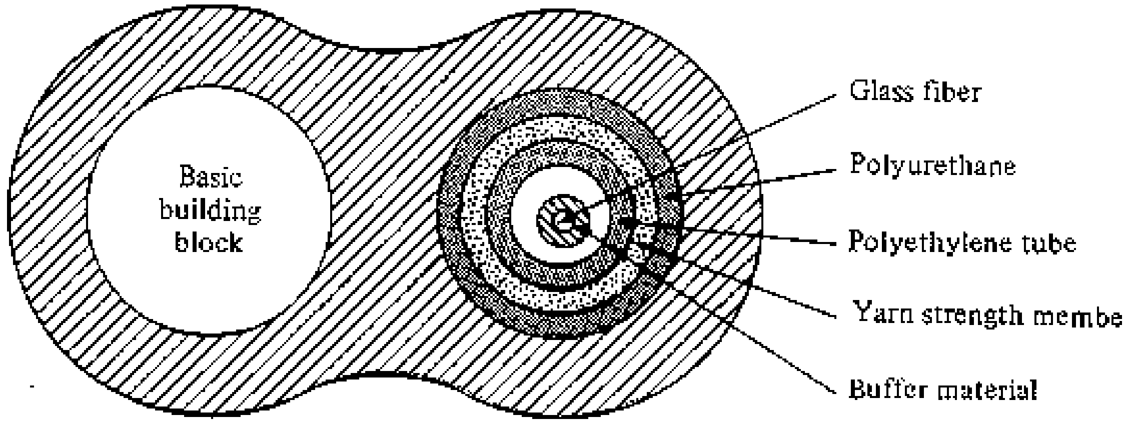
[*Optical Fiber Communications*, 3rd Edition, by Gerd Keiser, Mc Graw-Hill, 2000]

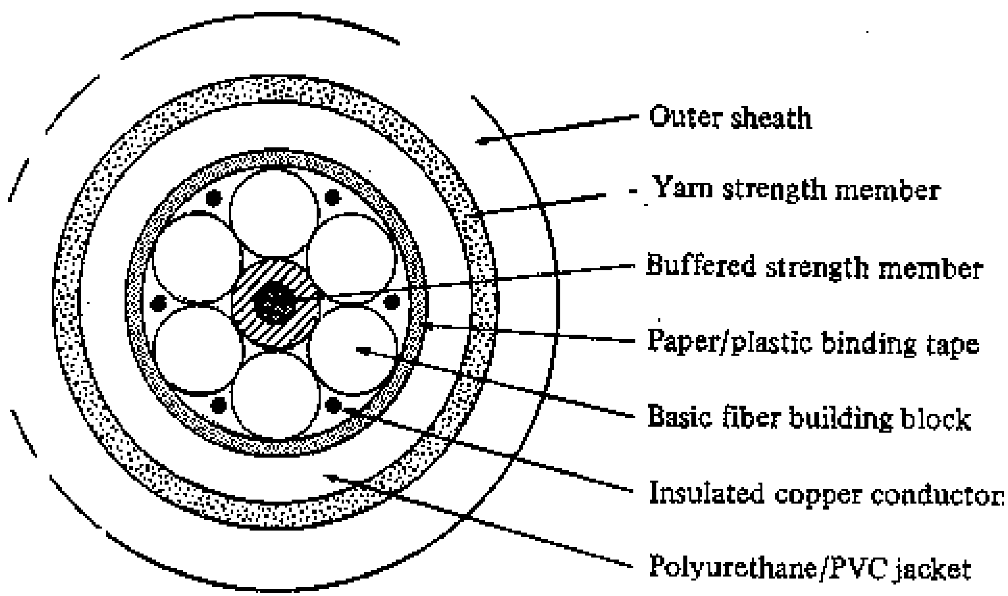
Fiber-drawing



[*Optical Fiber Communications*, 3rd Edition, by Gerd Keiser, Mc Graw-Hill, 2000]

Fiber cross section





<u>Chapter 3</u>

Signal Degradation in Optical Fibers

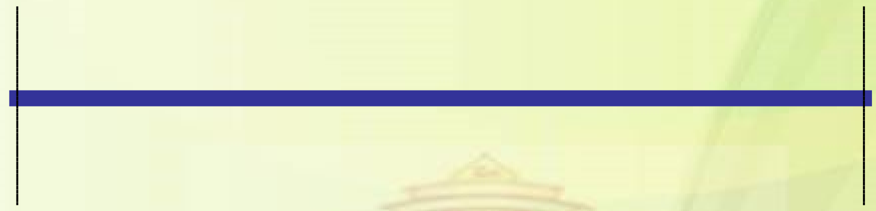
Signal Attenuation & Distortion in Optical Fibers

- What are the loss or signal attenuation mechanism in a fiber?
- Why & to what degree do optical signals get distorted as they propagate down a fiber?

- Signal attenuation (fiber loss) largely determines the maximum repeaterless separation between optical transmitter & receiver.
- Signal distortion cause that optical pulses to broaden as they travel along a fiber, the overlap between neighboring pulses, creating errors in the receiver output, resulting in the limitation of information-carrying capacity of a fiber.

Attenuation (fiber loss)

- Power loss along a fiber:



$$P(l) = P(0)e^{-\alpha_p l}$$

$$P(z) = P(0)e^{-\alpha_p z}$$

- The parameter is called fiber attenuation coefficient in a units of for example [1/km] or [nepers/km]. A more common unit is [dB/km] that is defined by:

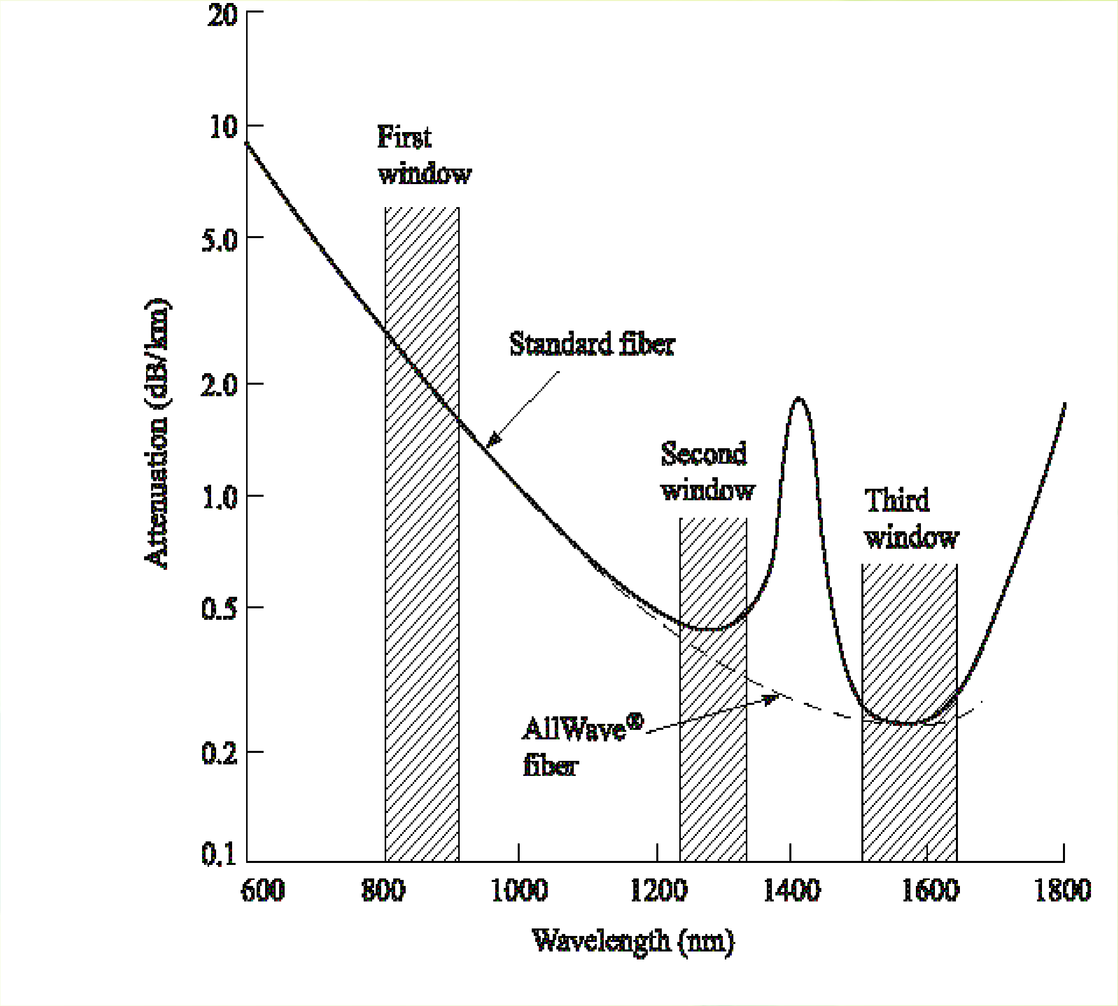
$$\alpha[\text{dB/km}] = \frac{10}{l}\log\left[\frac{P(0)}{P(l)}\right] = 4.343\alpha_p[1/\text{km}]$$

Fiber loss in dB/km

$$P(l)[\text{dBm}] = P(0)[\text{dBm}] - \alpha[\text{dB/km}] \times l[\text{km}]$$

- Where [dBm] or dB milliwat is 10log(P [mW]).

Optical fiber attenuation vs. wavelength



Absorption

- Absorption is caused by three different mechanisms:

1- Impurities in fiber material: from transition metal ions (must be in order of ppb) & particularly from OH ions with absorption peaks at wavelengths 2700 nm, 400 nm, 950 nm & 725nm.

2- Intrinsic absorption (fundamental lower limit): electronic absorption band (UV region) & atomic bond vibration band (IR region) in basic SiO_2.

3- Radiation defects

Scattering Loss

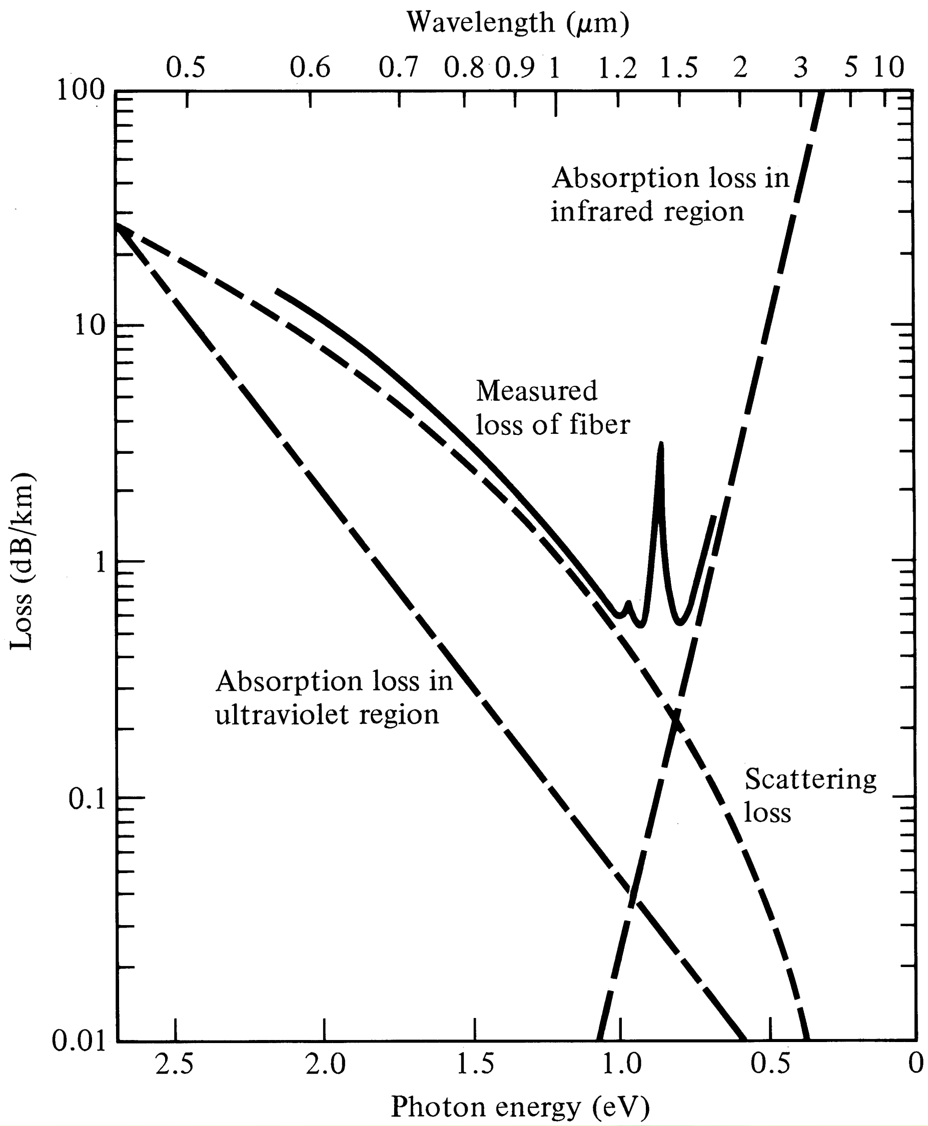
- Small (compared to wavelength) variation in material density, chemical composition, and structural inhomogeneity scatter light in other directions and absorb energy from guided optical wave.

- The essential mechanism is the Rayleigh scattering. Since the black body radiation classically is proportional to (this is true for wavelength typically greater than 5 micrometer), the attenuation coefficient due to Rayleigh scattering is approximately proportional to . This seems to me not precise, where the attenuation of fibers at 1.3 & 1.55 micrometer can be exactly predicted with Planck's formula & can not be described with Rayleigh-Jeans law. Therefore I believe that the more accurate formula for scattering loss is

$$\alpha_{scat} \propto \lambda^{-5}\left[\exp\left(\frac{hc}{\lambda k_B T}\right)\right]^{-1}$$

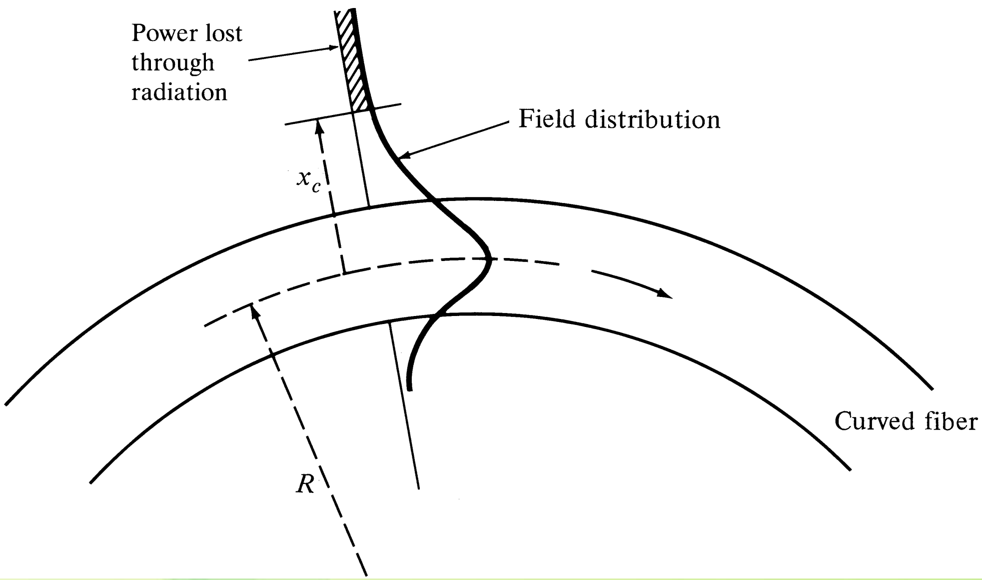
$$h = 6.626\times10^{-34}\ \text{Js},\quad k_B = 1.3806\times10^{-23}\ \text{JK}^{-1},\ T:\text{Temperature}$$

Absorption & scattering losses in fibers



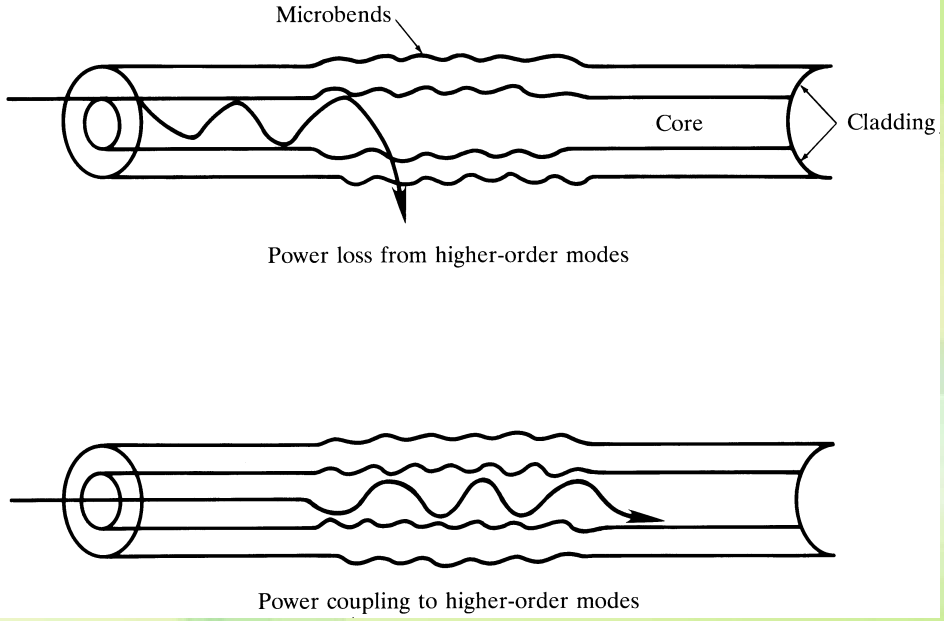
Bending Loss (Macrobending & Microbending)

- **Macrobending Loss**: The curvature of the bend is much larger than fiber diameter. Lightwave suffers sever loss due to radiation of the evanescent field in the cladding region. As the radius of the curvature decreases, the loss increases exponentially until it reaches at a certain critical radius. For any radius a bit smaller than this point, the losses suddenly becomes extremely large. Higher order modes radiate away faster than lower order modes.



Microbending Loss

- **Microbending Loss:** microscopic bends of the fiber axis that can arise when the fibers are incorporated into cables. The power is dissipated through the microbended fiber, because of the repetitive coupling of energy between guided modes & the leaky or radiation modes in the fiber.



Dispersion in Optical Fibers

- **Dispersion**: Any phenomenon in which the velocity of propagation of any electromagnetic wave is wavelength dependent.

- In communication, dispersion is used to describe any process by which any electromagnetic signal propagating in a physical medium is degraded because the various wave characteristics (i.e., frequencies) of the signal have different propagation velocities within the physical medium.

- There are 3 dispersion types in the optical fibers, in general:

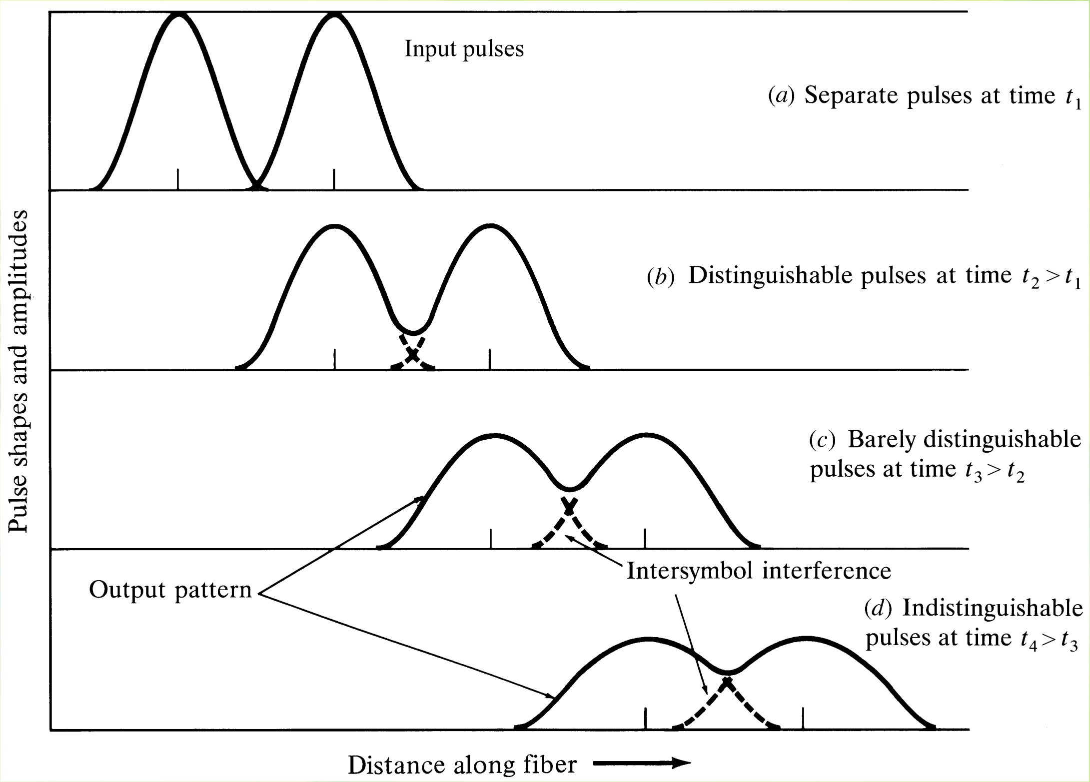
1- Material Dispersion
2- Waveguide Dispersion
3- Polarization-Mode Dispersion

Material & waveguide dispersions are main causes of Intramodal Dispersion.

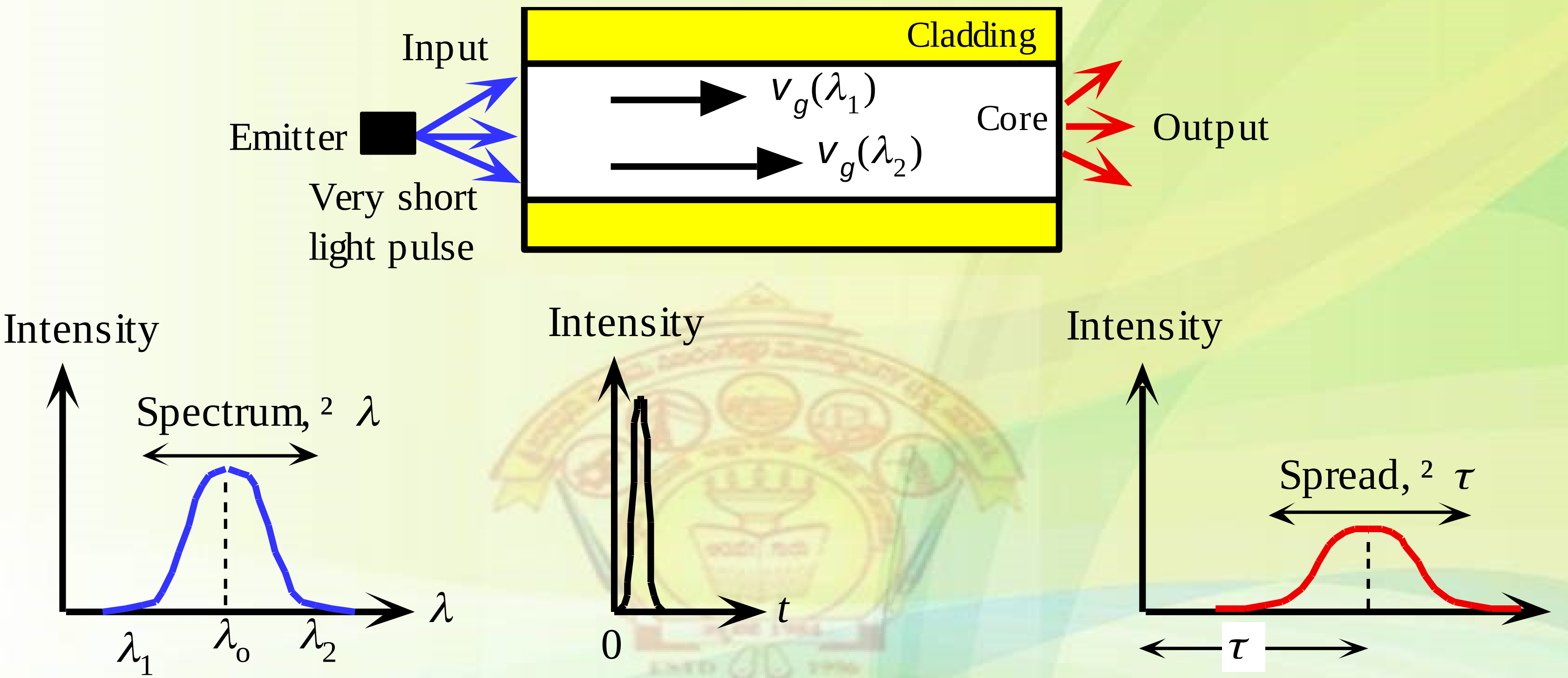
Dispersion & ISI

A measure of information capacity of an optical fiber for digital transmission is usually specified by the **bandwidth distance product in GHz.km.**

For multi-mode step index fiber this quantity is about 20 MHz.km, for graded index fiber is about 2.5 GHz.km & for single mode fibers are higher than 10 GHz.km.



Material Dispersion



All excitation sources are inherently non-monochromatic and emit within a spectrum, ² λ, of wavelengths. Waves in the guide with different free space wavelengths travel at different group velocities due to the wavelength dependence of n_1. The waves arrive at the end of the fiber at different times and hence result in a broadened output pulse.

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Material Dispersion Diagrams

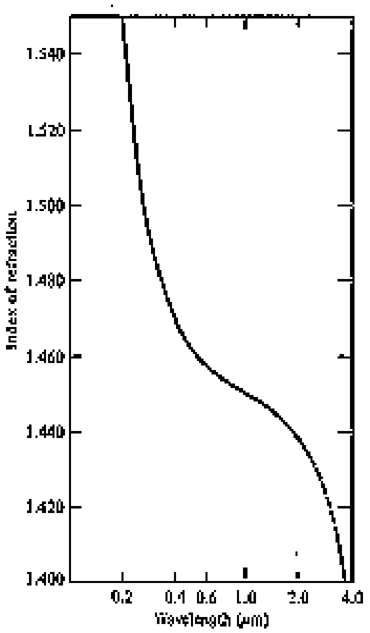


FIGURE 3-12
Variations in the index of refraction as a function of the optical wavelength for silica. (Reproduced with permission from I. H. Malitson, *J. Opt. Soc. Amer.*, vol. 55, pp. 1205–1209, Oct. 1965.)

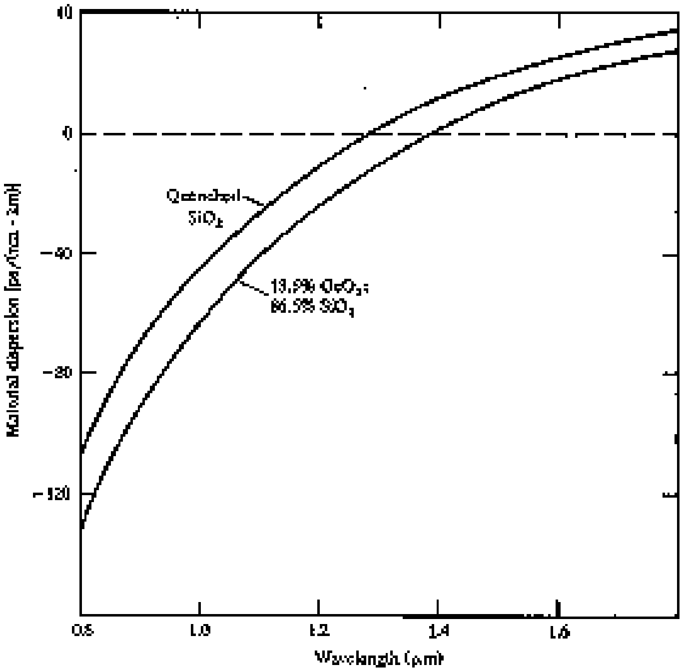


FIGURE 3-13
Material dispersion as a function of optical wavelength for pure silica and 13.5 percent GeO_2/86.5 percent SiO_2. (Reproduced with permission from J. W. Fleming, *Electron. Lett.*, vol. 14, pp. 326–328, May 1978.)

Waveguide Dispersion

- Waveguide dispersion is due to the dependency of the group velocity of the fundamental mode as well as other modes on the *V* number, (see Fig 2-18 of the textbook). In order to calculate waveguide dispersion, we consider that *n* is not dependent on wavelength. Defining the normalized propagation constant *b* as:

$$b = \frac{\beta^2 / k^2 - n_2^2}{n_1^2 - n_2^2} \approx \frac{\beta / k - n_2}{n_1 - n_2}$$

- solving for propagation constant:

$$\beta \approx n_2 k (1 + b\Delta)$$

- Using *V* number:

$$V = ka(n_1^2 - n_2^2)^{1/2} \approx k a n_2 \sqrt{2\Delta}$$

Chromatic & Total Dispersion

- Chromatic dispersion includes the material & waveguide dispersions.

$$D_{ch}(\lambda) \approx \left| D_{mat} + D_{wg} \right|$$

$$\sigma_{ch} = D_{ch}(\lambda) L \sigma_{\lambda}$$

- Total dispersion is the sum of chromatic , polarization dispersion and other dispersion types and the total rms pulse spreading can be approximately written as:

$$D_{total} \approx \left| D_{ch} + D_{pol} + \ldots \right|$$

$$\sigma_{total} = D_{total} L \sigma_{\lambda}$$

Total Dispersion, zero Dispersion

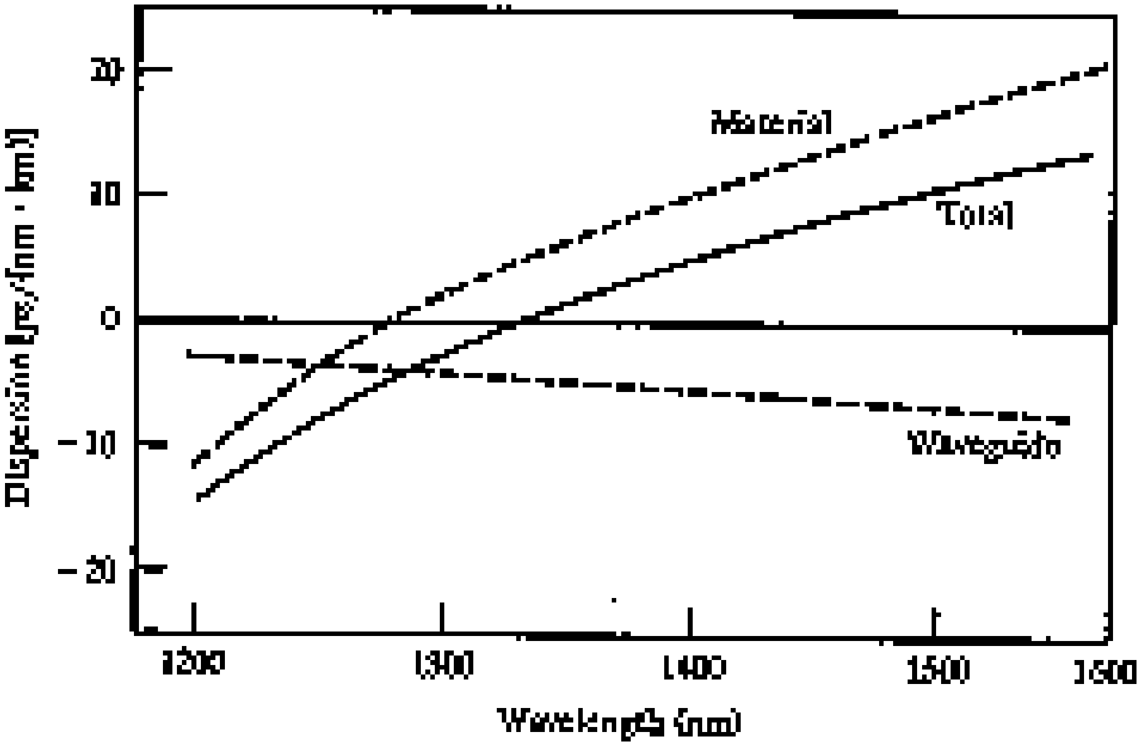
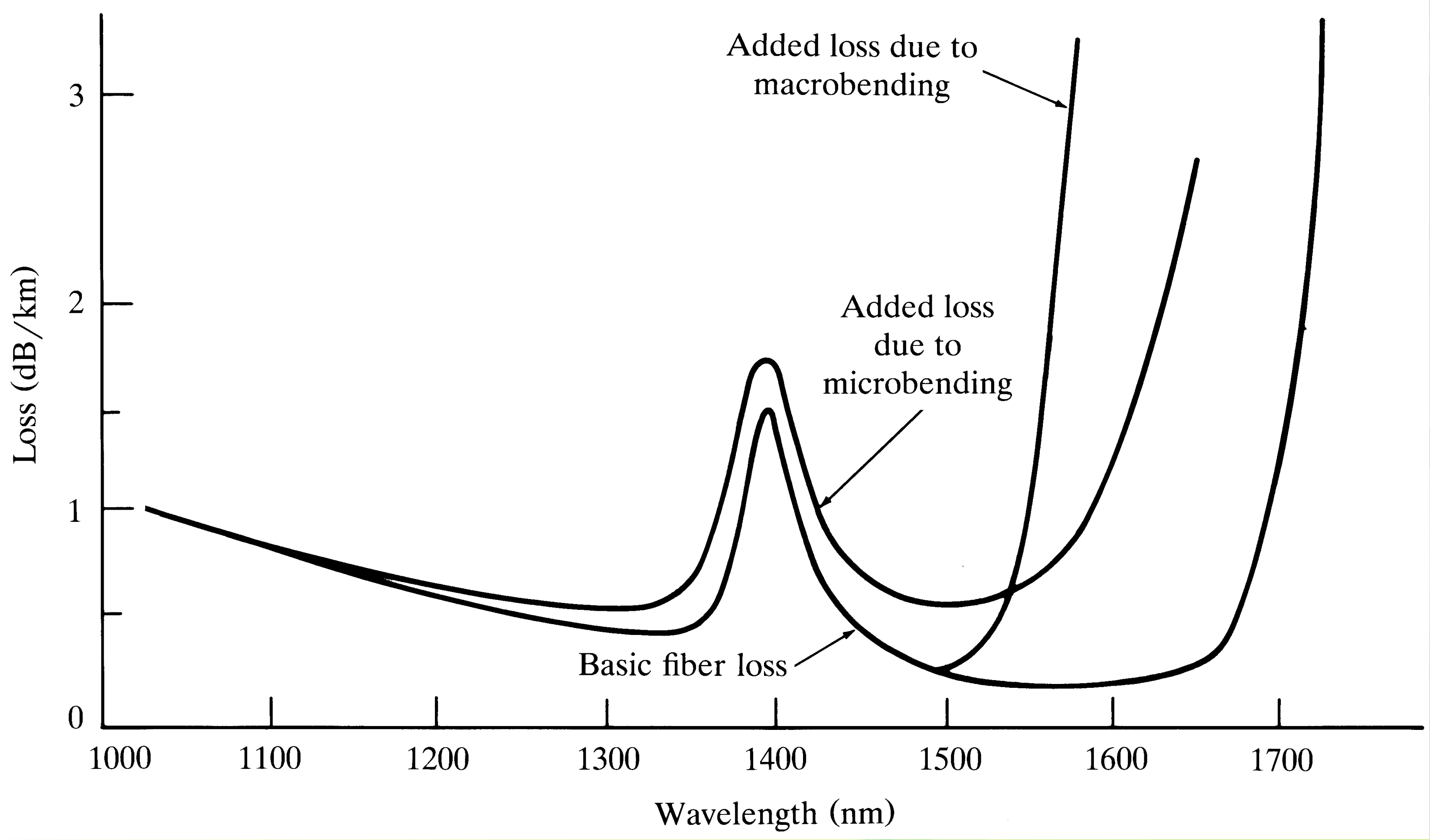


FIGURE 3-16
Examples of the magnitudes of material and waveguide dispersion as a function of optical wavelength for a single-mode fused-silica-core fiber. (Reproduced with permission from Keck,[16] © 1985, IEEE.)

Bending Loss



Chapter 4

- **Photonic Sources**

Light-Emitting Diodes (LEDs)

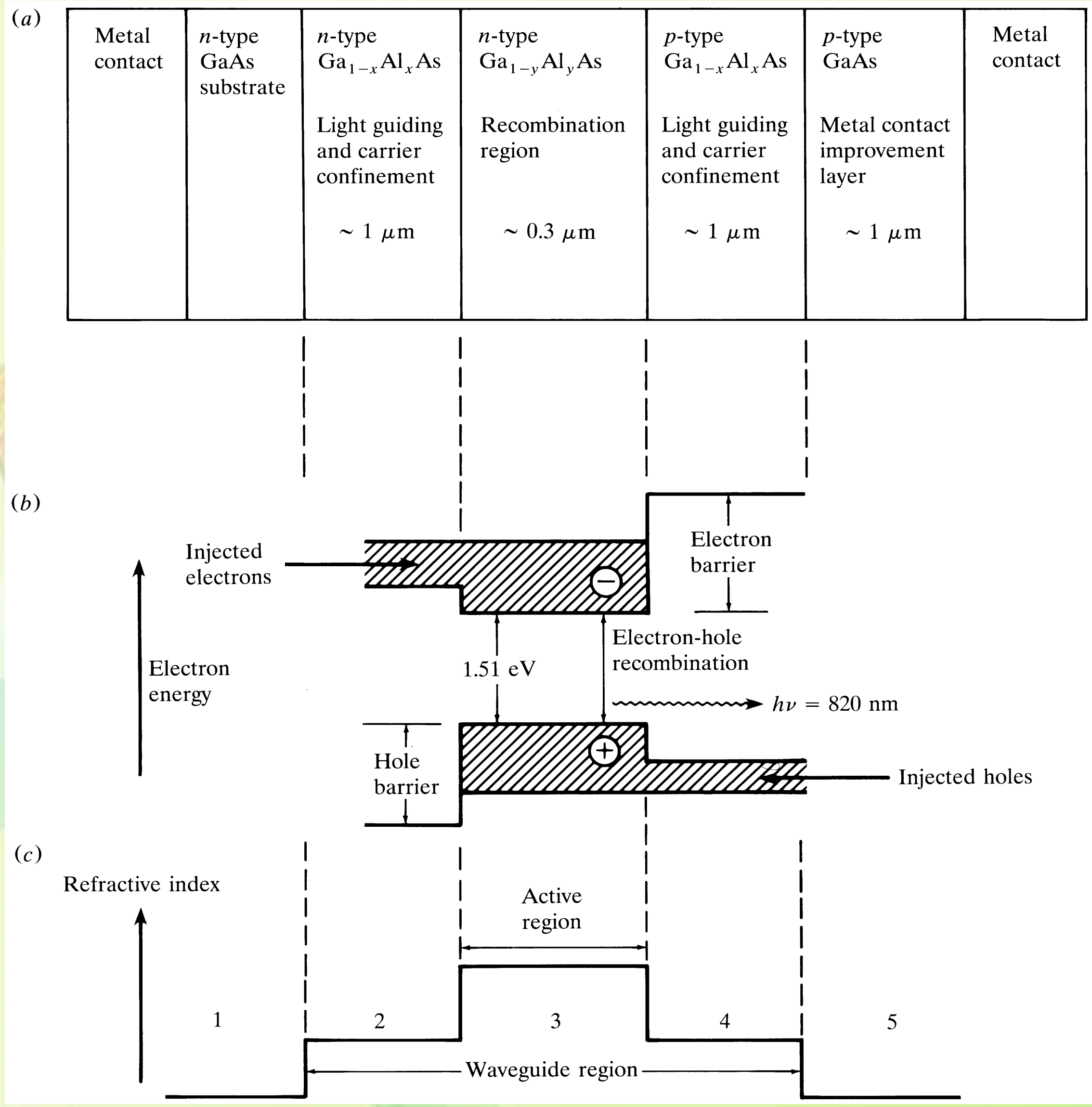
- For photonic communications requiring data rate 100-200 Mb/s with multimode fiber with tens of microwatts, LEDs are usually the best choice.
- LED configurations being used in photonic communications:

  1- Surface Emitters (Front Emitters)

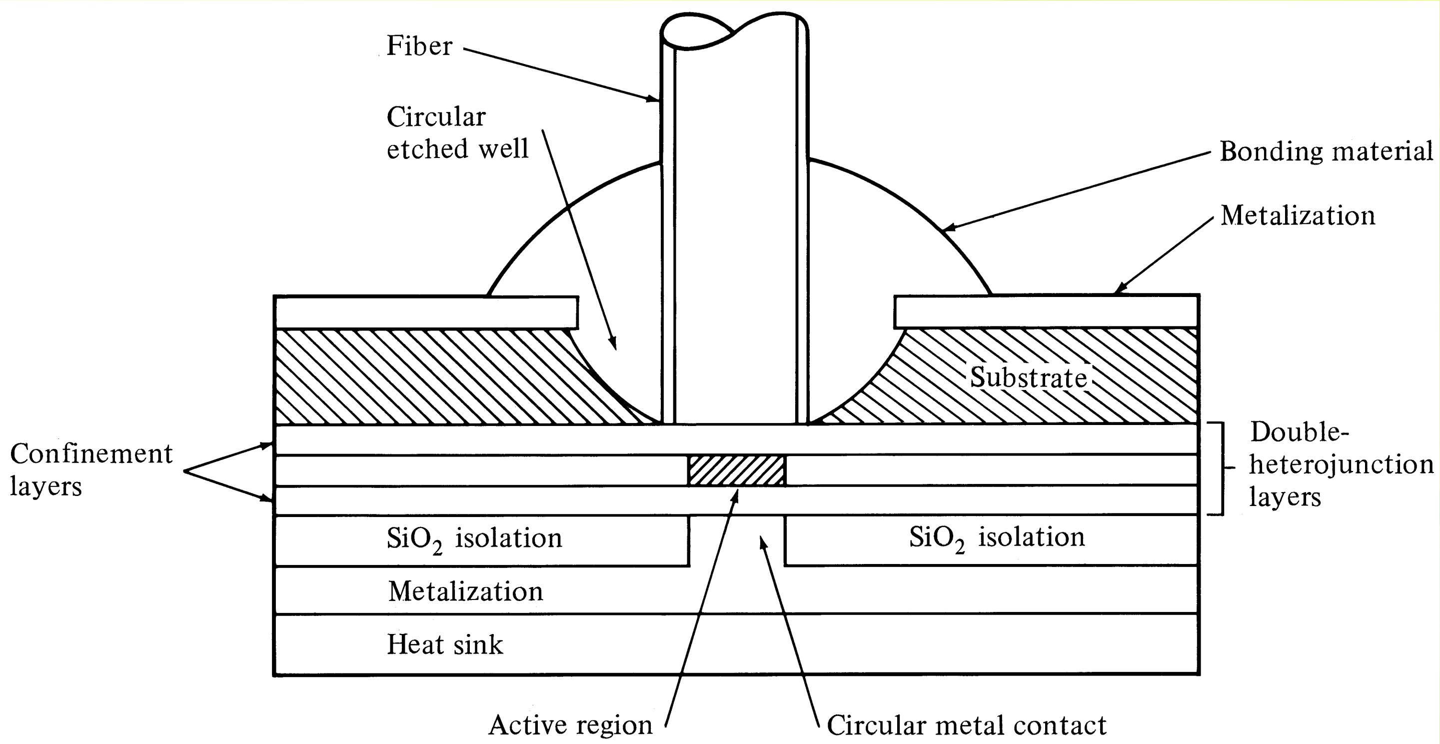
  2- Edge Emitters

Cross-section drawing of a typical GaAlAs double heterostructure light emitter. In this structure, x>y to provide for both carrier confinement and optical guiding.
b) Energy-band diagram showing the active region, the electron & hole barriers which confine the charge carriers to the active layer.
c) Variations in the refractive index; the lower refractive index of the material in regions 1 and 5 creates an optical barrier around the waveguide because of the higher band-gap energy of this material.

$$\lambda(\mu m) = \frac{1.240}{E_g(eV)}$$

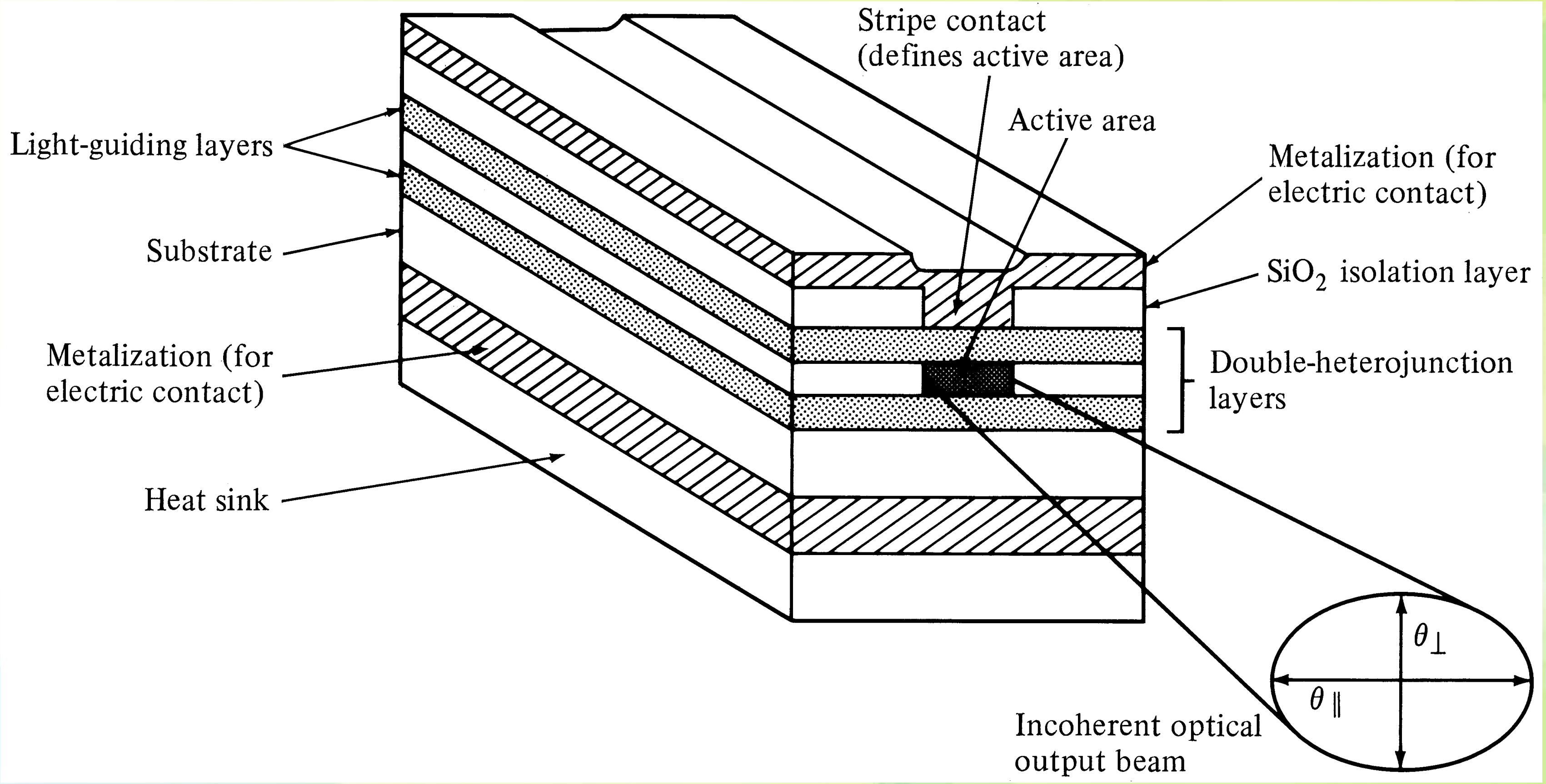


Surface-Emitting LED



Schematic of high-radiance surface-emitting LED. The active region is limitted to a circular cross section that has an area compatible with the fiber-core end face.

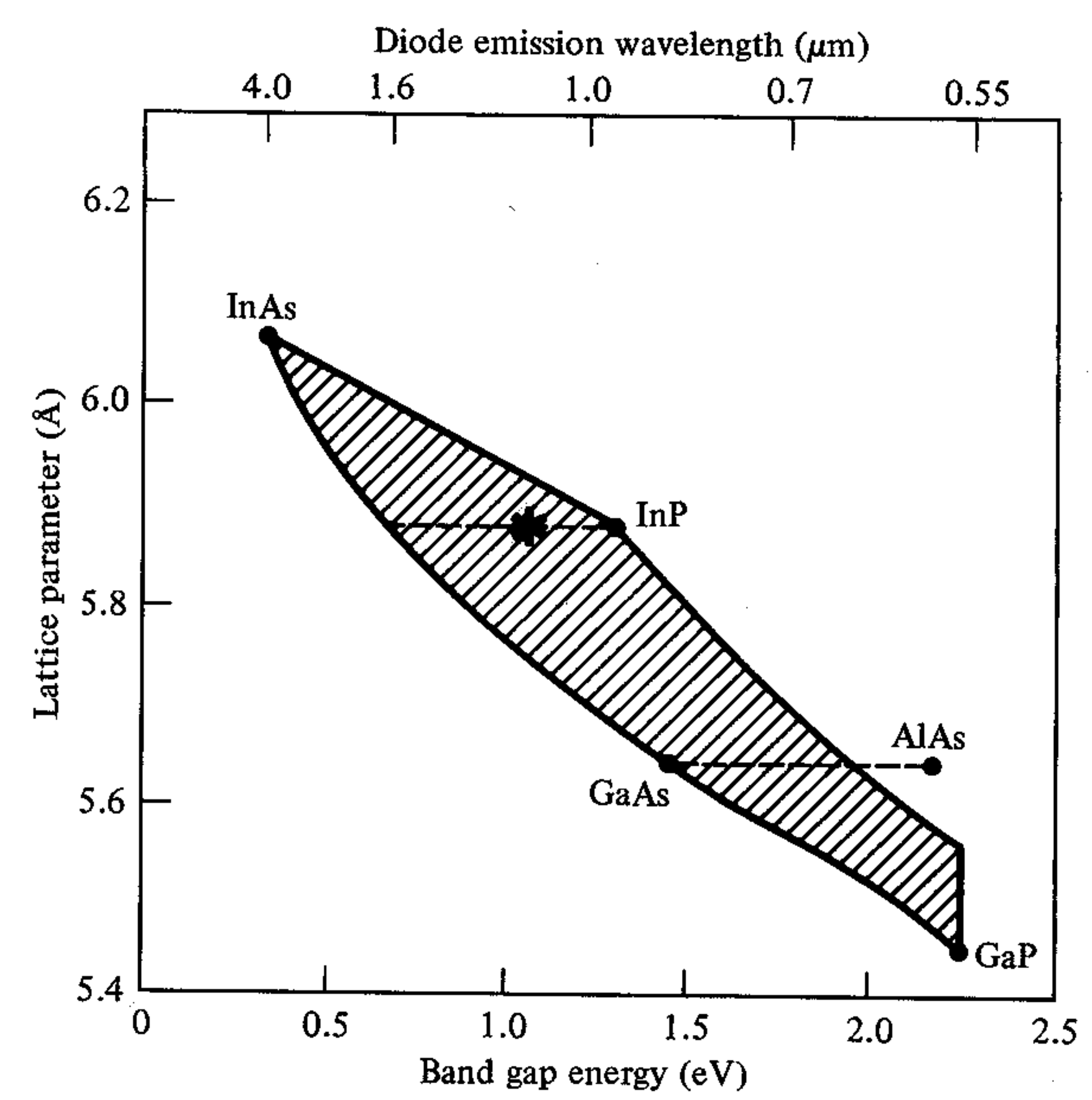
Edge-Emitting LED



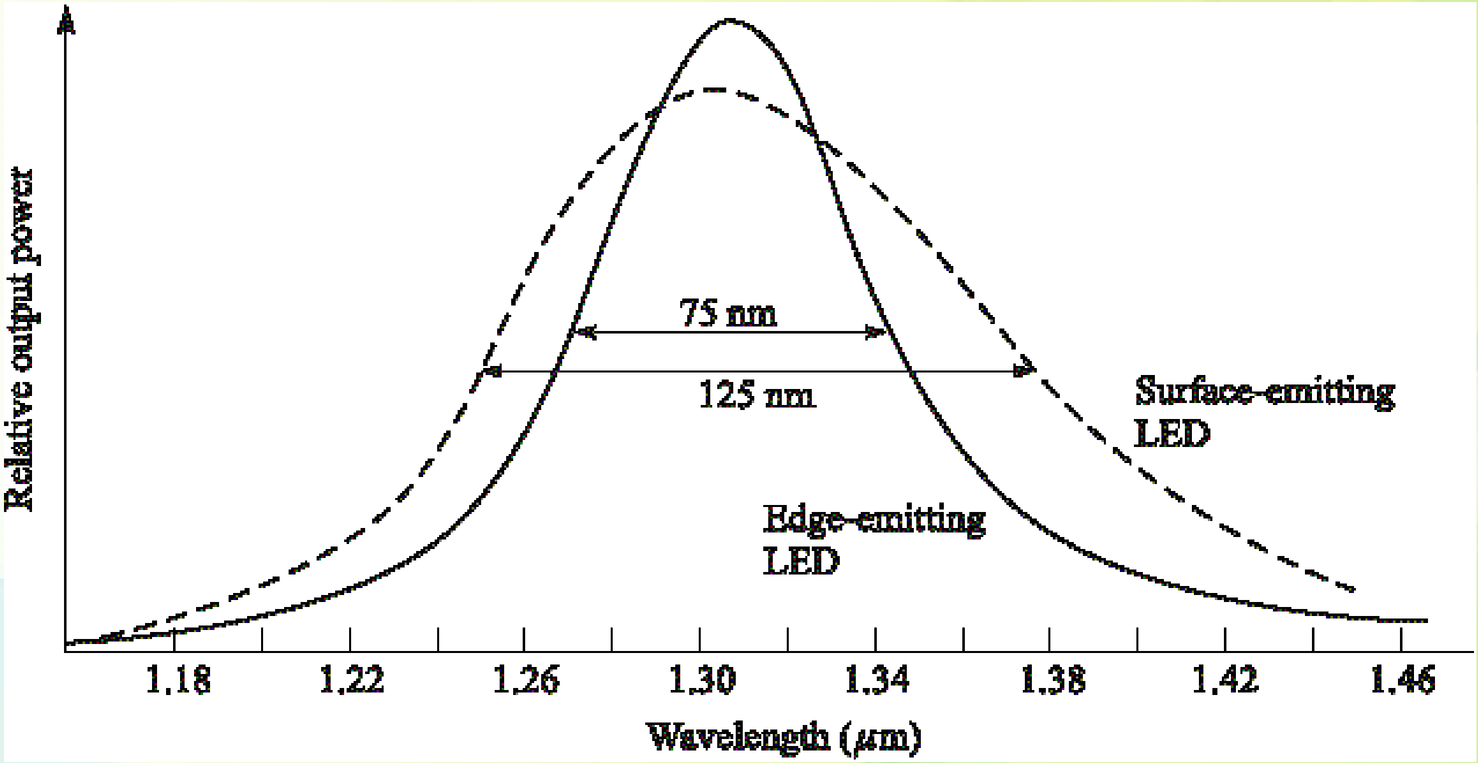
Schematic of an edge-emitting double heterojunction LED. The output beam is lambertian in the plane of junction and highly directional perpendicular to pn junction. They have high quantum efficiency & fast response.

Light Source Material

- Most of the light sources contain III-V ternary & quaternary compounds.
- by varying x it is possible to control the band-gap energy and thereby the emission wavelength over the range of 800 nm to 900 nm. The spectral width is around 20 to 40 nm.
- $In_{1-x}Ga_{x}As_{y}P_{1-y}$ By changing 0<x<0.47; y is approximately 2.2x, the emission wavelength can be controlled over the range of 920 nm to 1600 nm. The spectral width varies from 70 nm to 180 nm when the wavelength changes from 1300 nm to 1600 nm. These materials are lattice matched.


Diode emission wavelength (μm)
4.0
1.6
1.0
0.7
0.55
6.2
6.0
5.8
5.6
5.4
Lattice parameter (Å)
InAs
InP
AlAs
GaAs
GaP
0
0.5
1.0
1.5
2.0
2.5
Band gap energy (eV)

Spectral width of LED types



Internal Quantum Efficiency & Optical Power

$$\eta_{int} = \frac{R_r}{R_r + R_{nr}} = \frac{\tau_{nr}}{\tau_r + \tau_{nr}} = \frac{\tau}{\tau_r}$$

η_{int} : internal quantum efficiency in the active region

Optical power generated internally in the active region in the LED is:

$$P_{int} = \eta_{int} \frac{I}{q} h\nu = \eta_{int} \frac{hcI}{q\lambda}$$

P_{int} : Internal optical power,

I : Injected current to active region

External Quantum Eficiency

$$\eta_{ext} = \frac{\text{\# of photons emitted from LED}}{\text{\# of LED internally generated photons}}$$

- 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.

$$\text{LED emitted optical powr, } P = \eta_{ext} P_{int} \approx \frac{P_{int}}{n_1 (n_1 + 1)^2}$$

Modulation of LED

- The frequency response of an LED depends on:
  1- Doping level in the active region
  2- Injected carrier lifetime in the recombination region, .
  3- Parasitic capacitance of the LED
- If the drive current of an LED is modulated at a frequency of the output optical power of the device will vary as:

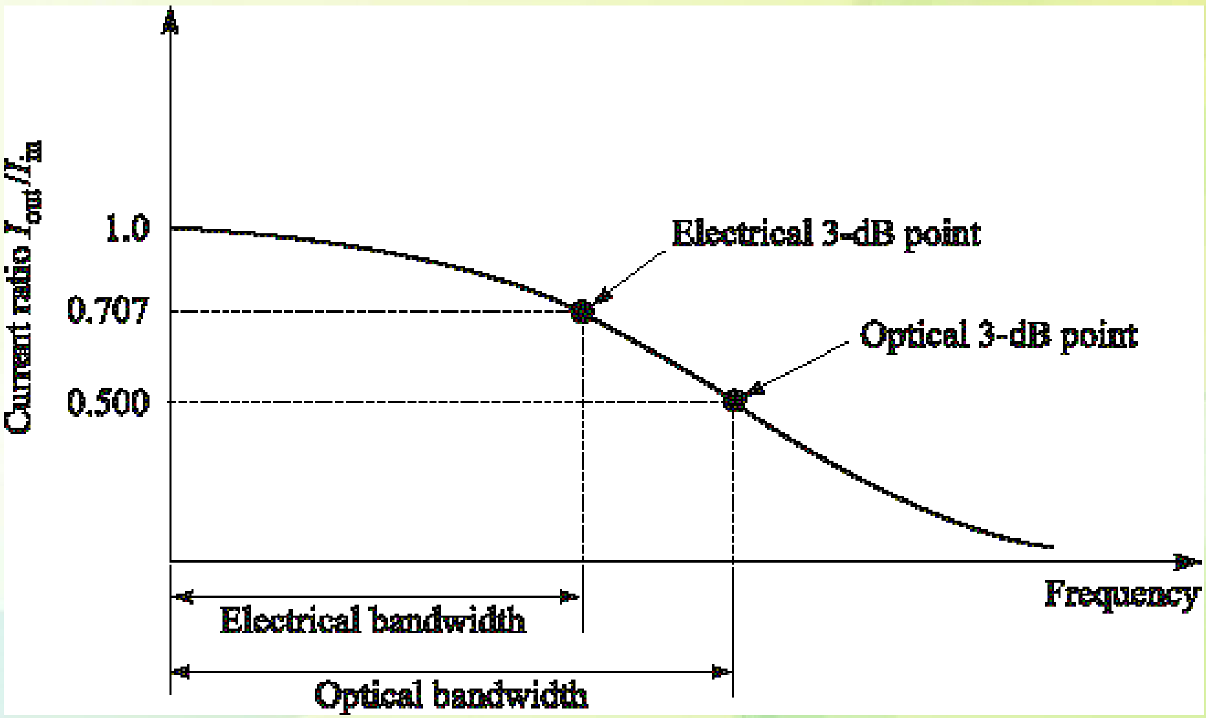
$$P(\omega) = \frac{P_0}{\sqrt{1 + (\omega \tau_i)^2}}$$

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

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

$$p : \text{electrical power}, \quad I : \text{electrical current}$$

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



LASER

(Light Amplification by the Stimulated Emission of Radiation)

- Laser is an optical oscillator. It comprises a resonant optical amplifier whose output is fed back into its input with matching phase. Any oscillator contains:

  1- An amplifier with a gain-saturated mechanism

  2- A feedback system

  3- A frequency selection mechanism

  4- An output coupling scheme

- In laser the amplifier is the pumped active medium, such as biased semiconductor region, feedback can be obtained by placing active medium in an optical resonator, such as Fabry-Perot structure, two mirrors separated by a prescribed distance. Frequency selection is achieved by resonant amplifier and by the resonators, which admits certain modes. Output coupling is accomplished by making one of the resonator mirrors partially transmitting.

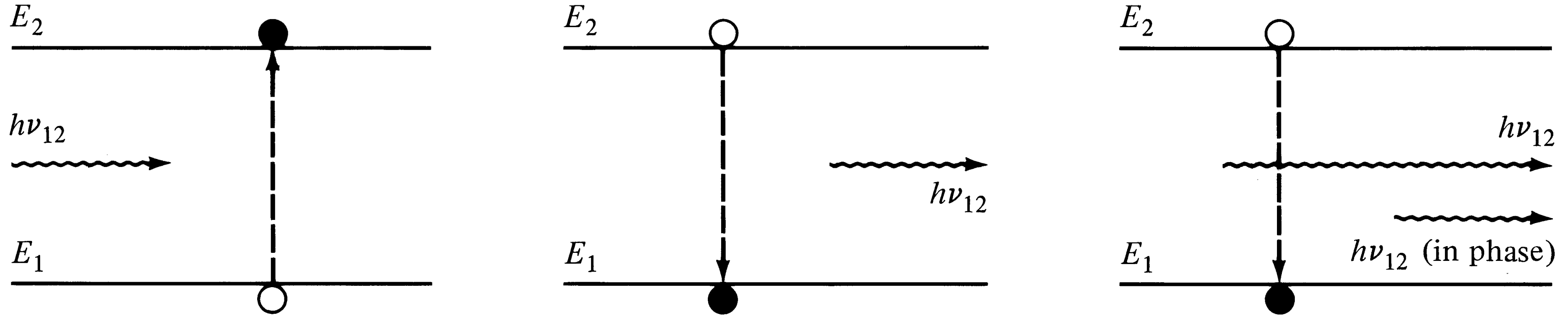
Pumped active medium

- Three main process for laser action:

  1- Photon absorption

  2- Spontaneous emission

  3- Stimulated emission



(a) Absorption (b) Spontaneous emission (c) Stimulated emission

Threshold gain & current density

$$\Gamma g_{th} = \bar{\alpha} + \frac{1}{2L}\ln\left(\frac{1}{R_1 R_2}\right)$$

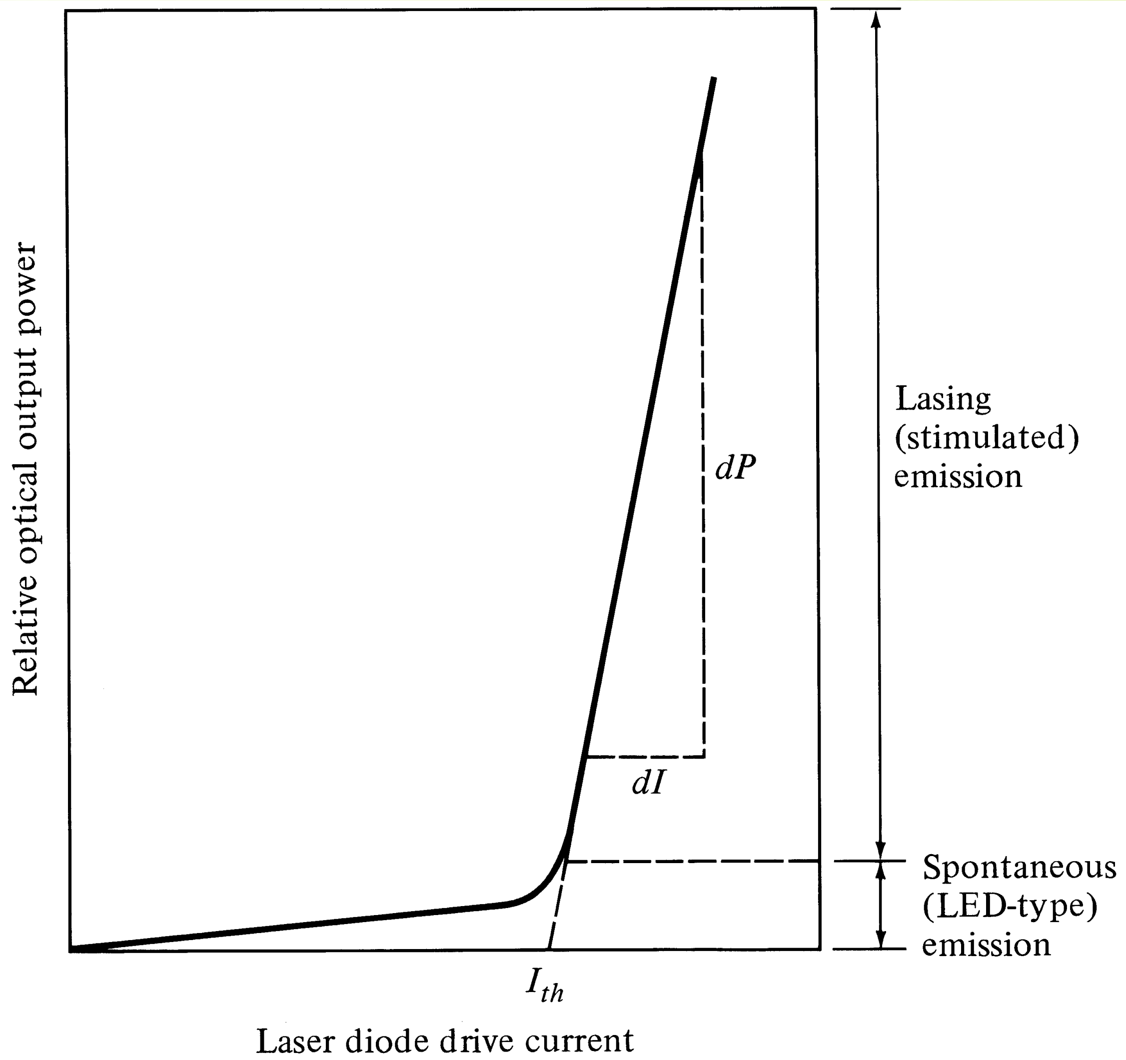
$$\text{Laser starts to "lase" iff} : g \geq g_{th}$$

For laser structure with strong carrier confinement, the threshold current Density for stimulated emission can be well approximated by:

$$g_{th} = \beta J_{th}$$

β : constant depends on specific device construction

Optical output vs. drive current



External quantum efficiency

- Number of photons emitted per radiative electron-hole pair recombination above threshold, gives us the external quantum efficiency.

$$\eta_{ext} = \frac{\eta_i (g_{th} - \bar{\alpha})}{g_{th}}$$

$$= \frac{q}{E_g} \frac{dP}{dI} = 0.8065 \lambda[\mu\text{m}] \frac{dP(\text{mW})}{dI(\text{mA})}$$

- Note that: $\eta_i \approx 60\% - 70\%; \quad \eta_{ext} \approx 15\% - 40\%$

Laser Resonant Frequencies

- Lasing condition, namely eq. [4-22]:

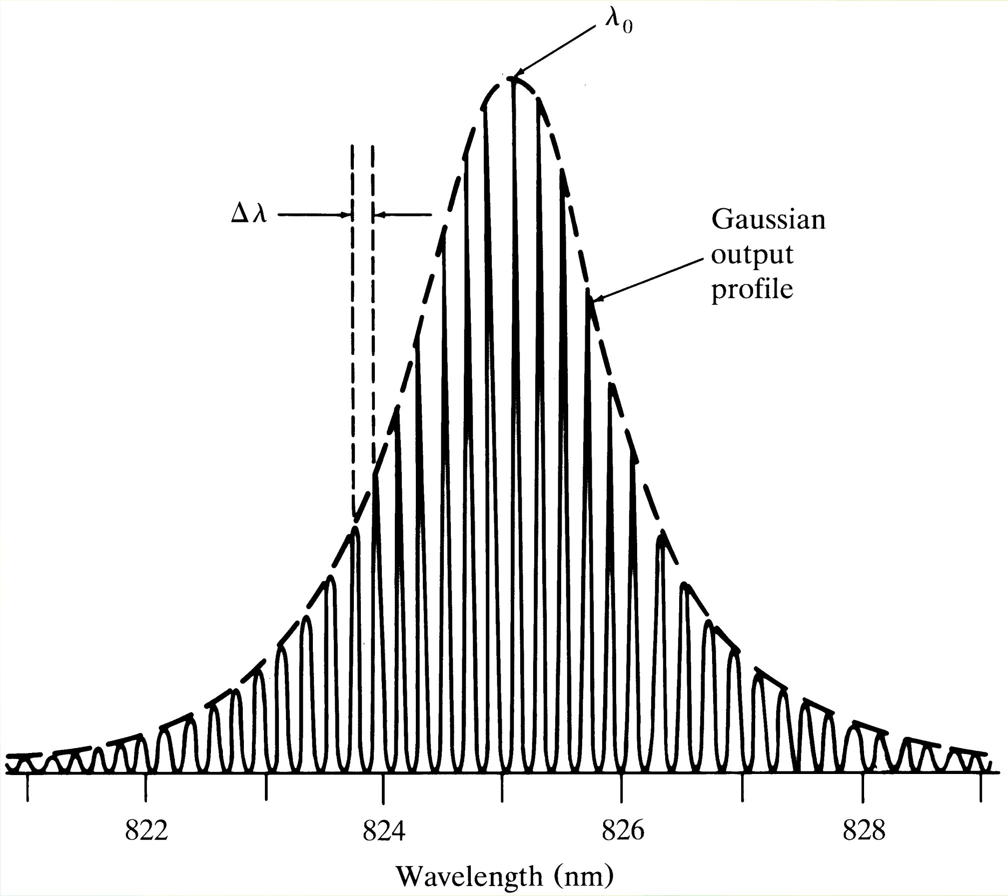
$$\exp(-j2\beta L) = 1 \Rightarrow \qquad 2\beta \mathrm{L} = 2m\pi, \quad m = 1,2,3,...$$

- Assuming $\beta = \dfrac{2\pi n}{\lambda}$ the resonant frequency of the *m*th mode is:

$$\upsilon_m = \frac{mc}{2Ln} \qquad\qquad m = 1,2,3,...$$

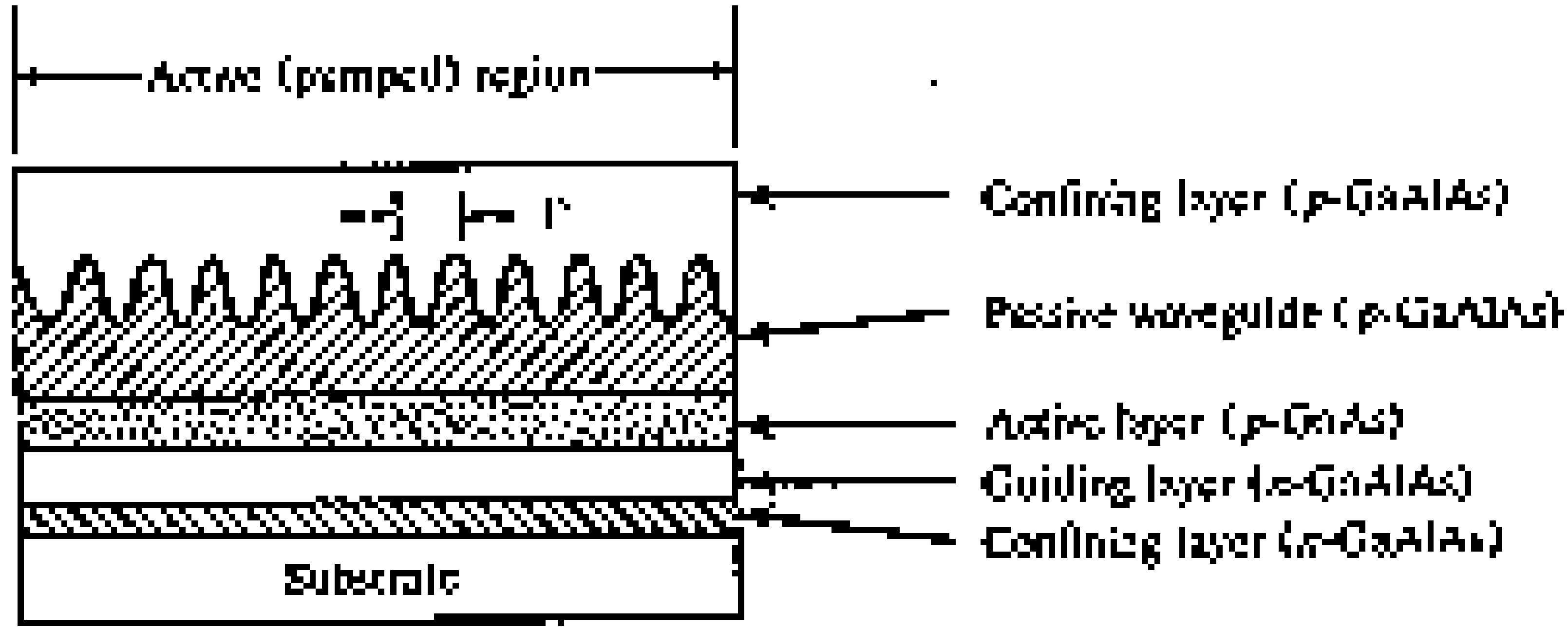
$$\Delta\upsilon = \upsilon_m - \upsilon_{m-1} = \frac{c}{2Ln} \Leftrightarrow \Delta\lambda = \frac{\lambda^2}{2Ln}$$

Spectrum from a laser Diode



$$g(\lambda) = g(0)\exp\left(-\frac{(\lambda - \lambda_0)}{2\sigma^2}\right) \quad \sigma : \text{spectral width}$$

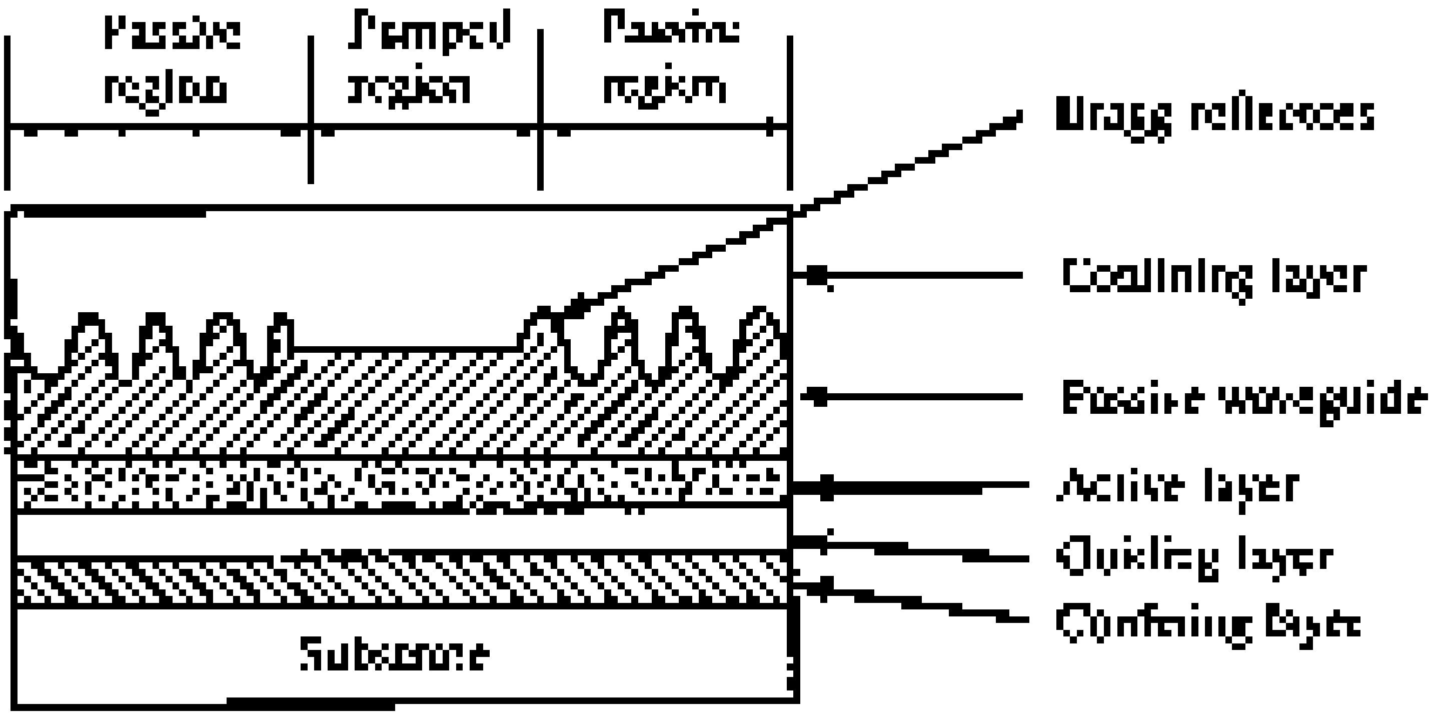
Frequency-Selective laser Diodes: Distributed Feedback (DFB) laser



(a)

Frequency-Selective laser Diodes:
Distributed Feedback Reflector (DBR) laser

(a)



Modulation of Laser Diodes

- Internal Modulation: Simple but suffers from non-linear effects.
- External Modulation: for rates greater than 2 Gb/s, more complex, higher performance.
- Most fundamental limit for the modulation rate is set by the photon life time in the laser cavity:

$$\frac{1}{\tau_{ph}} = \frac{c}{n}\left(\bar{\alpha} + \frac{1}{2L}\ln\frac{1}{R_1 R_2}\right) = \frac{c}{n} g_{th}$$

- Another fundamental limit on modulation frequency is the relaxation oscillation frequency given by:

$$f = \frac{1}{2\pi}\frac{1}{\sqrt{\tau_{sp}\tau_{ph}}}\left(\frac{I}{I_{th}} - 1\right)^{1/2}$$

Pulse Modulated laser

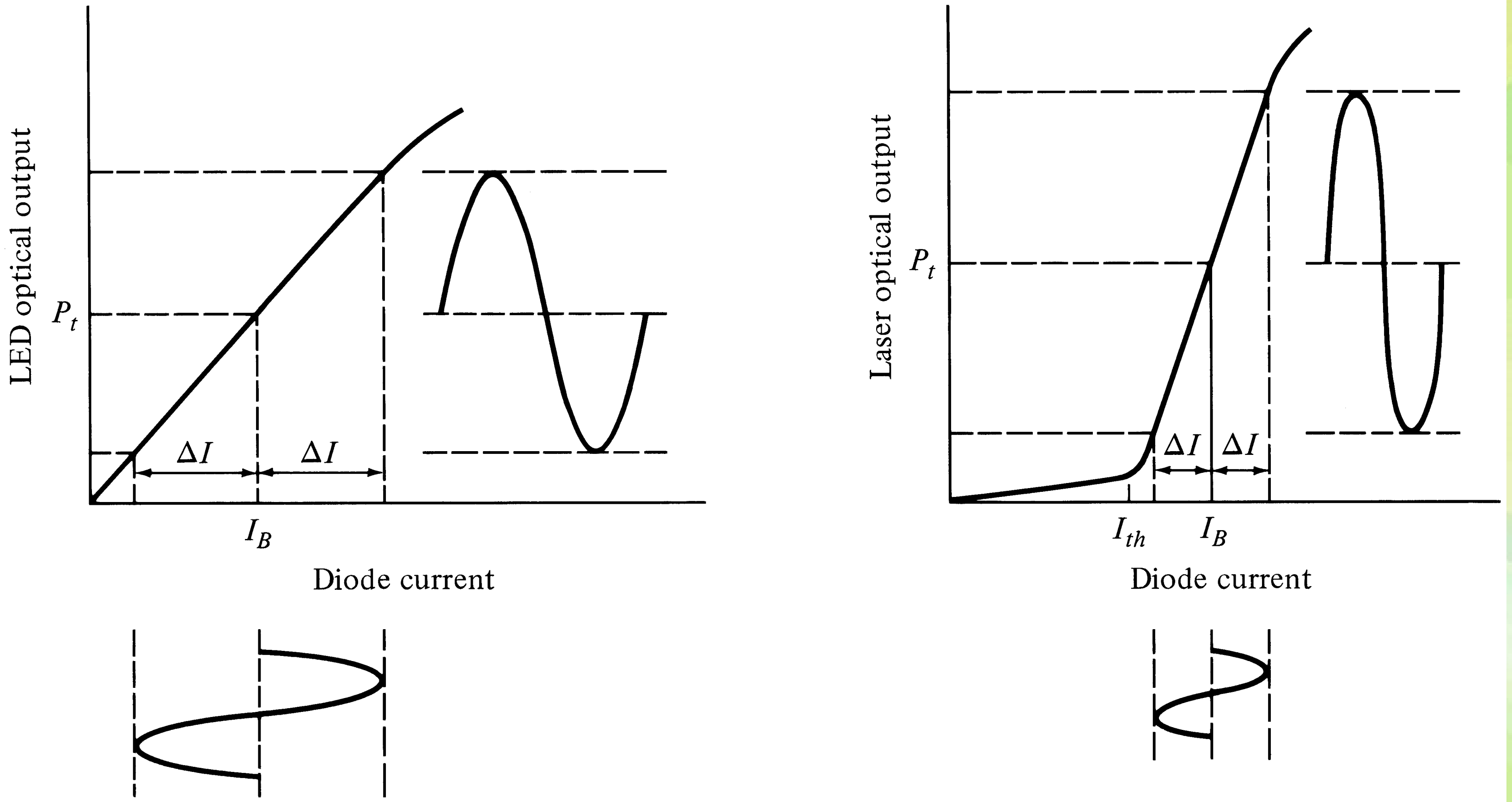
- In a pulse modulated laser, if the laser is completely turned off after each pulse, after onset of the current pulse, a time delay, given by:

$$t_d = \tau \ln\left[\frac{I_p}{I_p + (I_B - I_{th})}\right]$$

τ : carrier life time

I_p : Current pulse amplitude

I_B : Bias current



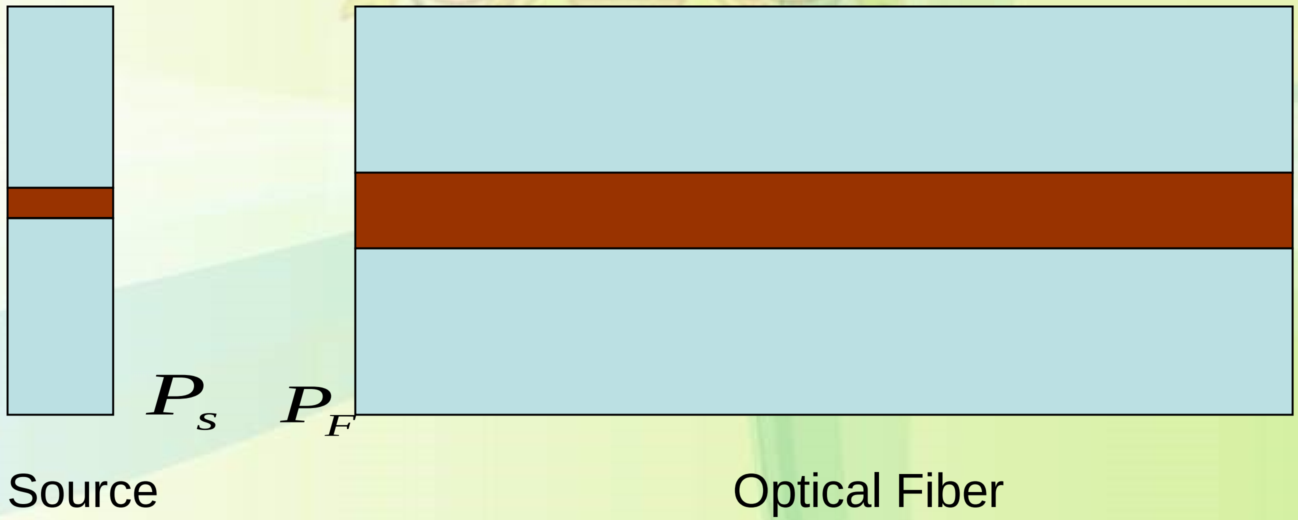
LED optical output
P_t
ΔI
ΔI
I_B
Diode current
Laser optical output
P_t
ΔI
ΔI
I_{th}
I_B
Diode current

Chapter 5

- Laser-Fiber Connection

Coupling Efficiency

$$\eta = \frac{\text{power coupled into the fiber}}{\text{power emitted from the sourse}} = \frac{P_F}{P_s}$$



Examples of possible lensing schemes used to improve optical source-to-fiber coupling efficiency

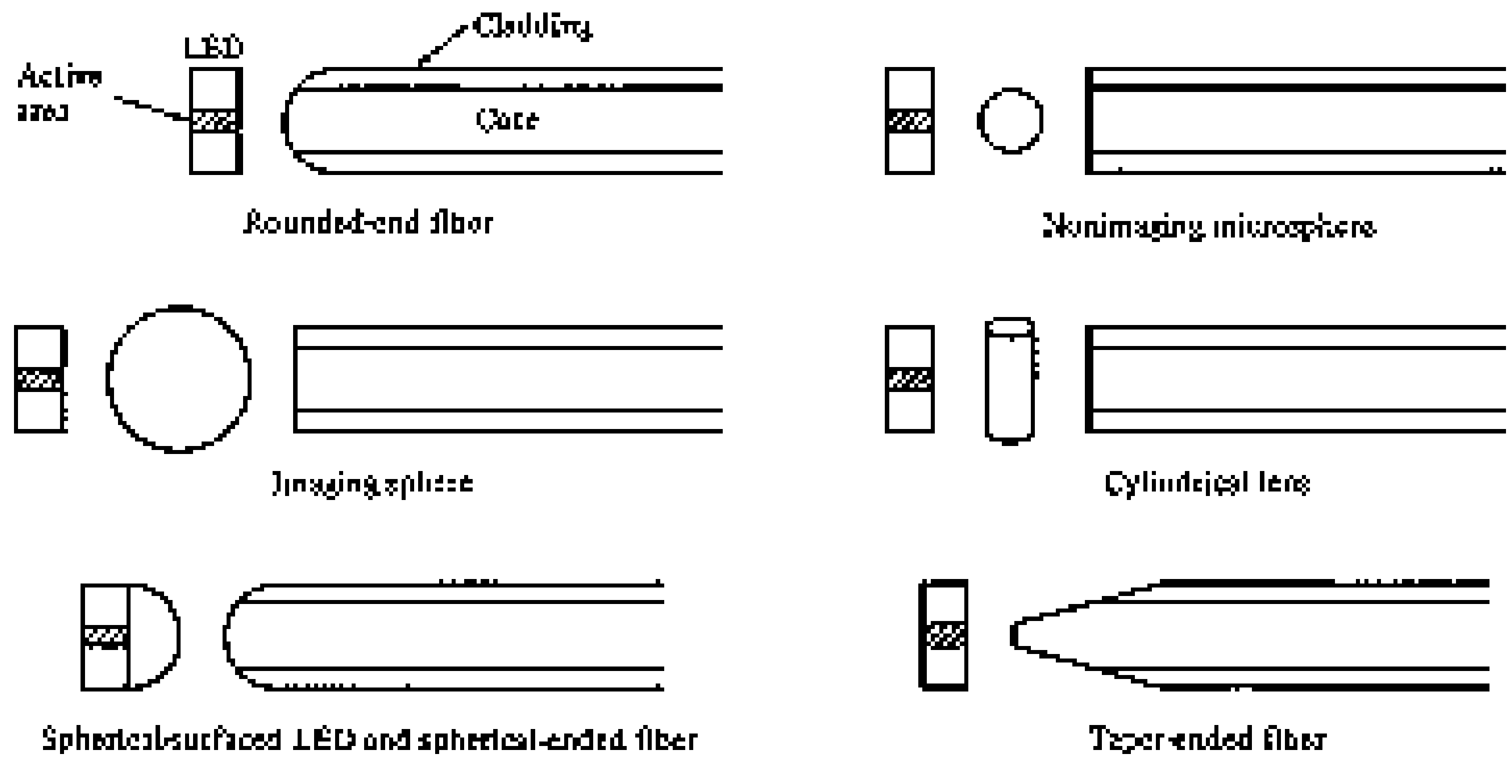
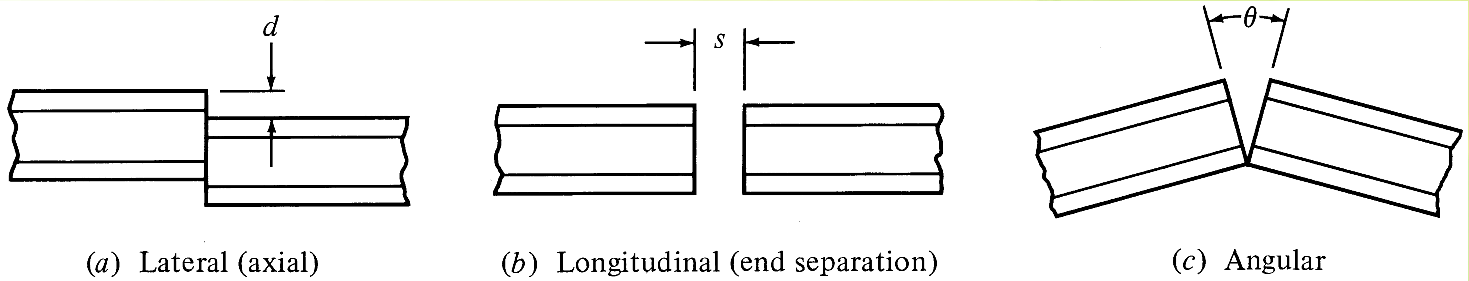
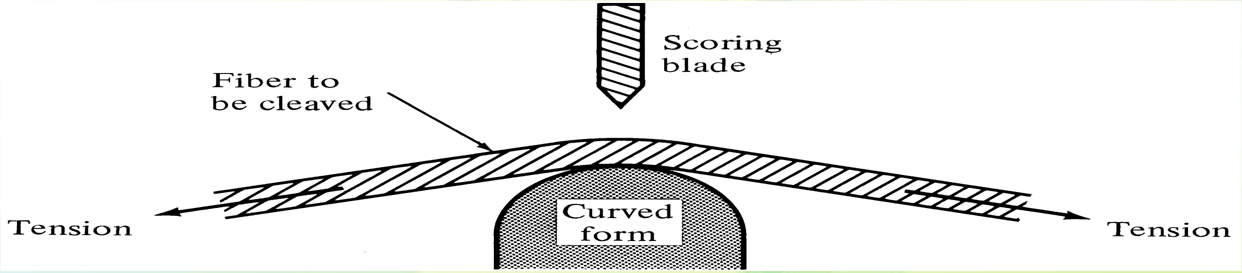


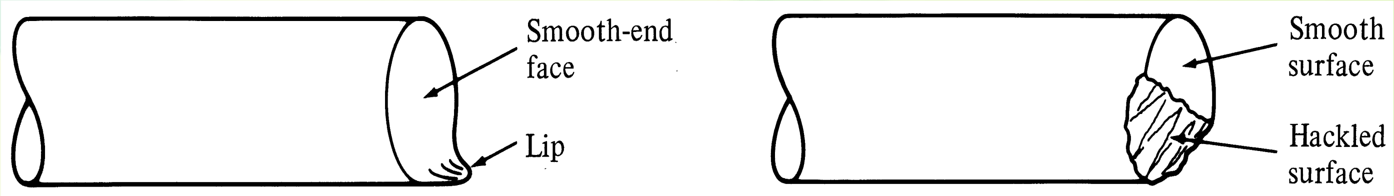
FIGURE 5-5

Mechanical misalignment losses

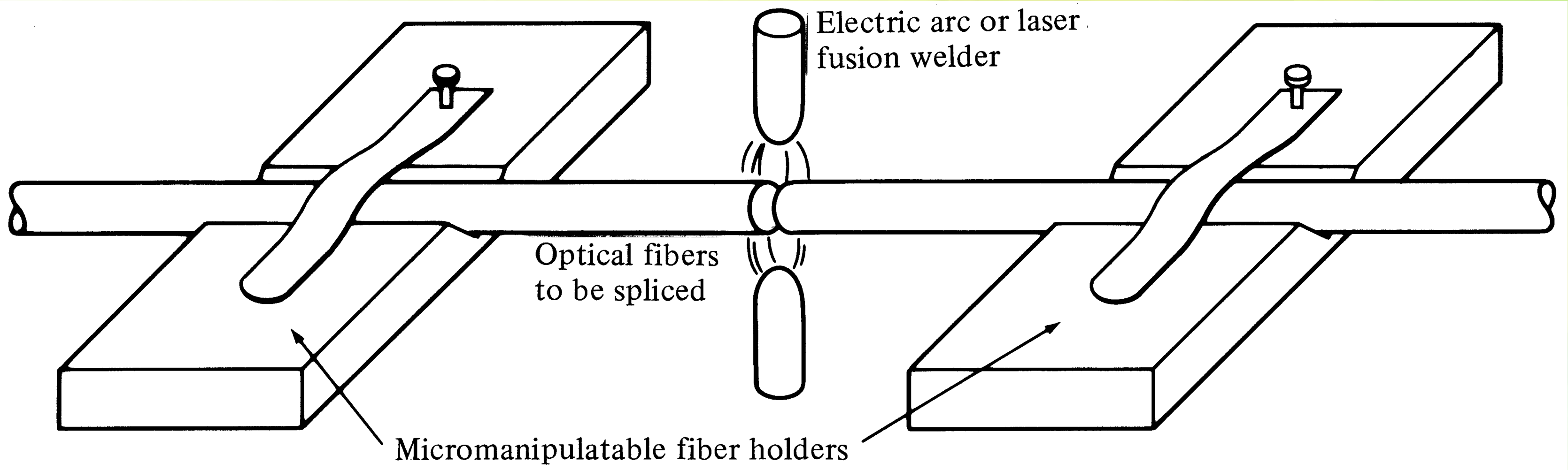


Fiber end face





Fiber splicing



V-groove optical fiber splicing

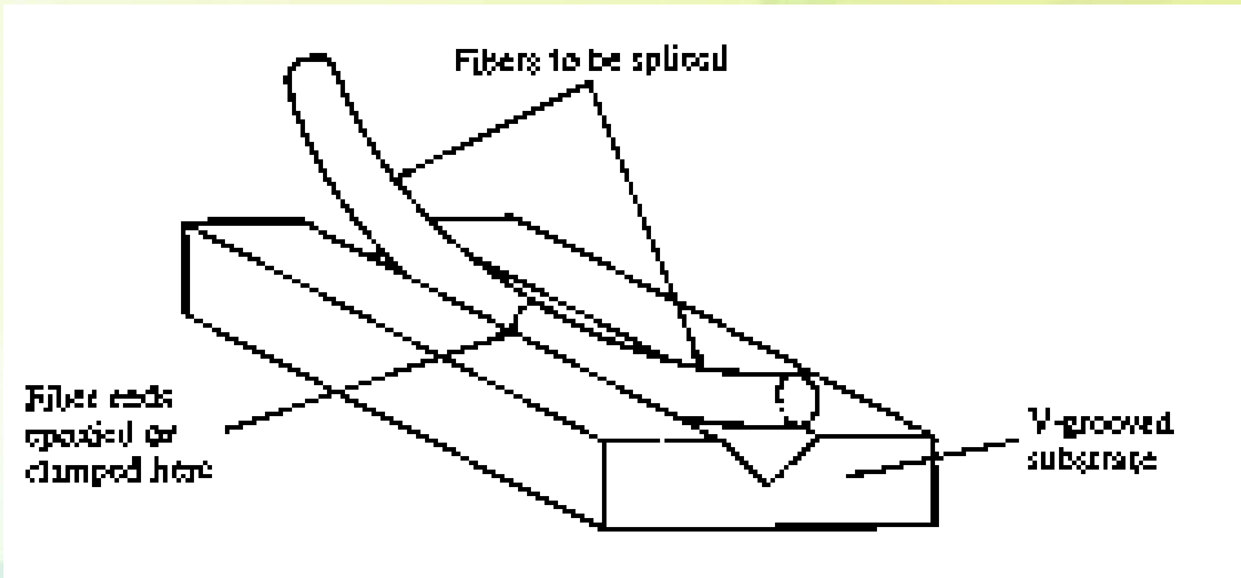


FIGURE 5-18

Optical Fiber Connectors

- Some of the principal requirements of a good connector design are as follows:

  1- low coupling losses

  2- Interchangeability

  3- Ease of assembly

  4- Low environmental sensitivity

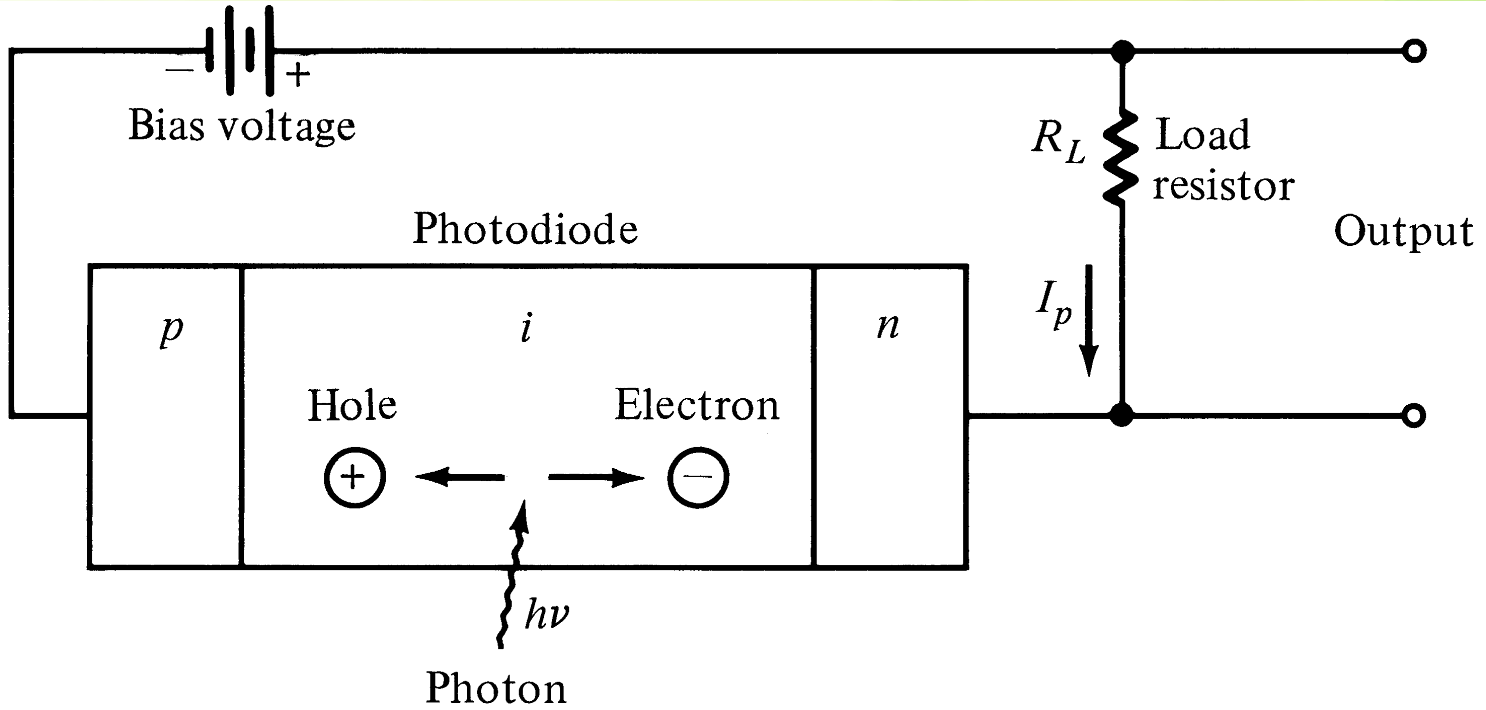
  5- Low-cost and reliable construction

  6- Ease of connection

Chapter 6

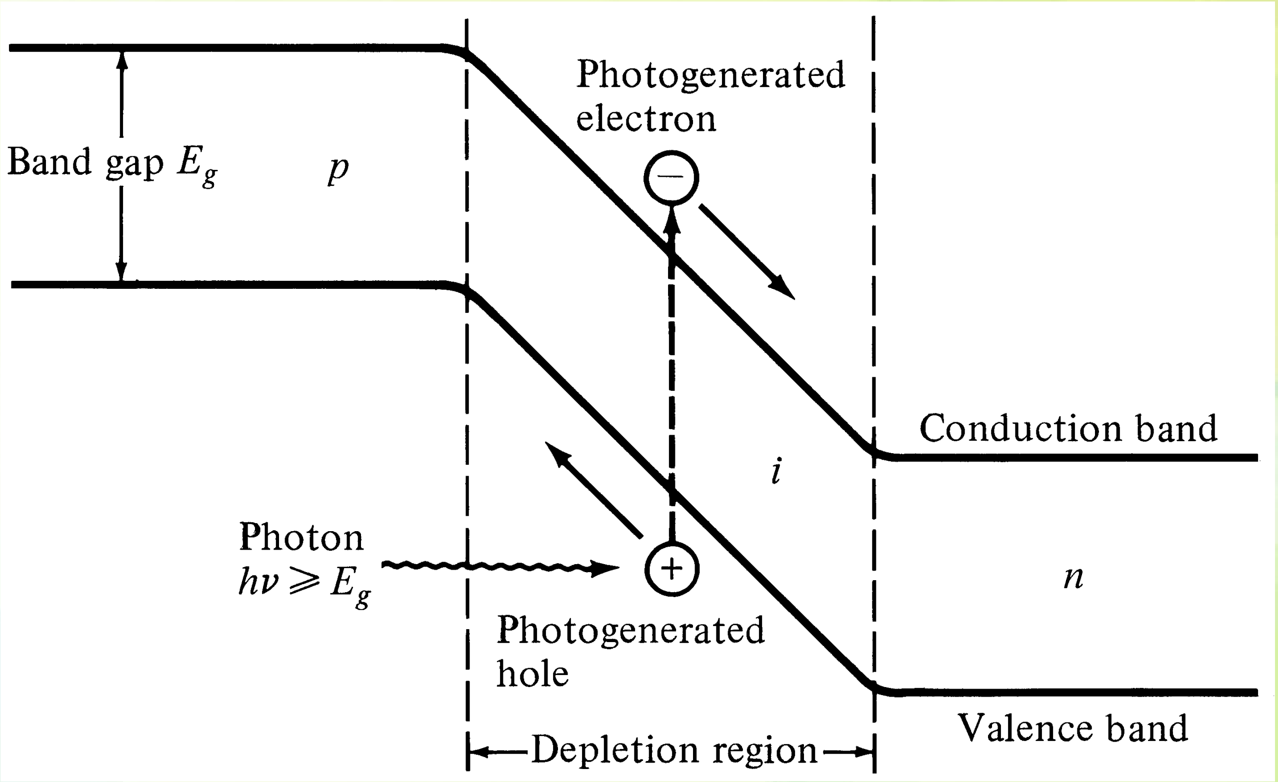
Photo detectors

pin Photodetector



The high electric field present in the depletion region causes photo-generated carriers to Separate and be collected across the reverse –biased junction. This give rise to a current Flow in an external circuit, known as **photocurrent**.

Energy-Band diagram for a *pin* photodiode



Photocurrent

- Optical power absorbed, in the depletion region can be written in terms of incident optical power, :

$$P(x) = P_0(1 - e^{-\alpha_s(\lambda)x})$$

- Absorption coefficient strongly depends on wavelength. The upper wavelength cutoff for any semiconductor can be determined by its energy gap as follows:

$$\lambda_c(\mu\text{m}) = \frac{1.24}{E_g(\text{eV})}$$

- Taking entrance face reflectivity into consideration, the absorbed power in the width of depletion region, *w*, becomes:

$$(1 - R_f)P(w) = P_0(1 - e^{-\alpha_s(\lambda)w})(1 - R_f)$$

Responsivity

- The primary photocurrent resulting from absorption is:

$$I_p = \frac{q}{h\nu} P_0 (1 - e^{-\alpha_s(\lambda) w})(1 - R_f)$$

- Quantum Efficiency:

$$\eta = \frac{\text{\# of electron - hole photogenerated pairs}}{\text{\# of incident photons}}$$

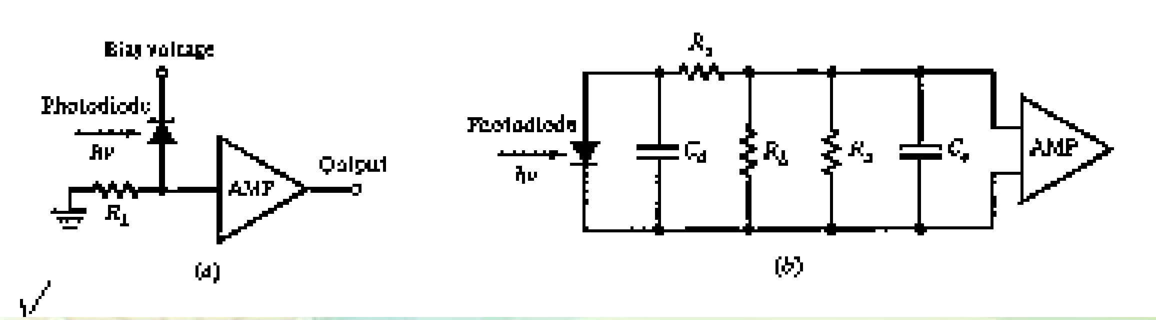
$$\eta = \frac{I_P / q}{P_0 / h\nu}$$

- **Responsivity:**

$$\Re = \frac{I_P}{P_0} = \frac{\eta q}{h\nu} \quad \text{[A/W]}$$

Photo detector Noise & S/N

- Detection of weak optical signal requires that the photodetector and its following amplification circuitry be optimized for a desired signal-to-noise ratio.
- It is the noise current which determines the minimum optical power level that can be detected. This minimum detectable optical power defines the **sensitivity** of photodetector. That is the optical power that generates a photocurrent with the amplitude equal to that of the total noise current (*S/N=1*)



$$\frac{S}{N} = \frac{\text{signal power from photocurrent}}{\text{photodetector noise power} + \text{amplifier noise power}}$$

Signal Calculation

- Consider the modulated optical power signal *P(t)* falls on the photodetector with the form of:

$$P(t) = P_0[1 + ms(t)]$$

- Where *s(t)* is message electrical signal and *m* is modulation index. Therefore the primary photocurrent is (for pin photodiode *M=1*):

$$i_{\text{ph}} = \frac{\eta q}{h\nu} MP(t) = I_P[\text{DC value}] + i_p(t)[\text{AC current}]$$

- The root mean square signal current is then:

$$\langle i_s{}^2 \rangle = \langle i_p{}^2 \rangle M^2 = \sigma_s{}^2$$

$$\langle i_p{}^2 \rangle = \sigma_p{}^2 = \frac{m^2 I_P^2}{2} \quad \text{for sinusoidal signal}$$

Noise Sources in Photo detectors

- The principal noises associated with photodetectors are :

  1- Quantum (Shot) noise: arises from statistical nature of the production and collection of photo-generated electrons upon optical illumination. It has been shown that the statistics follow a Poisson process.

  2- Dark current noise: is the current that continues to flow through the bias circuit in the absence of the light. This is the combination of **bulk dark current**, which is due to thermally generated e and h in the *pn* junction, and the **surface dark current**, due to surface defects, bias voltage and surface area.
- In order to calculate the total noise presented in photodetector, we should sum up the root mean square of each noise current by assuming that those are uncorrelated.

- **Total photodetector noise current=quantum noise current +bulk dark current noise + surface current noise**

Noise calculation (1)

- **Quantum noise current** (lower limit on the sensitivity):

$$\langle i_Q^{\,2} \rangle = \sigma_Q^{\,2} = 2qI_P BM^2 F(M)$$

- B: Bandwidth, *F(M)* is the noise figure and generally is $F(M) \approx M^x \quad 0 \le x \le 1.0$

- **Bulk dark current noise:**

$$\langle i_{DB}^{\,2} \rangle = \sigma_{DB}^2 = 2qI_D BM^2 F(M)$$

is bulk dark current

Note that for *pin* photodiode

- **Surface dark current noise:** is the surface current.

$$\langle i_{DS}^{\,2} \rangle = \sigma_{DS}^2 = 2qI_L B$$

Noise calculation (2)

- The total rms photo detector noise current is:

$$\langle i_N{}^2 \rangle = \sigma_N{}^2 = \langle i_Q{}^2 \rangle + \langle i_{DB}{}^2 \rangle + \langle i_{DS}{}^2 \rangle$$

$$= 2q(I_P + I_D)BM^2 F(M) + 2qI_L B$$

- The thermal noise of amplifier connected to the photodetector is:

$$\langle i_T{}^2 \rangle = \sigma_T{}^2 = \frac{4k_B TB}{R_L}$$

input resistance of amplifier, and is Boltzmann cte.

Noise calculation (2)

- The total rms photodetector noise current is:

$$\langle i_N{}^2 \rangle = \sigma_N{}^2 = \langle i_Q{}^2 \rangle + \langle i_{DB}{}^2 \rangle + \langle i_{DS}{}^2 \rangle$$

$$= 2q(I_P + I_D)BM^2F(M) + 2qI_L B$$

- The thermal noise of amplifier connected to the photodetector is:

$$\langle i_T{}^2 \rangle = \sigma_T{}^2 = \frac{4k_B TB}{R_L}$$

input resistance of amplifier, and $k_B = 1.38 \times 10^{-23}$ JK^{-1} is Boltzmann cte.

S/N Calculation

- Having obtained the signal and total noise, the signal-to-noise-ratio can be written as:

$$\frac{S}{N} = \frac{\left\langle i_P^{\,2} \right\rangle M^2}{2q(I_P + I_D)BM^2 F(M) + 2qI_L B + 4k_B TB / R_L}$$

- Since the noise figure *F(M)* increases with M, there always exists an optimum value of *M* that maximizes the S/N. For sinusoidally modulated signal with *m=1* and :

$$M_{\text{opt}}^{x+2} = \frac{2qI_L + 4k_B T / R_L}{xq(I_P + I_D)}$$

Photo detector Response Time

- The response time of a photo detector with its output circuit depends mainly on the following three factors:

1- The transit time of the photo carriers in the depletion region. The transit time depends on the carrier drift velocity and the depletion layer width *w*, and is given by:

$$t_d = \frac{w}{v_d}$$

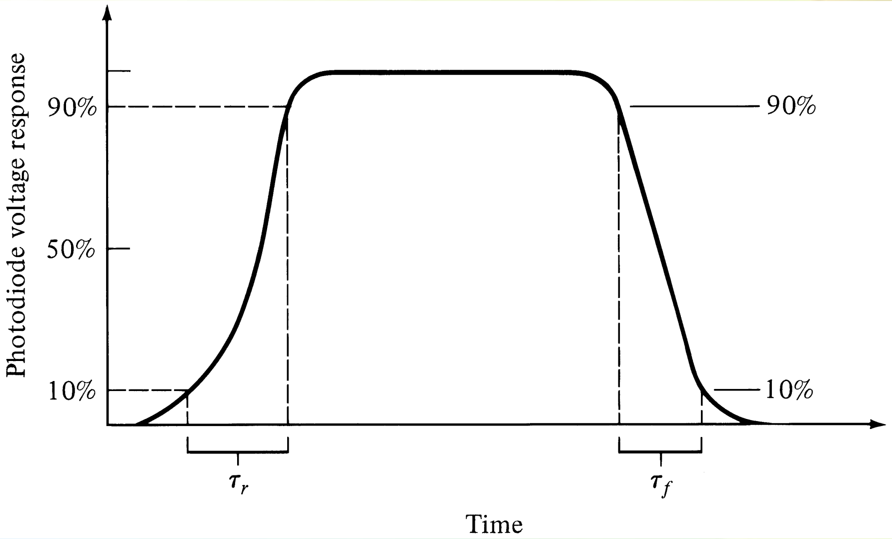
2- Diffusion time of photo carriers outside depletion region.

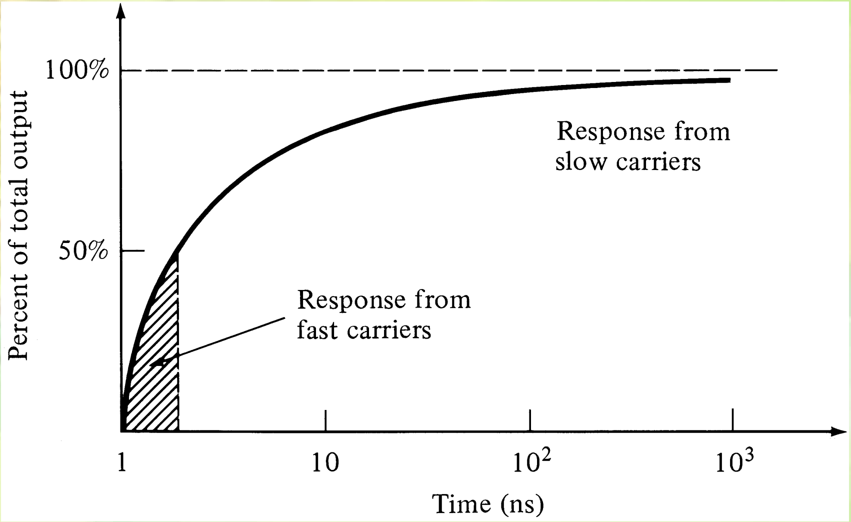
3- *RC* time constant of the circuit. The circuit after the photo detector acts like *RC* low pass filter with a pass band given by:

$$B = \frac{1}{2\pi R_T C_T}$$

$$R_T = R_s \parallel R_L \text{ and } C_T = C_a + C_d$$

Photodiode response to optical pulse

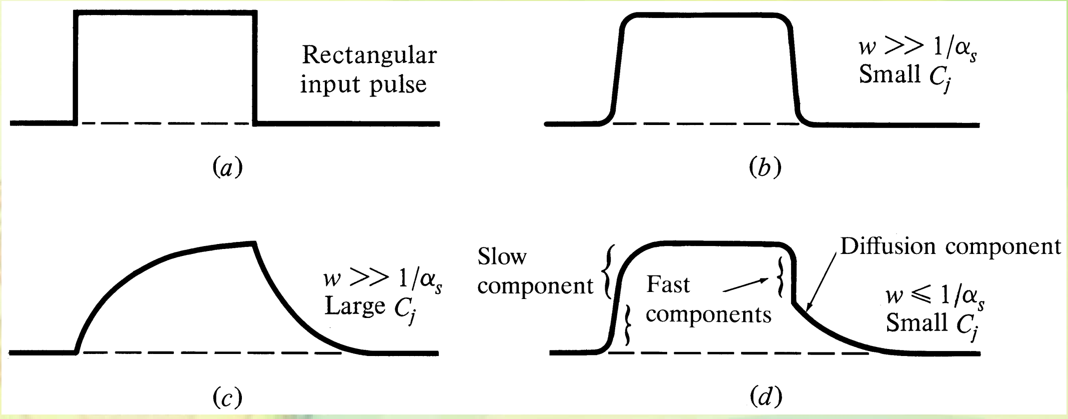


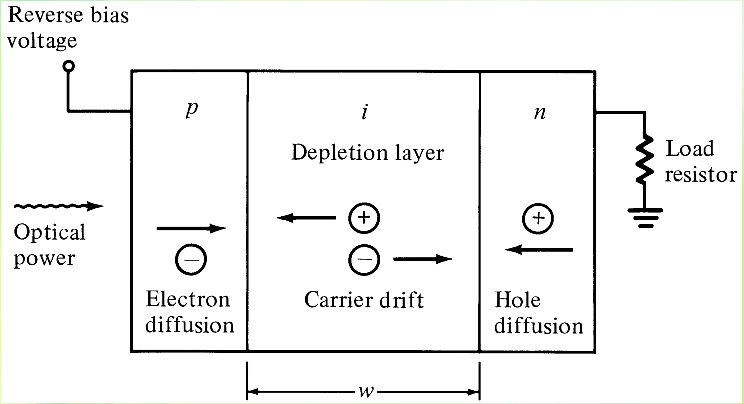


Various optical responses of photodetectors: Trade-off between quantum efficiency & response time

- To achieve a high quantum efficiency, the depletion layer width must be larger than

  (the inverse of the absorption coefficient), so that most of the light will be absorbed. At the same time with large width, the capacitance is small and *RC* time constant getting smaller, leading to faster response, but wide width results in larger transit time in the depletion region. Therefore there is a trade-off between width and QE. It is shown that the best is:





Comparison of photo detectors

Parameter	Symbol	Unit	Si	Ge	InGaAs
Wavelength range	λ	nm	400–1100	800–1650	1100–1700
Responsivity	$\mathcal{R}$	A/W	0.4–0.6	0.4–0.5	0.75–0.95
Dark current	I_D	nA	1–10	50–500	0.5–2.0
Rise time	τ_r	ns	0.5–1	0.1–0.5	0.05–0.5
Bandwidth	B	GHz	0.3–0.7	0.5–3	1–2
Bias voltage	V_B	V	5	5–10	5

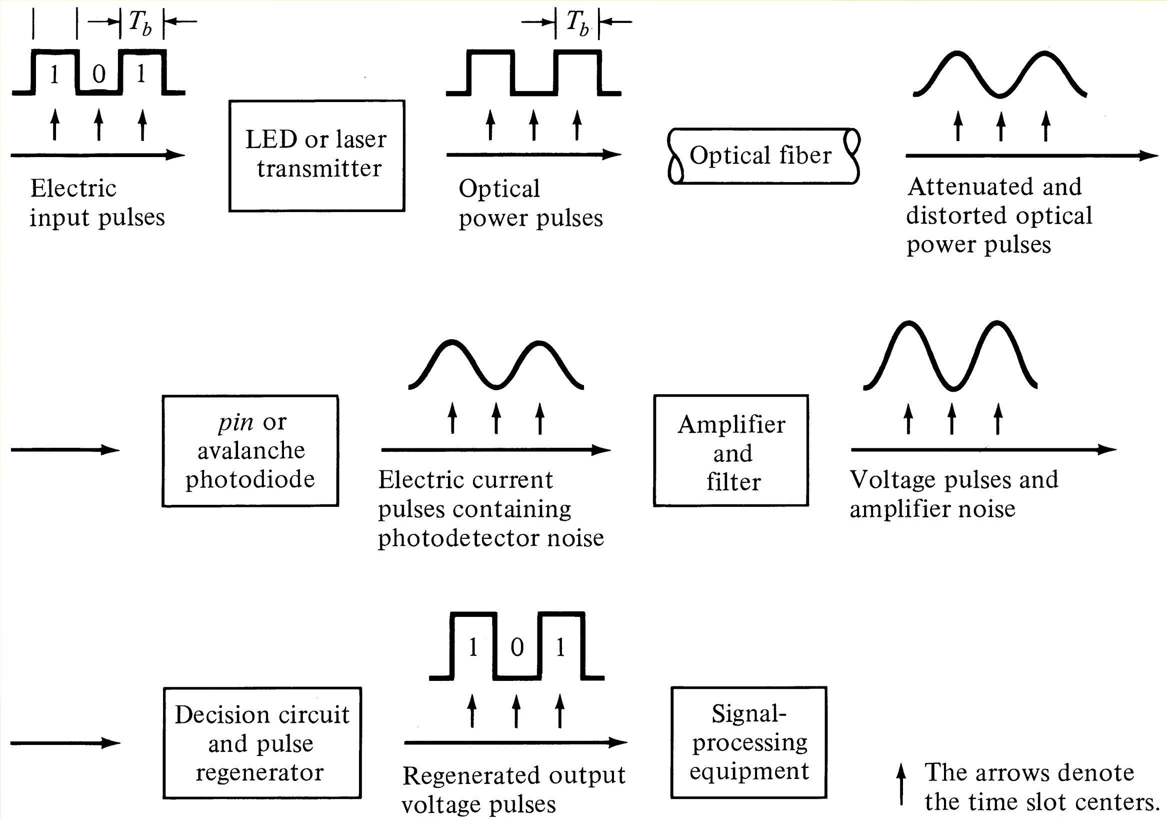
TABLE 6-2
Generic operating parameters of Si, Ge, and InGaAs avalanche photodiodes

Parameter	Symbol	Unit	Si	Ge	InGaAs
Wavelength range	λ	nm	400–1100	800–1650	1100–1700
Avalanche gain	M	—	20–400	50–200	10–40
Dark current	I_D	nA	0.1–1	50–500	10–50 @ $M = 10$
Rise time	τ_r	ns	0.1–2	0.5–0.8	0.1–0.5
Gain · bandwidth	$M \cdot B$	GHz	100–400	2–10	20–250
Bias voltage	V_B	V	150–400	20–40	20–30

Chapter 7

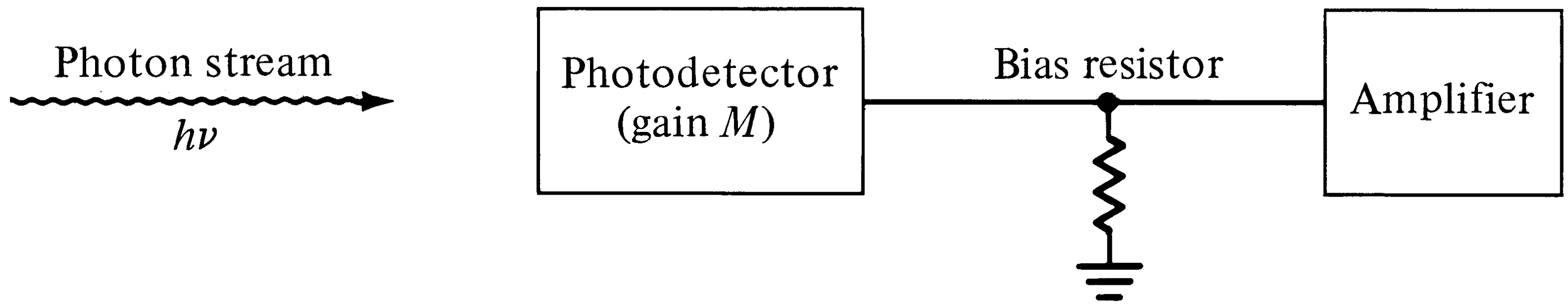
Photonic Transmission Systems (Digital & Analog)

Digital Transmission System (DTS)



- The design of optical receiver is much more complicated than that of optical transmitter because the receiver must first detect weak, distorted signals and the n make decisions on what type of data was sent.

Error Sources in DTS



- Photon detection quantum noise (Poisson fluctuation)

- Bulk dark current
- Surface leakage current
- Statistical gain fluctuation (for avalanche photodiodes)

- Thermal noise

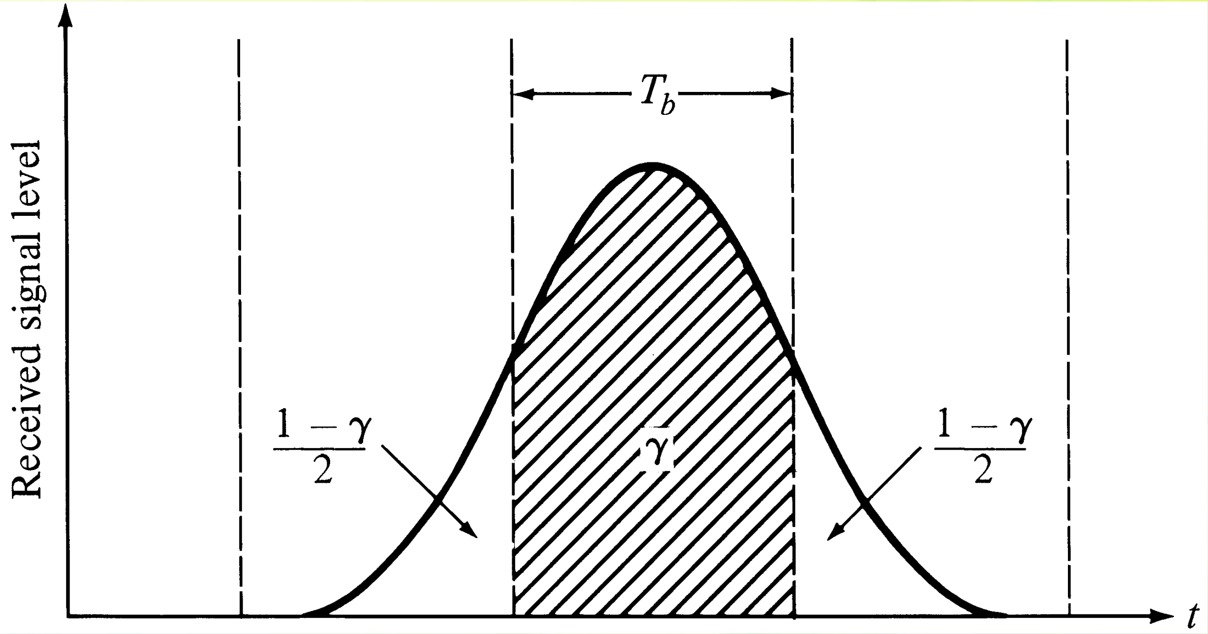
- Amplifier noise

$$\bar{N} = \frac{\eta}{h\nu}\int_0^{\tau} P(t)dt = \frac{\eta}{h\nu}E$$

$$P_r(n) = \bar{N}^n \frac{e^{-\bar{N}}}{n!}$$

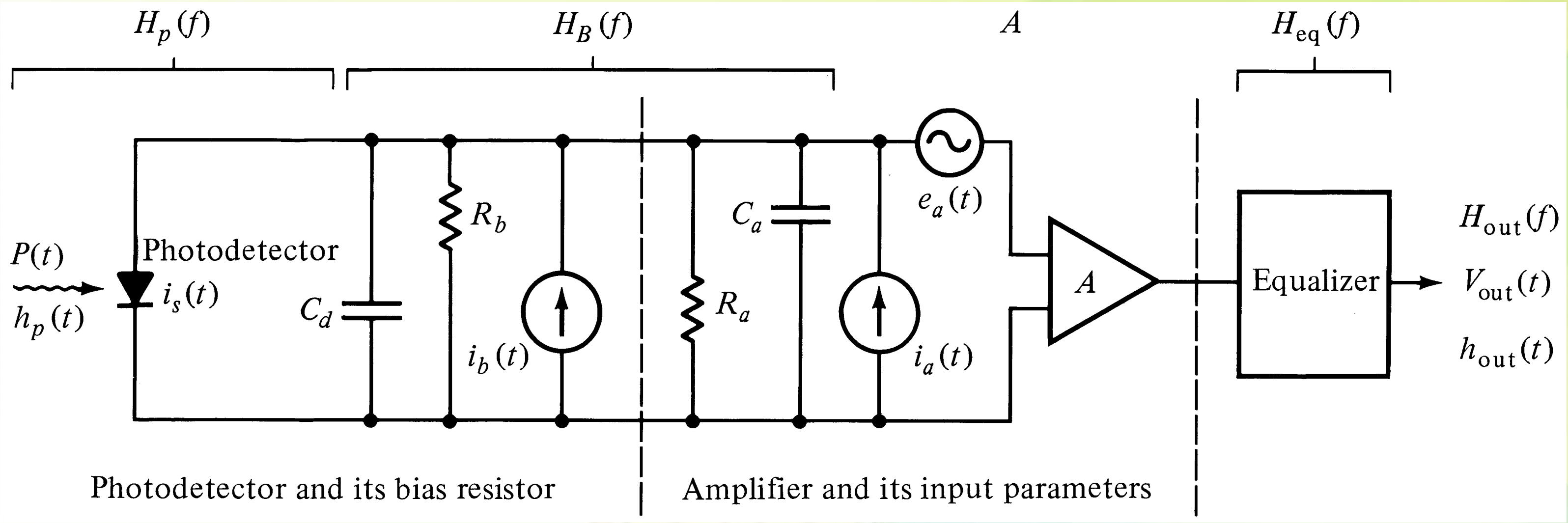
is the average number of electron-hole pairs in photodetector, is the detector quantum efficiency and *E* is energy received in a time interval and is photon energy, where is the probability that *n* electrons are emitted in an interval .

Inter Symbol Interference (ISI)



Pulse spreading in an optical signal, after traversing along optical fiber, leads to ISI. Some fraction of energy remaining in appropriate time slot is designated by , so the rest is the fraction of energy that has spread Into adjacent time slots.

Receiver Configuration



The binary digital pulse train incident on the photodetector can be written in the following form:

$$P(t) = \sum_{n=-\infty}^{+\infty} b_n h_p(t - nT_b)$$

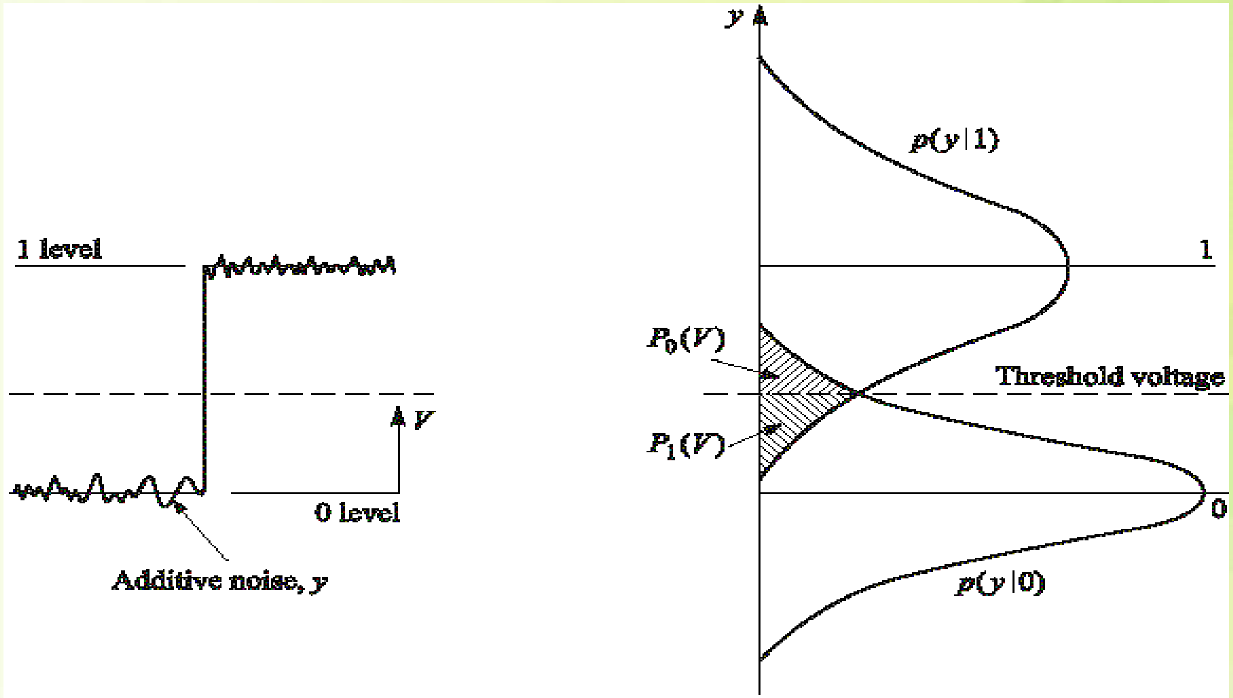
where T_b is bit period, b_n is an amplitude parameter of the nth message digit and $h_p(t)$ is the received pulse shape which is positive for all t.

Bit Error Rate (BER)

$$\text{BER} = \text{Probability of Error} = \frac{\text{\# of error over a certain time interval } t}{\text{total \# of pulses transmitted during } t} =$$

$$\frac{N_e}{N_t} = \frac{N_e}{Bt} \qquad B = 1/T_b$$

- **Probability of Error**= probability that the output voltage is less than the threshold when a 1 is sent + probability that the output voltage is more than the threshold when a 0 has been sent.



Probability distributions for received logical 0 and 1 signal pulses.
the different widths of the two distributions are caused by various signal distortion effects.

$P_1(v) = \int_{-\infty}^{v} p(y\,|\,1)dy$ probablity that the equalizer output voltage is less than v, if 1 transmitted

$P_0(v) = \int_{v}^{\infty} p(y\,|\,0)dy$ probablity that the equalizer output voltage exceeds v, if 0 transmitted

$$P_e = q_1 P_1(v_{th}) + q_0 P_0(v_{th})$$

$$= q_1 \int_{-\infty}^{v_{th}} p(y\,|\,1)\,dy + q_0 \int_{v_{th}}^{\infty} p(y\,|\,1)\,dy$$

- Where are the probabilities that the transmitter sends 0 and 1 respectively.

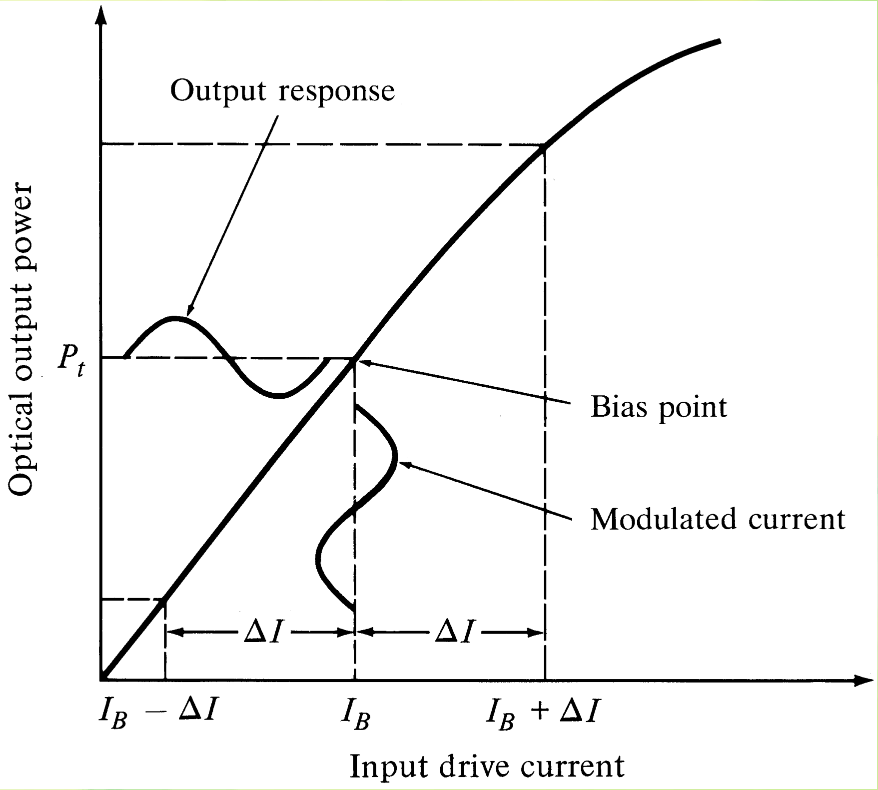
- For an unbiased transmitter

Analog Transmission System

- In photonic analog transmission system the performance of the system is mainly determined by signal-to-noise ratio at the output of the receiver.
- In case of amplitude modulation the transmitted optical power *P(t)* is in the form of:

where *m* is modulation index, and *s(t)* is analog modulation signal.

- The photocurrent at receiver can be expressed as:



- By calculating mean square of the signal and mean square of the total noise, which consists of quantum, dark and surface leakage noise currents plus resistance thermal noise, the S/N can be written as:

$$\frac{S}{N} = \frac{\left\langle i_s^2 \right\rangle}{\left\langle i_N^2 \right\rangle} = \frac{(1/2)(\Re_0 M m P_r)^2}{2q(\Re_0 P_r + I_D) M^2 F(M) B + (4 k_B T B / R_{eq}) F_t}$$

$$= \frac{(1/2)(M m I_P)^2}{2q(I_P + I_D) M^2 F(M) B + (4 k_B T B / R_{eq}) F_t}$$

I_P : primary photocurrent $= \Re_0 P_r$; I_D : primary bulk dark current;

I_L : Surface - leakage current; $F(M)$: excess photodiode noise factor $\approx M^x$

B : effective noise bandwidth; R_{eq} : equivalent resistance of photodetector load and amplifier

F_t : noise figure of baseband amplifier; P_r : average received optical power

pin Photodiode *S/N*

- For *pin* photodiode, *M=1:*

$$\frac{S}{N} \cong \frac{(1/2)(I_P m)^2}{(4k_B TB/R_{eq})F_t} = \frac{(1/2)m^2 \Re_0{}^2 P_r{}^2}{(4k_B TB/R_{eq})F}$$

$$\frac{S}{N} \cong \frac{m^2 \Re_0 P_r}{4qB}$$

Large signal level

Photonic Digital Link Analysis & Design

- Point-to-Point Link Requirement:

 - Data Rate

 - BER

 - Distance

 - Cost & Complexity

- Analysis Methods:

 - Link loss & S/N analysis (link power budget analysis and loss allocation) for a prescribed BER

 - Dispersion (rise-time) analysis (rise-time budget allocation)

System Design Choices: Photo detector, Optical Source, Fiber

- Photodetectors: Compared to APD, PINs are less expensive and more stablewith temperature. However PINs have lower sensitivity.
- Optical Sources:

1- LEDs: 150 (Mb/s).km @ 800-900 nm and larger than 1.5 (Gb/s).km @ 1330 nm

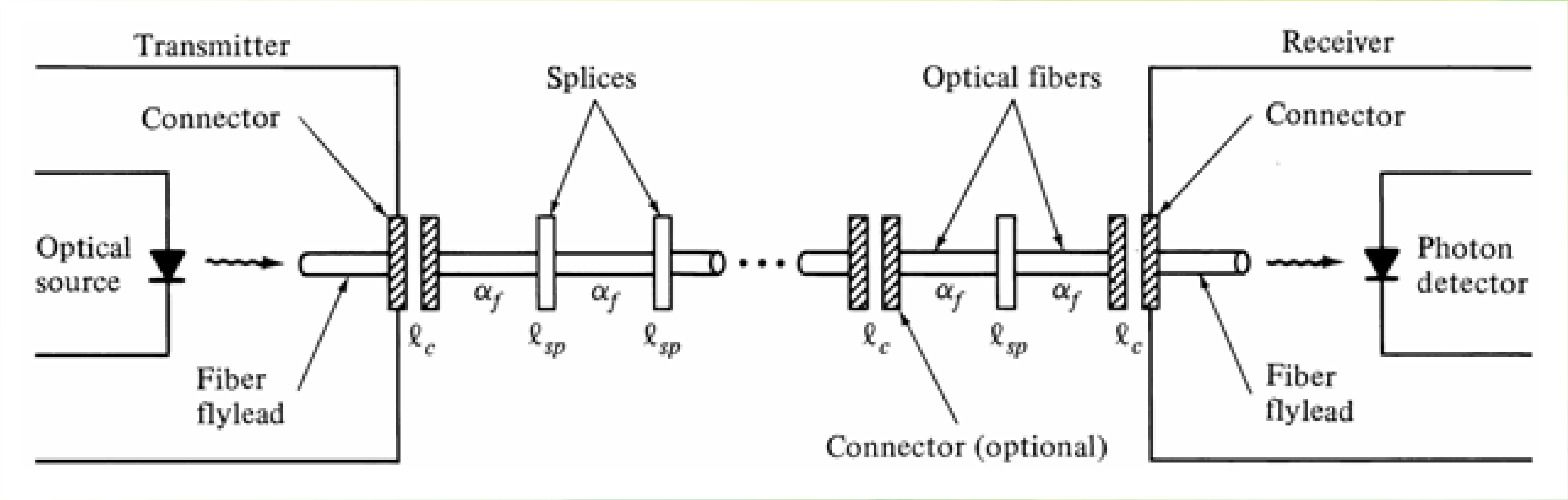
2- InGaAsP lasers: 25 (Gb/s).km @ 1330 nm and ideally around 500 (Gb/s).km @ 1550 nm. 10-15 dB more power. However more costly and more complex circuitry.

- Fiber:

1- Single-mode fibers are often used with lasers or edge-emitting LEDs.

2- Multi-mode fibers are normally used with LEDs. NA and should be optimized for any particular application.

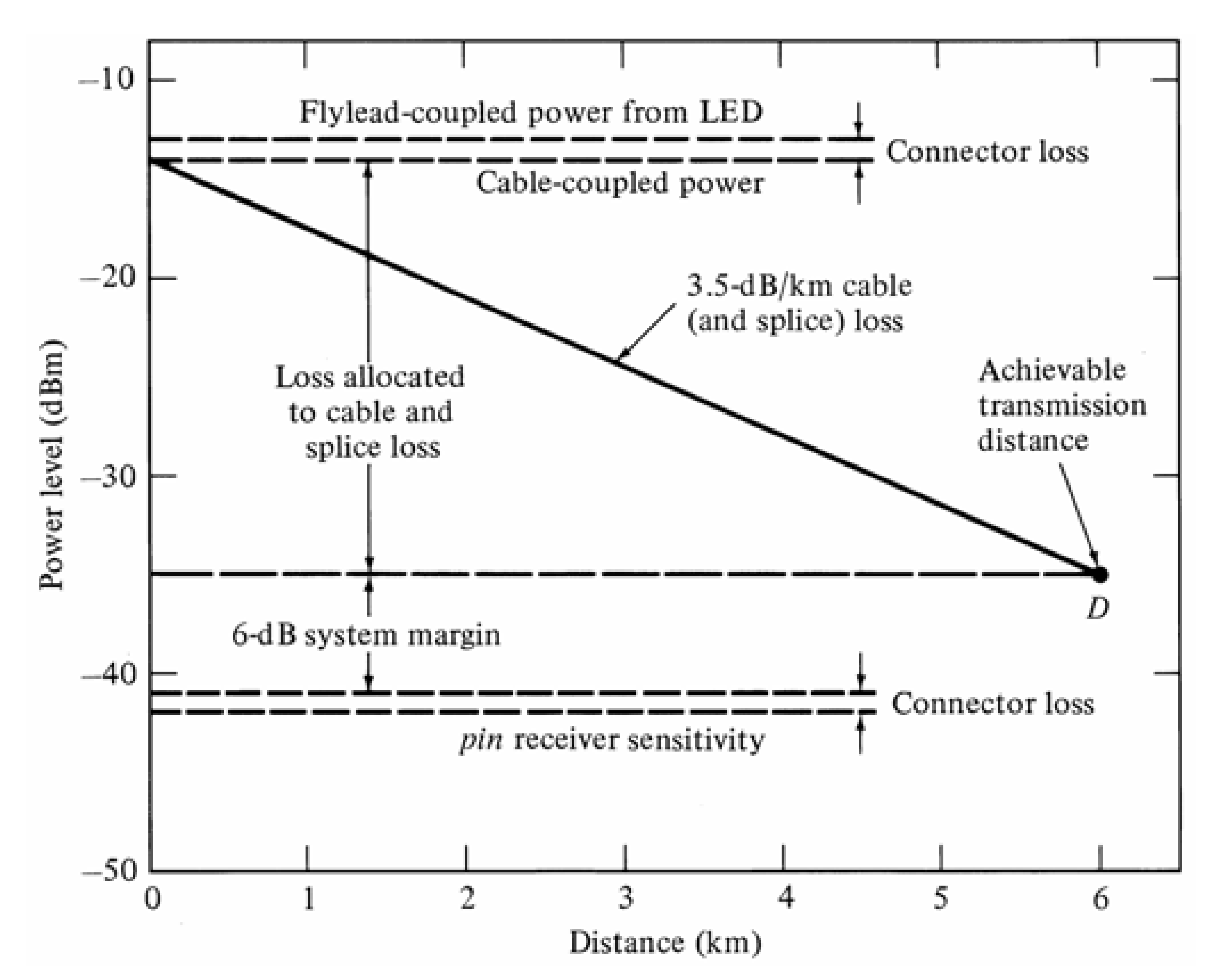
Link Power/Loss Analysis



$$P_T[dB] = P_s[dBm] - P_R[dBm]$$

$$P_T = 2l_c[dB] + \alpha_f[dB/km] \times L[km] + \text{System Margin}$$

Link Loss Budget [Example 8.1]



Link Power Budget Table [Example 8.2]

- Example: [SONET OC-48 (2.5 Gb/s) link]

  Transmitter: 3dBm @ 1550 nm; Receiver: InGaAs APD with -32 dBm sensitivity @ 2.5 Gb/s;

  Fiber: 60 km long with o.3 dB/km attenuation; jumper cable loss 3 dB each, connector loss of 1 dB each.

Component/loss parameter	Output/sensitivity /loss	Power margin (dB)
Laser output	3 dBm	
APD Sensitivity @ 2.5 Gb/s	-32 dBm	
Allowed loss	3-(-32) dBm	35
Source connector loss	1 dB	34
Jumper+Connect or loss	3+1 dB	30
Cable attenuation	18 dB	12
Jumper+Connect or loss	3+1 dB	8
Receiver Connector loss	1 dB	7(final margin)

Dispersion Analysis (Rise-Time Budget)

$$t_{sys} = [t_{tx}^2 + t_{\mathrm{mod}}^2 + t_{GVD}^2 + t_{rx}^2]^{1/2}$$

$$= \left[t_{tx}^2 + \left(\frac{440L^q}{B_0} \right)^2 + D^2 \sigma_\lambda^2 L^2 + \left(\frac{350}{B_{rx}} \right)^2 \right]^{1/2}$$

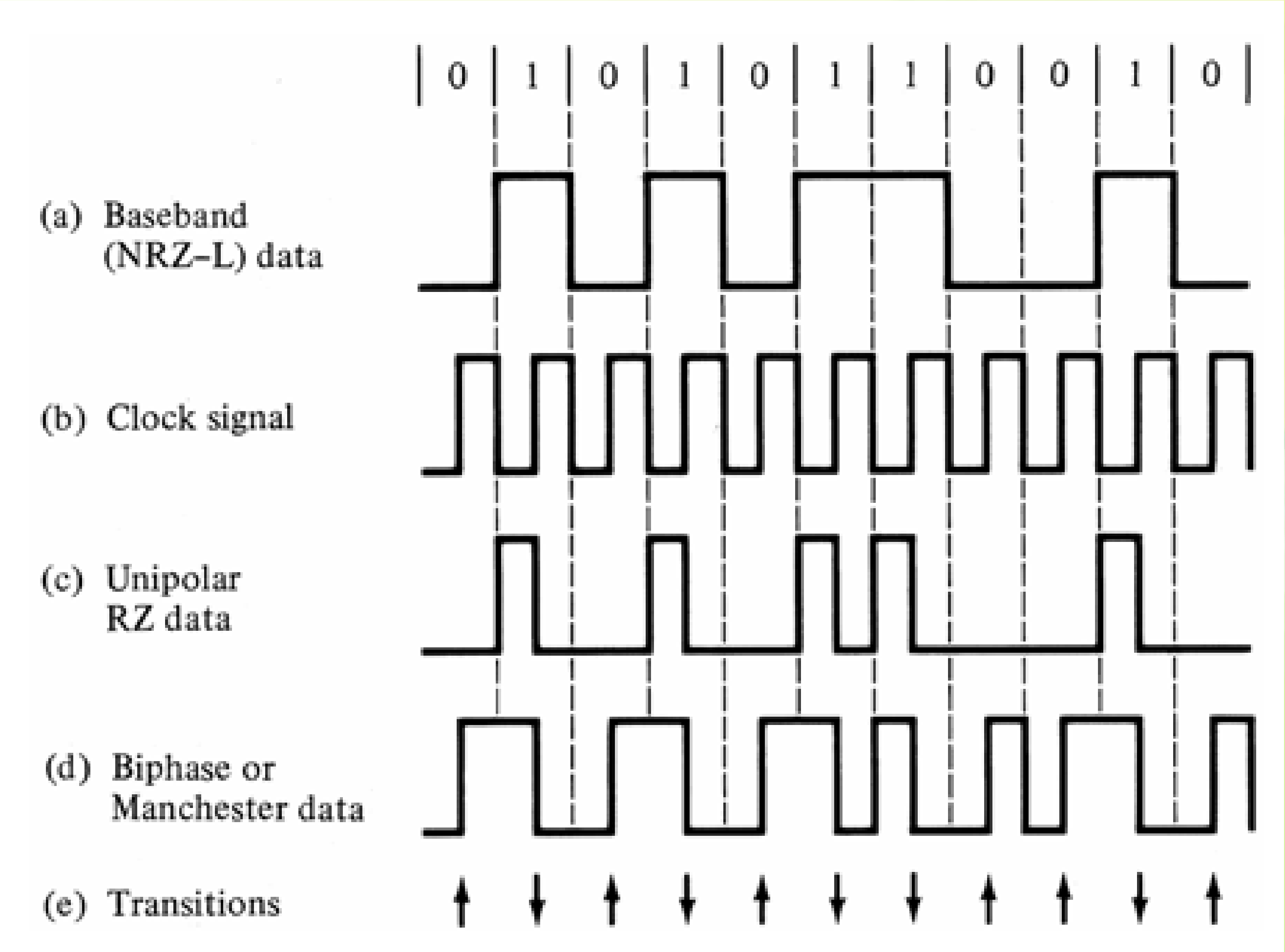
$t_{tx}[ns]$: transmitter rise time $t_{rx}[ns]$: receiver rise time $t_{\mathrm{mod}}[n]$: modal dispersion

$B_{rx}[MHz]$:3dB Electrical BW $L[km]$:Length of the fiber $B_0[MHz]$:BW of the 1 km of the fiber;

$q \approx 0.7$ t_{GVD}[ns]: rise-time due to group velocity dispersion

$D[ns/(km.nm)]$:Dispersion σ_λ[nm]: Spectral width of the source

Two-level Binary Channel Codes



System rise-Time & Information Rate

- In digital transmission system, the system rise-time limits the bit rate of the system according to the following criteria:

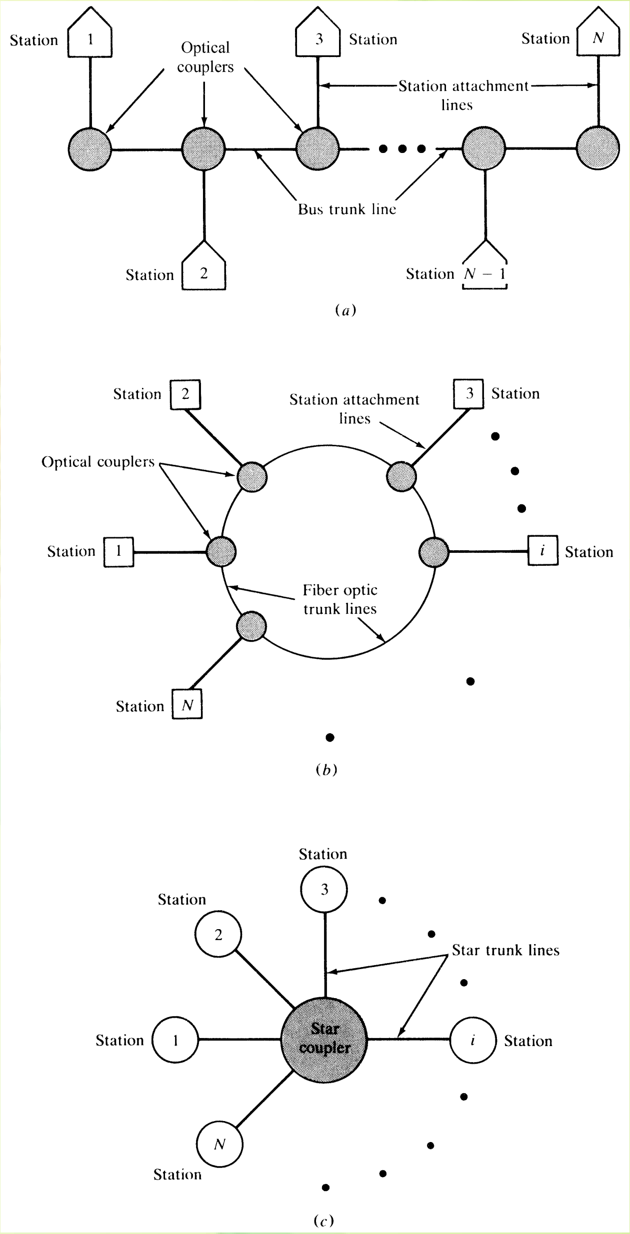
$$t_{sys} < 70\% \text{ of NRZ bit period}$$

$$t_{sys} < 35\% \text{ of RZ bit period}$$

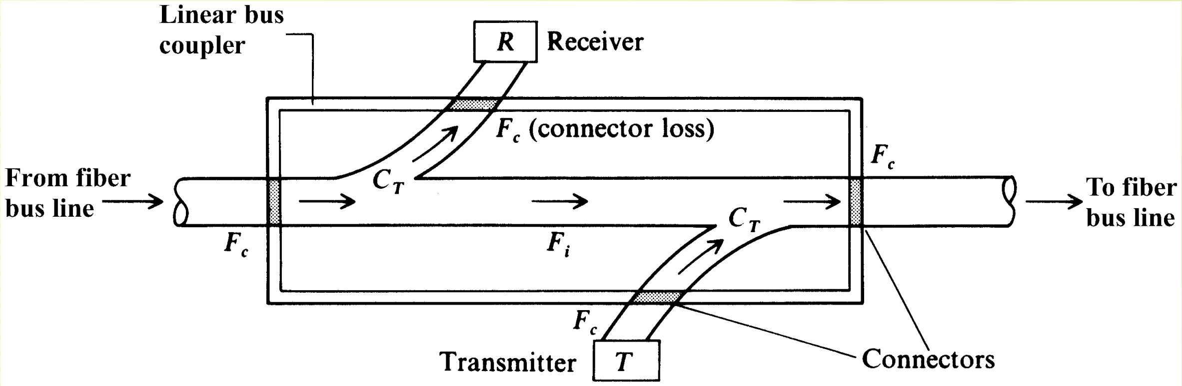
Chapter 8

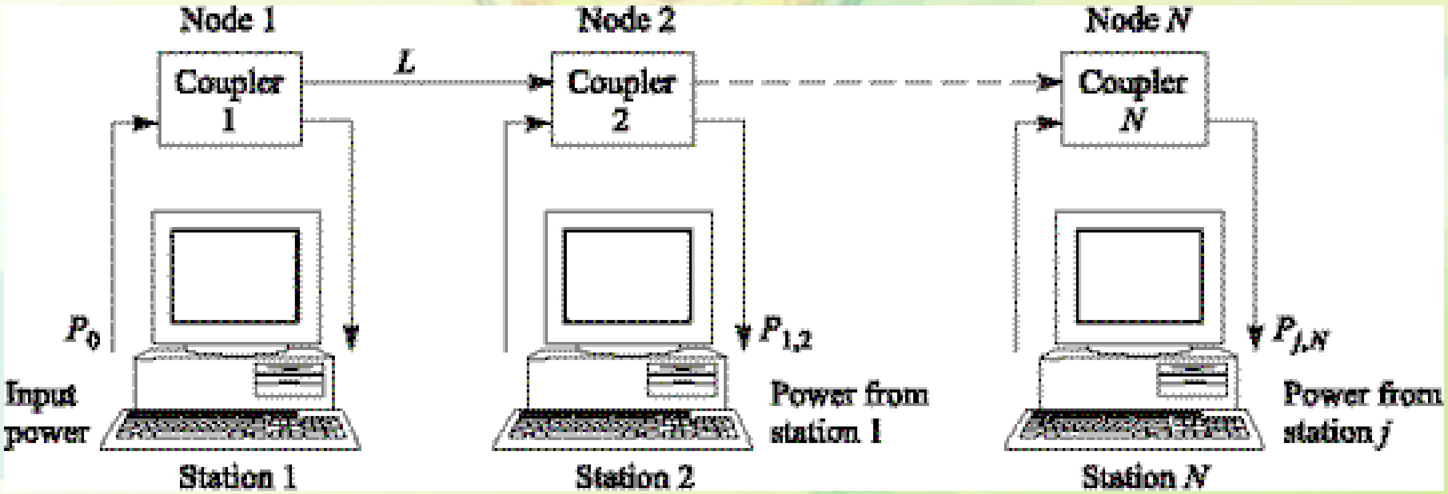
- Photonic Networks

3 Network Topologies

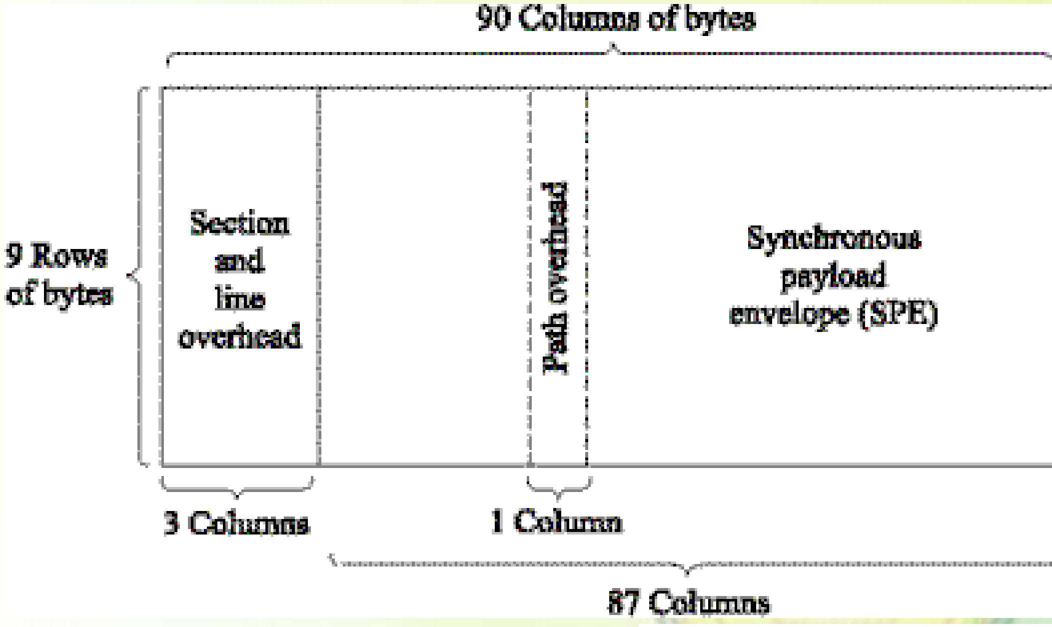


Passive Linear Bus Topology





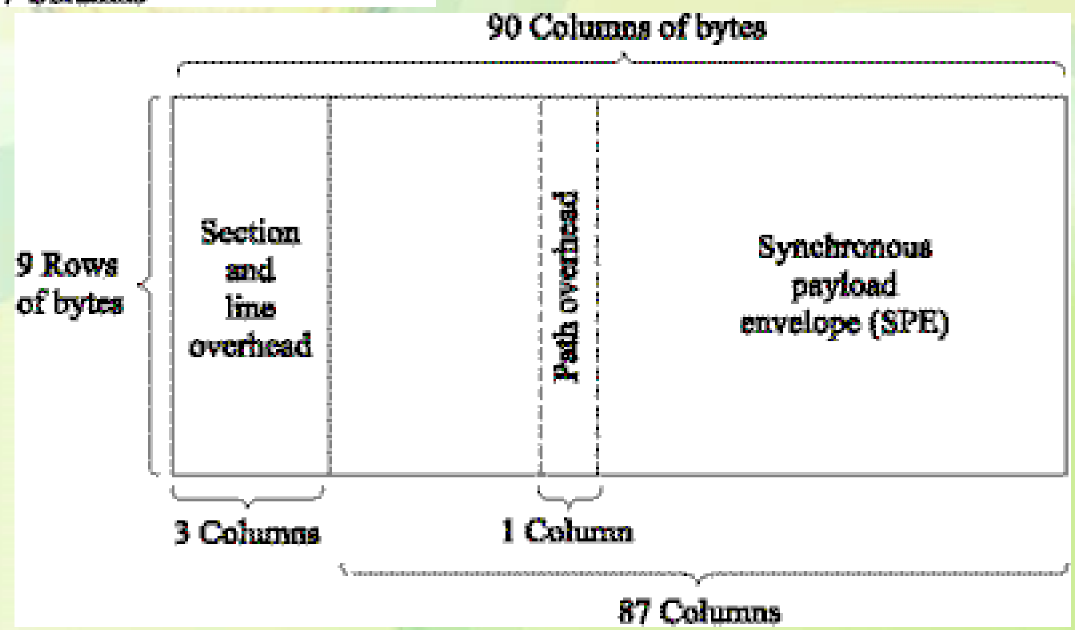
SONET/SDH



STS-1 SONET frame
with 51.84 Mb/s

(90 bytes/row)(9 rows/frame)(8 bits/byte)
(125 microsecond/frame)=51.84 Mb/s

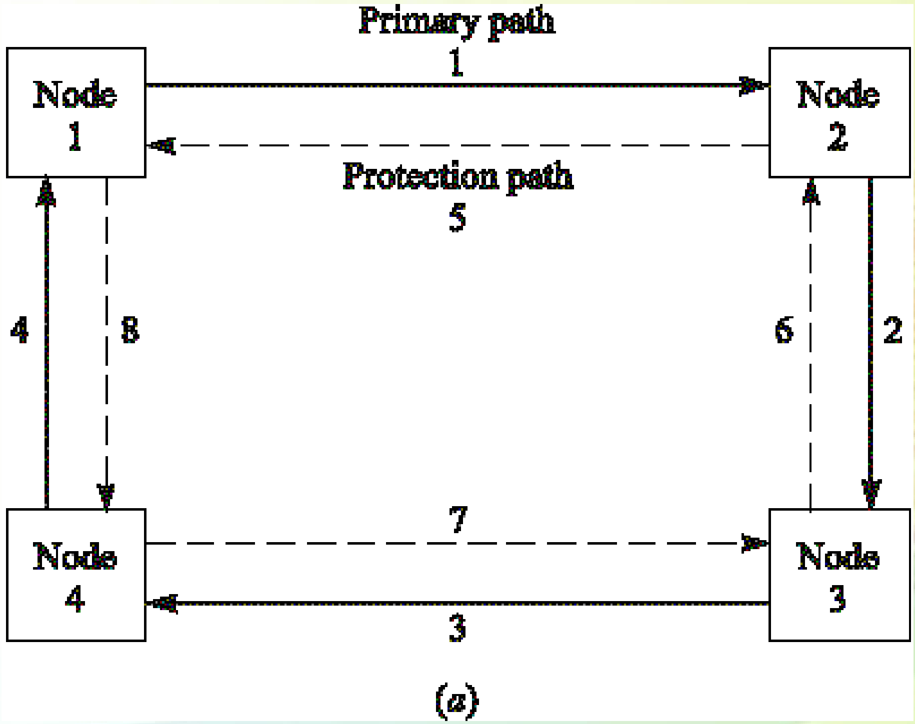
STS-N SONET frame
with 51.84N Mb/s
N=1,3,12,24,48,192



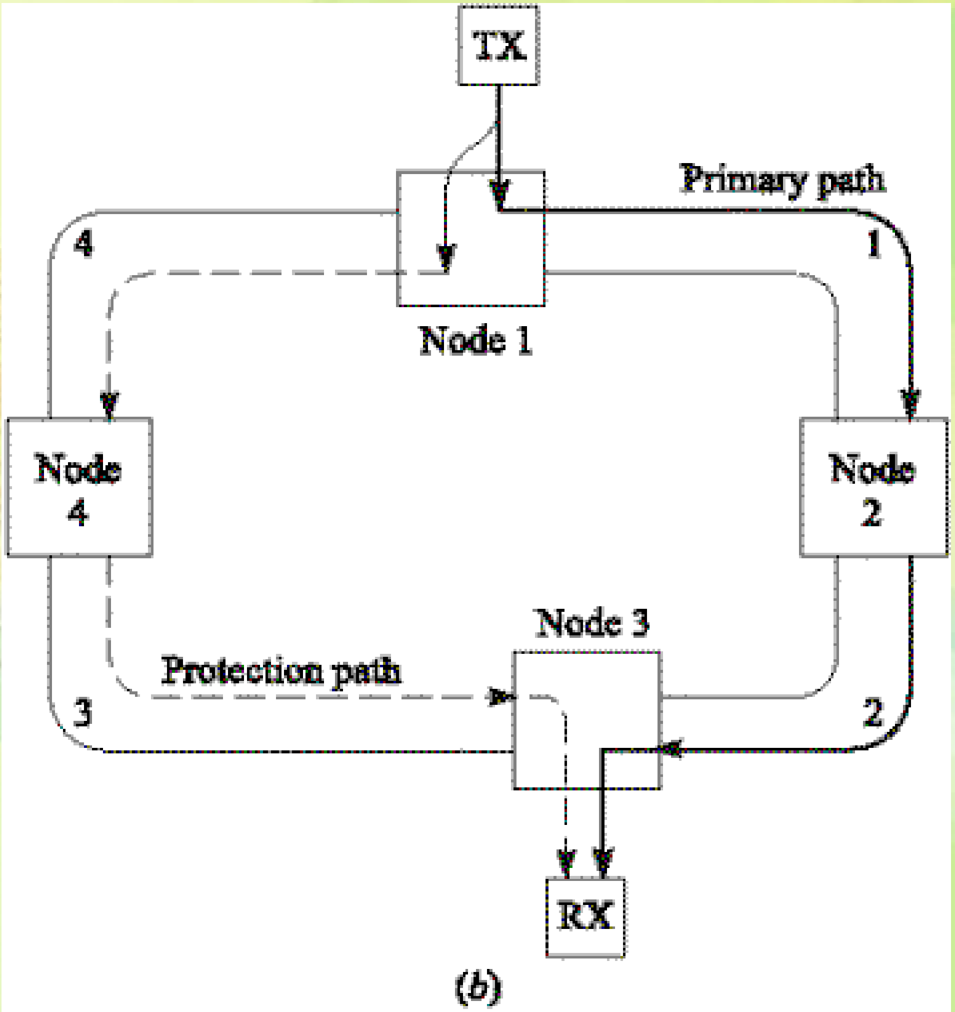
SONET/SDH

SONET level	Electrical level	Line rate (Mb/s)	SDH equivalent
OC-1	STS-1	51.84	-
OC-3	STS-3	155.52	STM-1
OC-12	STS-12	622.08	STM-4
OC-24	STS-24	1244.16	STM-8
OC-48	STS-48	2488.32	STM-16
OC-96	STS-96	4976.64	STM-32
OC-12	STS-192	9953.28	STM-64

SONET/SDH Ring
2-Fiber UPSR (Unidirectional Path Switched Ring)

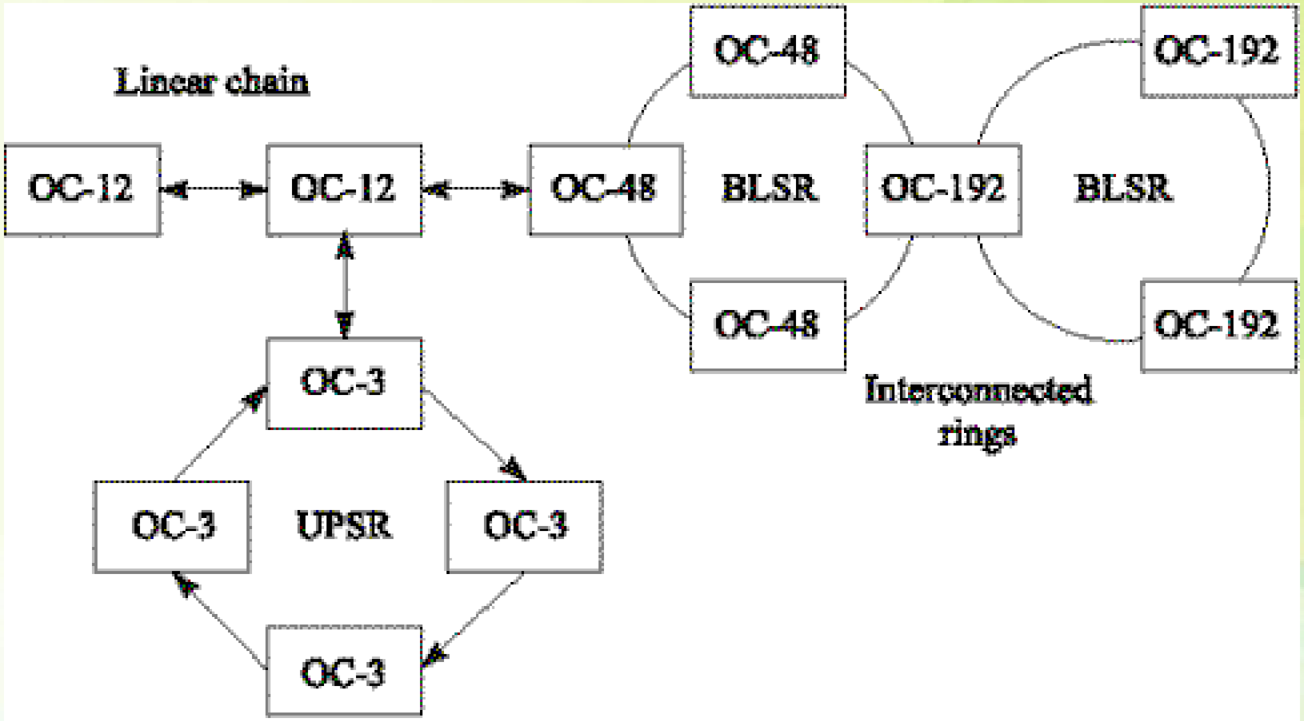


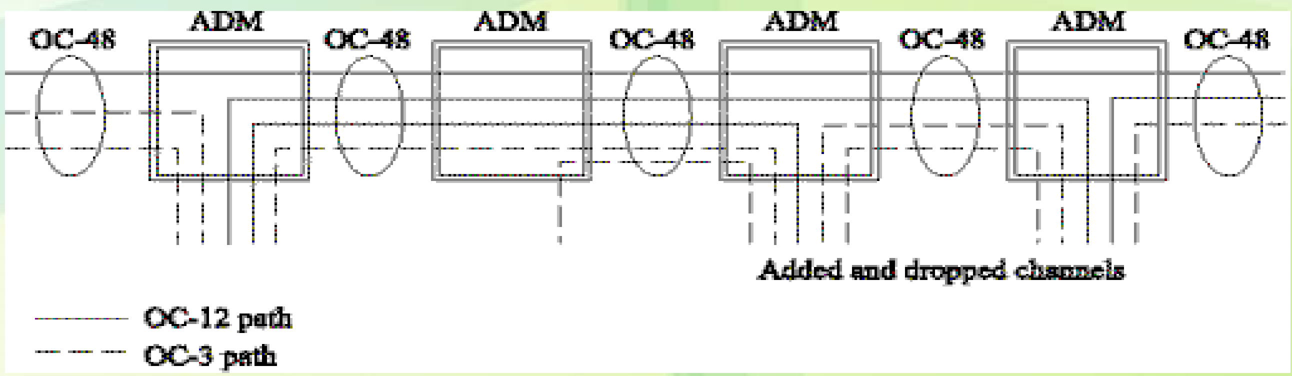
Generic two-fiber unidirectional network with counter-rotating protection path.



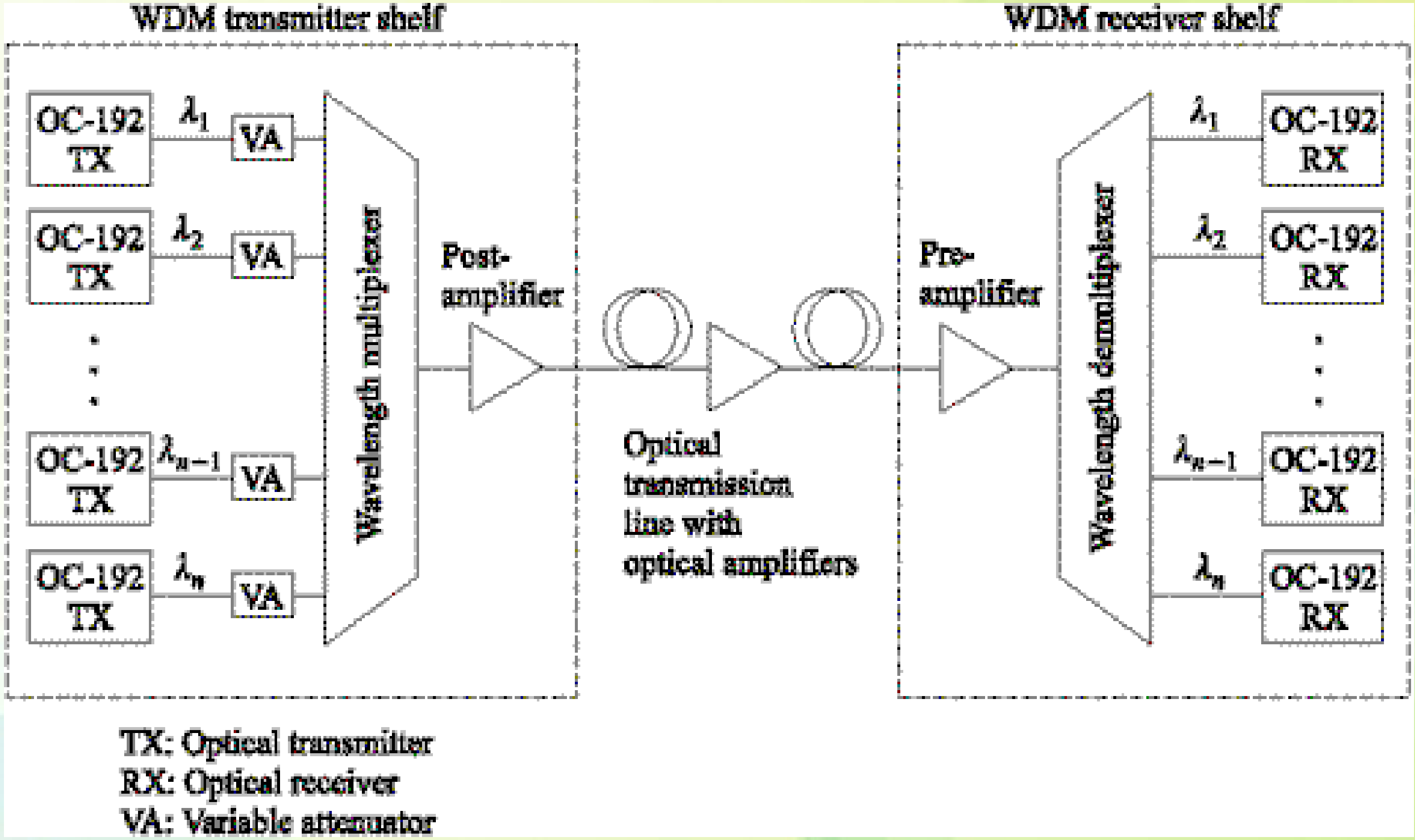
Flow of primary and protection traffic from node 1 to node 3.

SONET/SDH Networks



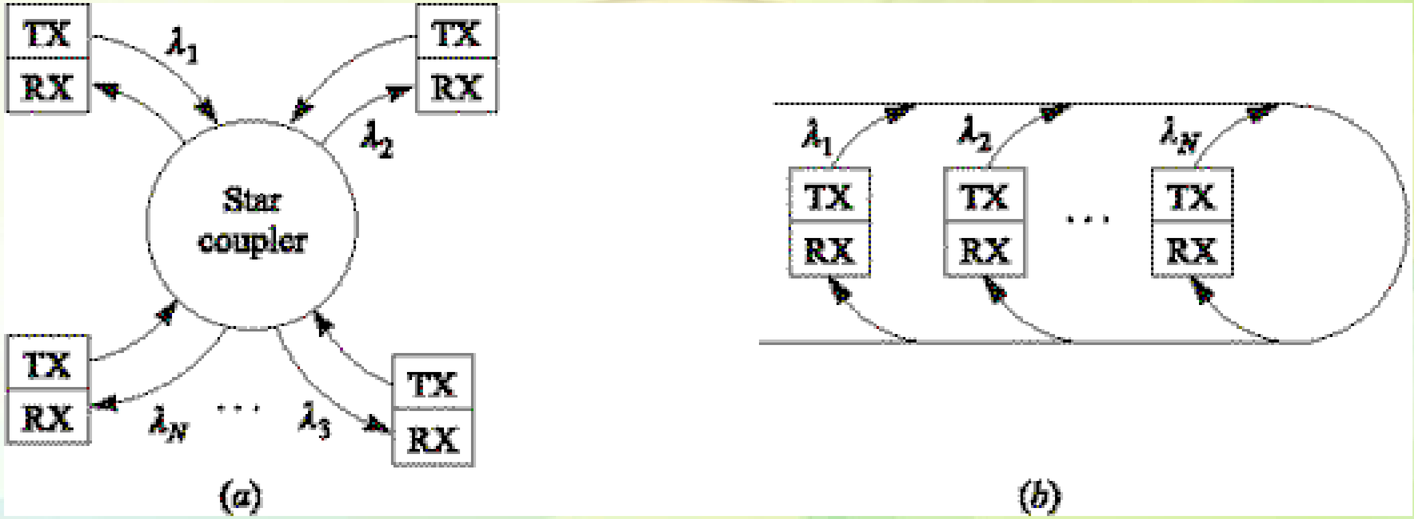


WDM Network



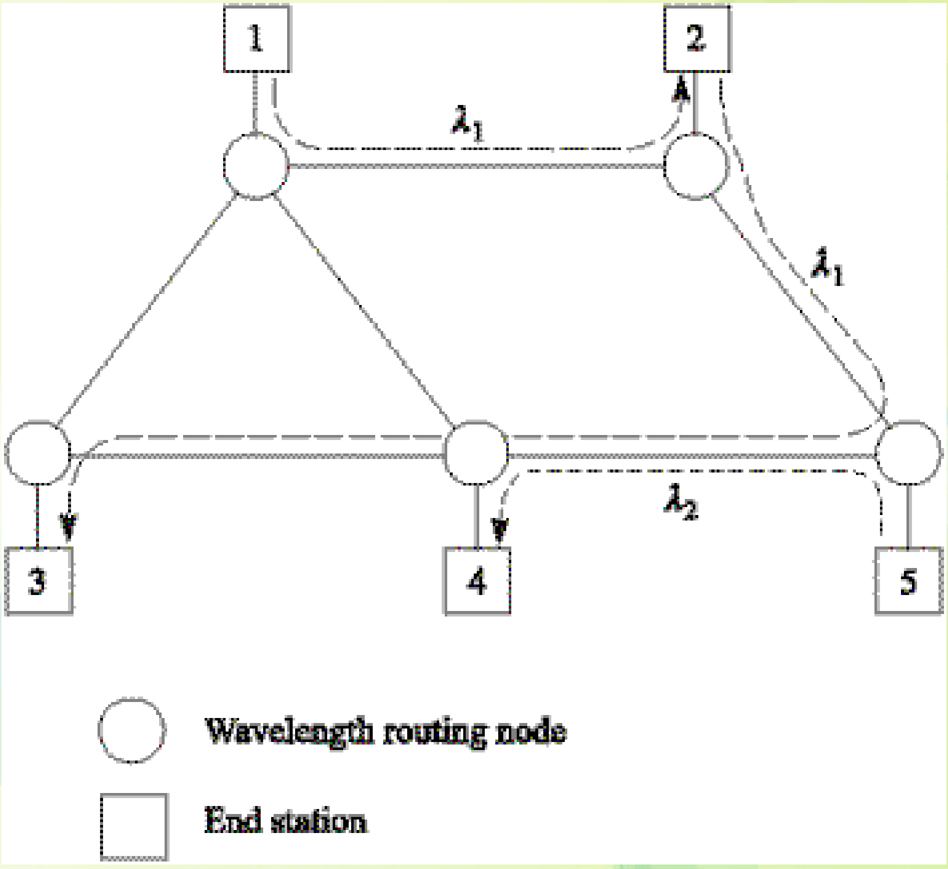
Dense WDM deployment of *n* wavelengths in an OC-192 trunk ring

Broadcast & Select Networks



Two physical architectures for a WDM LAN

Wavelength-Routed Networks
(Wavelength reuse, wavelength conversion & optical switching)



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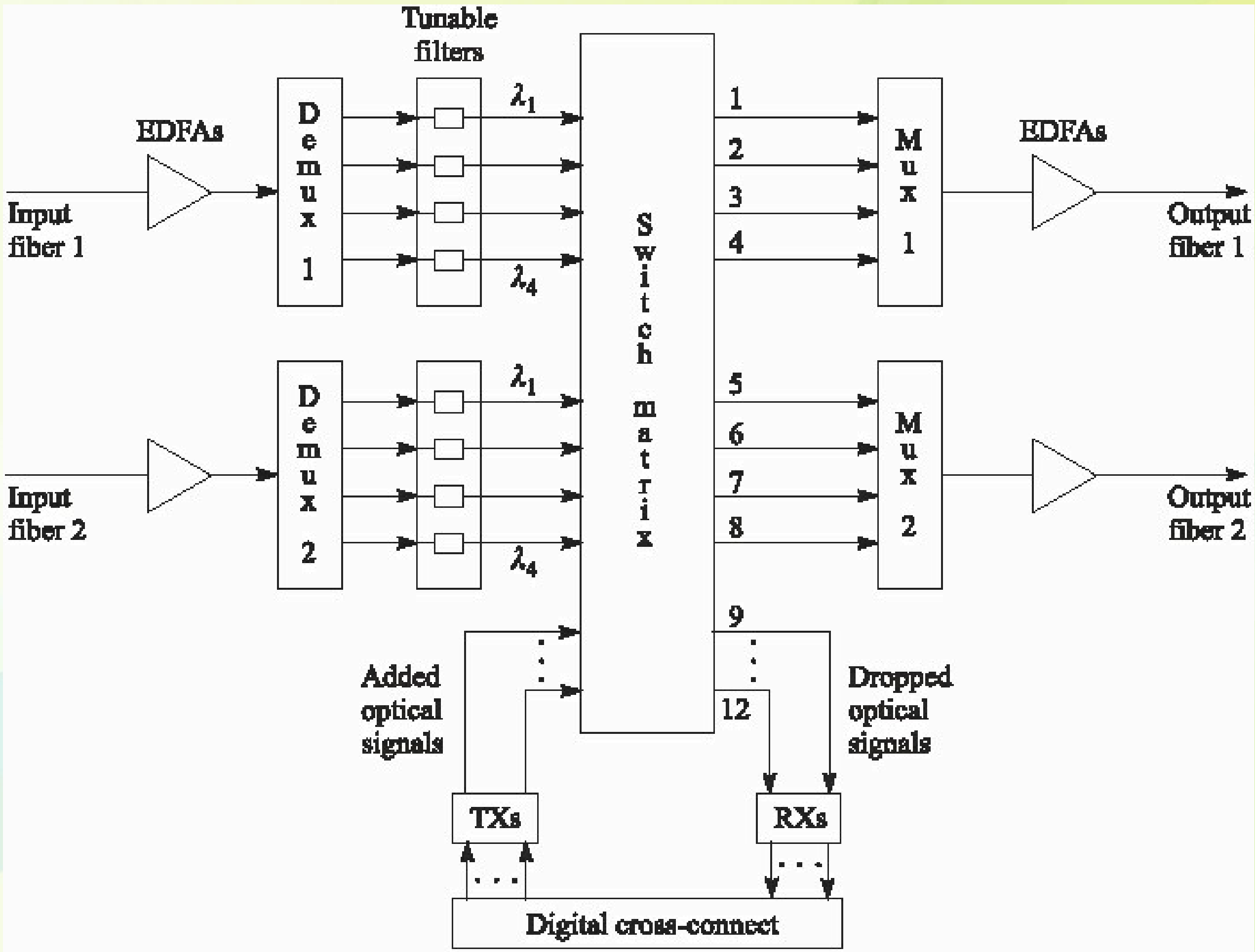
Optical Cross-Connects (OXC)



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Queries ...?