COURSE: *OPTICAL COMMUNICATION* (EC317)

UNIT-III OPTICAL SOURCES

LASER

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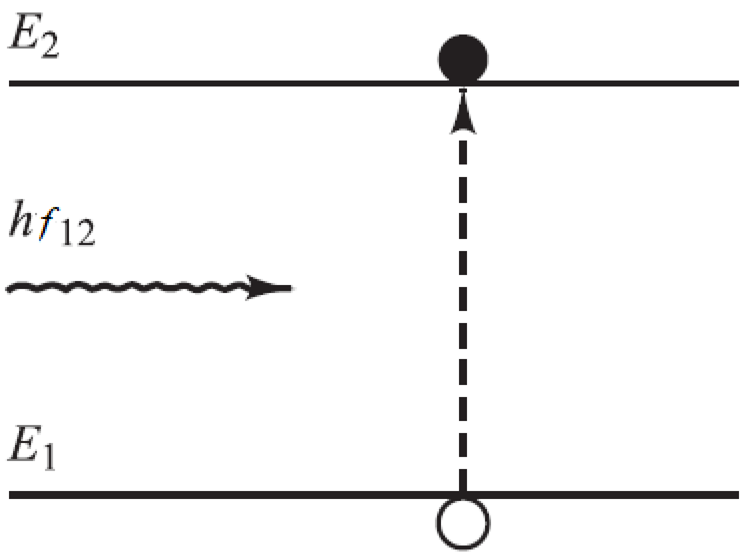
BASIC CONCEPTS (LASER)

- Unlike the LED, the laser is a device which amplifies light –**Light Amplification by Stimulated Emission of Radiation**
- The lasing medium can be a gas, a liquid, an insulating crystal (solid state), or a semiconductor.
- For optical fiber systems, the laser sources are used exclusively semiconductor laser diodes.
- Laser action is the result of three key processes:
  - photon absorption
  - spontaneous emission
  - stimulated emission

Basic concepts (laser): absorption

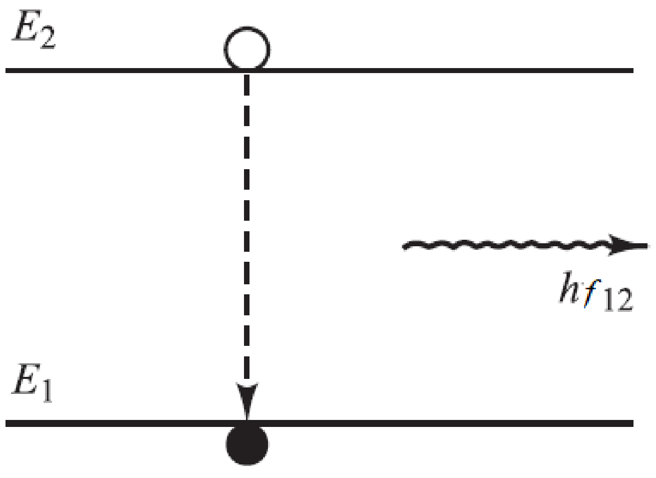
- According to Planck's law, a transition from one state of energy to another involves the absorption and emission of photon (light) of energy $E = E_2 - E_1 = hf$
- When a photon of energy impinges on the system, an electron in the ground state E_1 can absorb the photon energy and be excited to the exited state $E_{2.}$ This phenomenon is called **absorption**.



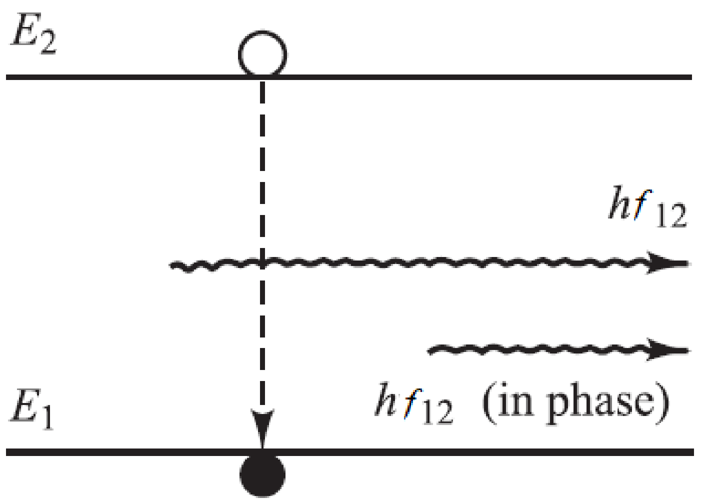
Absorption

BASIC CONCEPTS (LASER): EMISSION

- **Spontaneous emission:**
  - If the atom is in the ground state, with energy E_1, the photon may be absorbed so that it is excited to the upper level of energy E_2. Since this is an unstable state, the electron will shortly return to the ground state, thereby emitting a photon of energy. This is called spontaneous emission
  - entirely random manner and it gives incoherent radiation
- **Stimulated emission:**
  - If the atom is already in the excited state, then the incident photon may stimulate a downward transition with the emission of radiation.
  - Both are in phase and same polarization, therefore coherent radiation is obtained
  - When an atom is stimulated to emit light energy by an incident wave, the liberated energy can add to the wave, providing amplification.



Spontaneous emission



Stimulated emission

BASIC CONCEPTS (LASER):

- In thermal equilibrium, spontaneous emission is the dominant mechanism, that the radiation emitted from optical source in the visible spectrum occurs in a random manner, providing these sources are incoherent.
- In order to produce a coherent optical source and amplification of light beam, the rate of stimulated emission must be increased far above the lower level. This condition is known as **Population Inversion.**
- Population inversion is achieved by various **pumping** techniques (i.e., injecting electrons into the material to fill the lower energy states of the conduction band).

The Einstein relations: Optical amplification in the two-level atomic system

- Let consider N_1 and N_2 are the density of electrons in energy levels E_1 and E_2
- The rate of **absorptive transitions** of electrons from the ground state (level 1) to the excited state (level 2) is directly proportional to the density of electrons in the ground state and the spectral density $\rho(f)$ of the radiation energy at the transition frequency f

$$R_{12} = B_{12} N_1 \rho(f)$$

- The rate of **spontaneous emission** as a result of electron transitions from the excited state to the ground state is directly proportional to the number of electrons in the excited state.

$$R_{21}(spont.) = A_{21} N_2$$

- The rate of **stimulated downward transition** of an electron from level 2 to level 1 may be obtained in a similar manner to the rate of stimulated upward transition.

$$R_{21}(Stimu.) = B_{21} N_2 \rho(f)$$

- For a system in thermal equilibrium, the upward and downward transition rates must be equal and therefore $R_{12} = R_{21}$,

$$B_{12} N_1 \rho(f) = A_{21} N_2 + B_{21} N_2 \rho(f)$$

where the proportionality constants B_{12}, A_{21}, and B_{21} are known as the Einstein coefficients

The spectral density $\rho(f)$ of the radiation energy

$$\rho(f) = \frac{\frac{A_{21}}{B_{21}}}{\frac{B_{12}N_1}{B_{21}N_2} - 1}$$

We know that

$$\frac{N_1}{N_2} = e^{\frac{hf}{kT}}$$

$$\rho(f) = \frac{8\pi hf^3}{c^3} \frac{1}{e^{\frac{hf}{kT}} - 1}$$

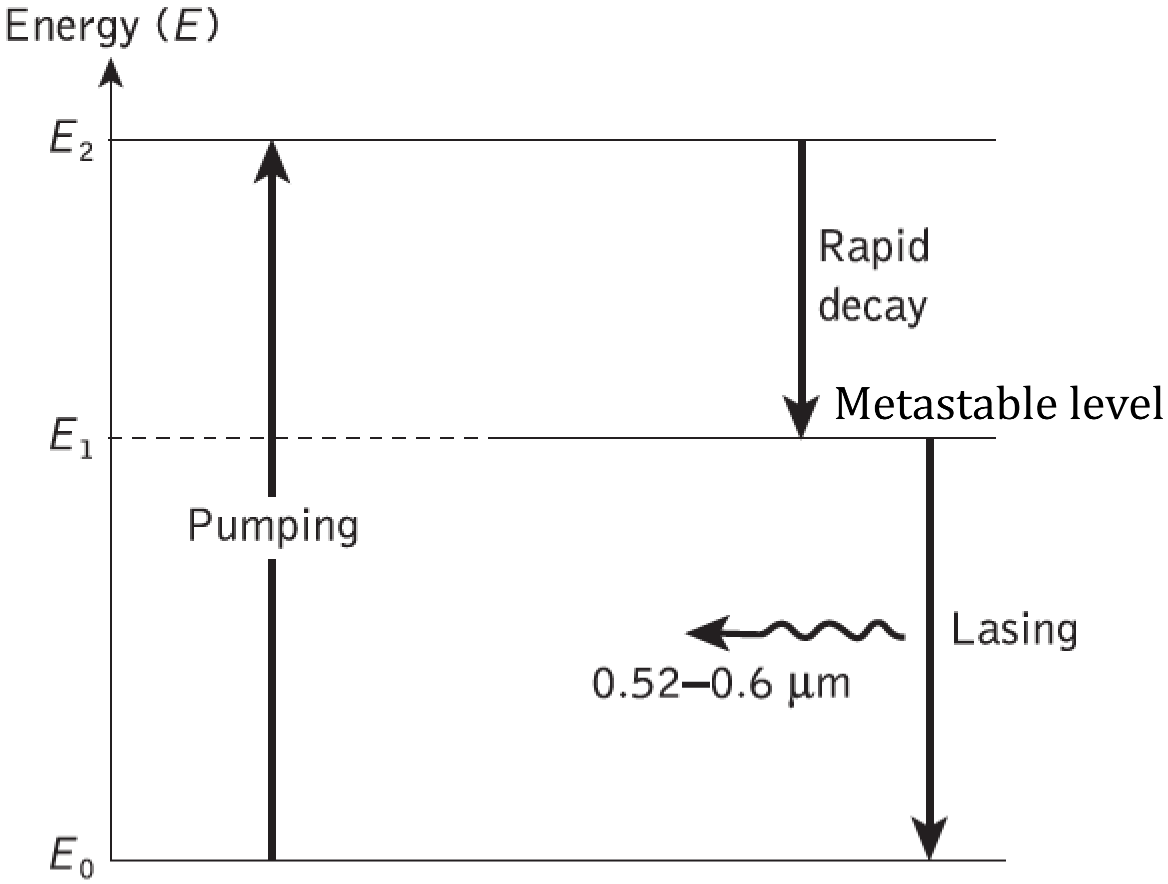
Where $\frac{A_{21}}{B_{21}} = \frac{8\pi hf^3}{c^3}$ and $B_{12} = B_{21}$;

- The ratio of the stimulated emission rate to the spontaneous emission rate is given by

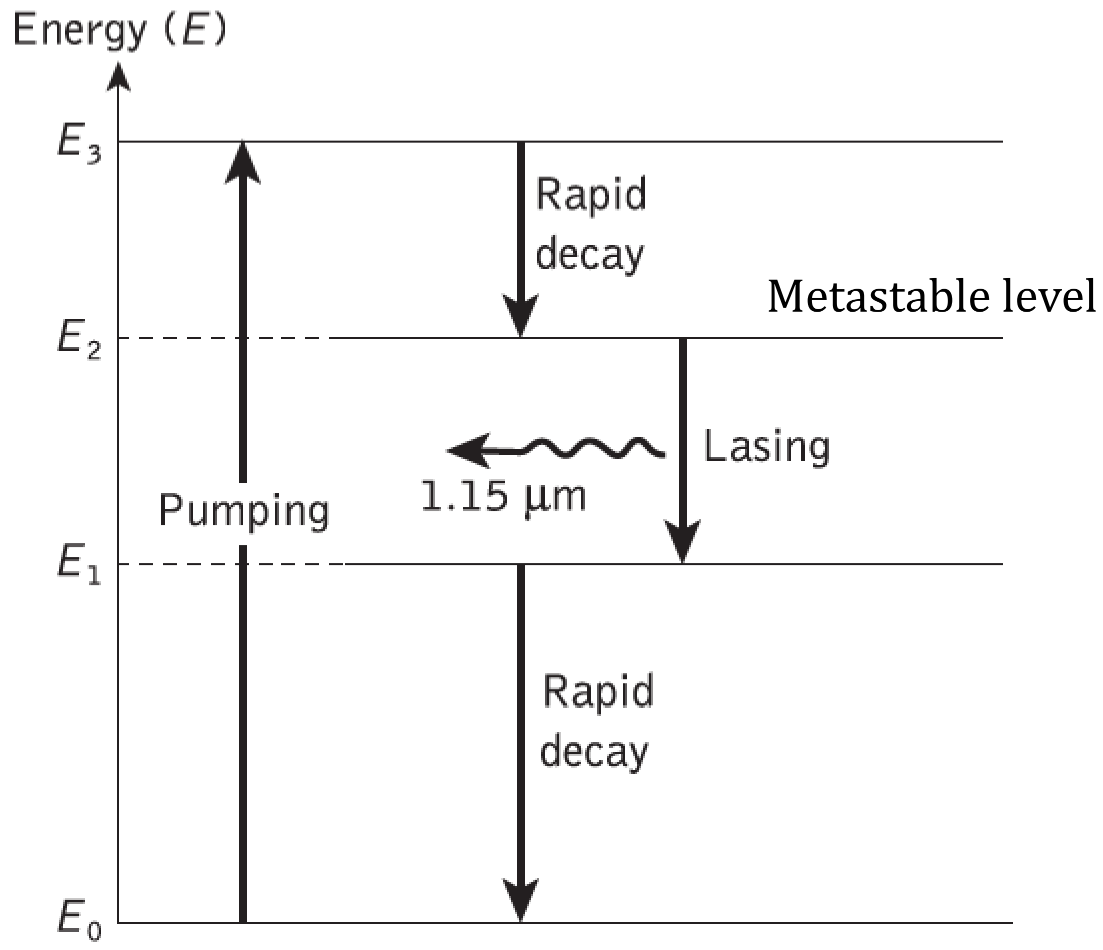
$$\frac{B_{21}\rho(f)}{A_{21}} = \frac{1}{e^{\frac{hf}{kT}} - 1}$$

POPULATION INVERSION

- In order to produce stimulated emission, it is essential to create a non-equilibrium situation in which the population of atoms in the upper energy level is greater than that in the lower energy level, that is, $N_2 > N_1$. This non-equilibrium condition is called **population inversion**.
- In order to achieve population inversion it is necessary to excite atoms into the upper energy level E_2 and hence obtain a nonequilibrium distribution. This process is achieved using an external energy source and is referred to as '**pumping**'.
- In a two-level atomic system that is pumped externally, stimulated emission cannot become a dominant process because it has to compete with stimulated absorption
- either three-level or four-level atomic systems are used for achieving laser action (population inversion)

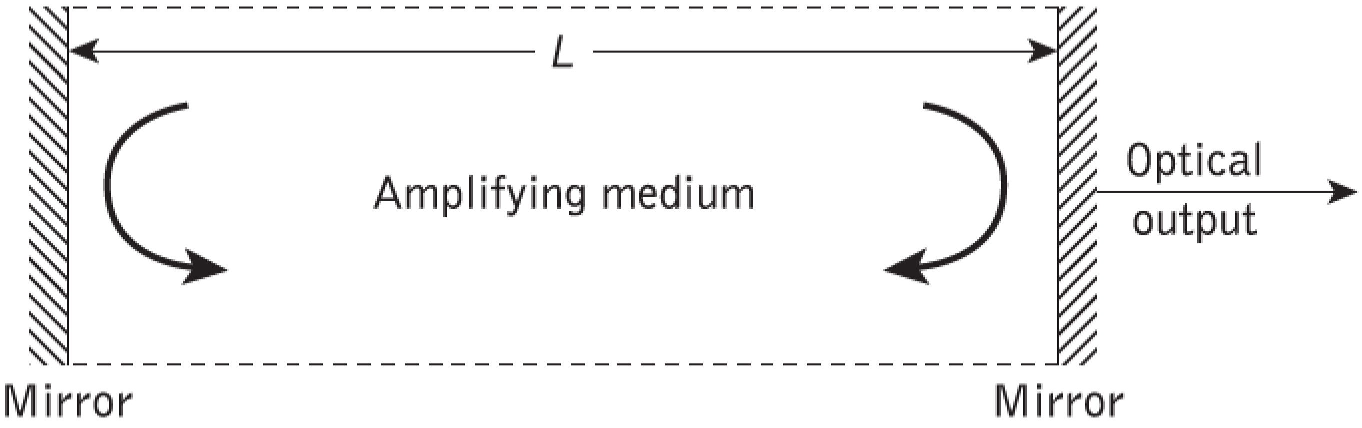


- The metastable level E_1 exhibits a much longer lifetime than E_2 which allows a large number of atoms to accumulate at E_1.
- Over a period the density of atoms in the metastable state N_1 increases above those in the ground state N_0 and a population inversion is obtained between these two levels.
- Stimulated emission and hence lasing can then occur, creating radiative electron transitions between levels E_1 and E_0.


Energy (E)
E3
E2
E1
E0
Rapid
decay
Metastable level
Lasing
1.15 µm
Pumping
Rapid
decay

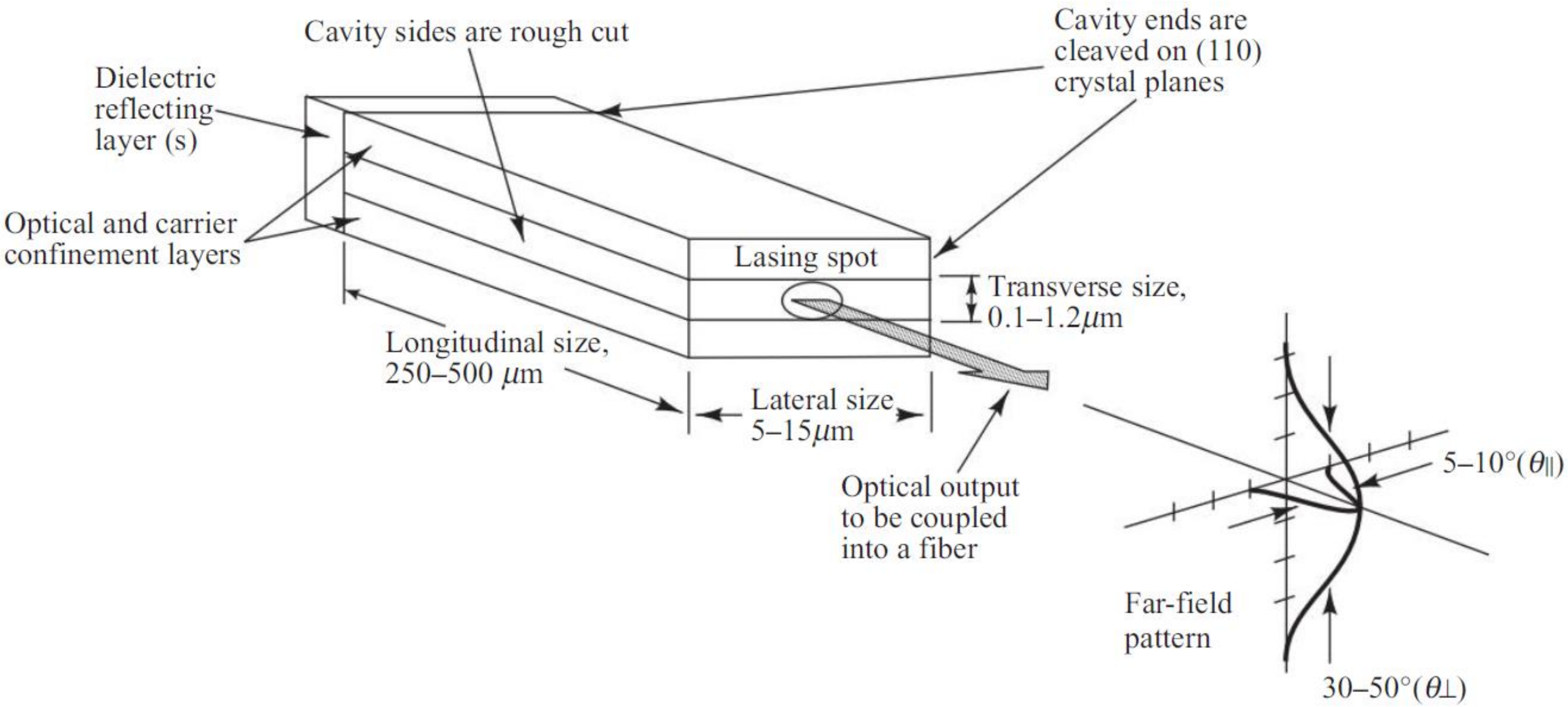
OPTICAL FEEDBACK AND LASER OSCILLATION

- Light amplification in the laser occurs when a photon colliding with an atom in the excited energy state causes the stimulated emission of a second photon and then both these photons release two more and so on (avalanche multiplication), and when the electromagnetic waves associated with these photons are in phase, amplified coherent emission is obtained.
- To achieve this laser action it is necessary to **place or form mirrors** (plane or curved) at either end of the amplifying medium.



OPTICAL FEEDBACK AND LASER OSCILLATION

- The positive feedback of the photons by reflection at the mirrors at either end of the cavity gives an oscillatory condition than an amplifier (optical cavity). This structure is called a **Fabry– Pérot resonator**.
- If one mirror is made partially transmitting, useful radiation may escape from the cavity.
- A stable output is obtained at saturation when the **optical gain is exactly matched by the losses** incurred in the amplifying medium.
- The major losses result from factors such as absorption and scattering in the amplifying medium, absorption, scattering and diffraction at the mirrors and non-useful transmission through the mirrors.
- Oscillations occur in the laser cavity over a small range of frequencies where the cavity gain is sufficient to overcome the above losses.



Fabry-Perot resonator cavity for a LASER diode

Threshold condition for Lasing action

- Lasing occurs when the gain of one or several guided modes is sufficient to exceed the optical loss during one roundtrip (z = 2L) through the cavity.
- During this roundtrip, only the fractions R_1 and R_2 of the optical radiation are reflected from the two laser ends 1 and 2, respectively
- On each round trip the beam passes through the medium twice. Hence the fractional loss incurred by the light beam is: $R_1 R_2 e^{-2\alpha L}$
- If the gain coefficient per unit length produced by stimulated emission is g cm^{-1}, the fractional round trip gain is given by: e^{2gL}
- The optical field intensity

$$I(2L) = I(0) R_1 R_2 e^{2(g-\alpha)L}$$

At the lasing threshold

$$R_1 R_2 e^{2(g_{th}-\alpha)L} = 1$$

$$g_{th} = \alpha + \frac{1}{2L} \ln \frac{1}{R_1 R_2}$$

Resonant Frequencies and laser modes

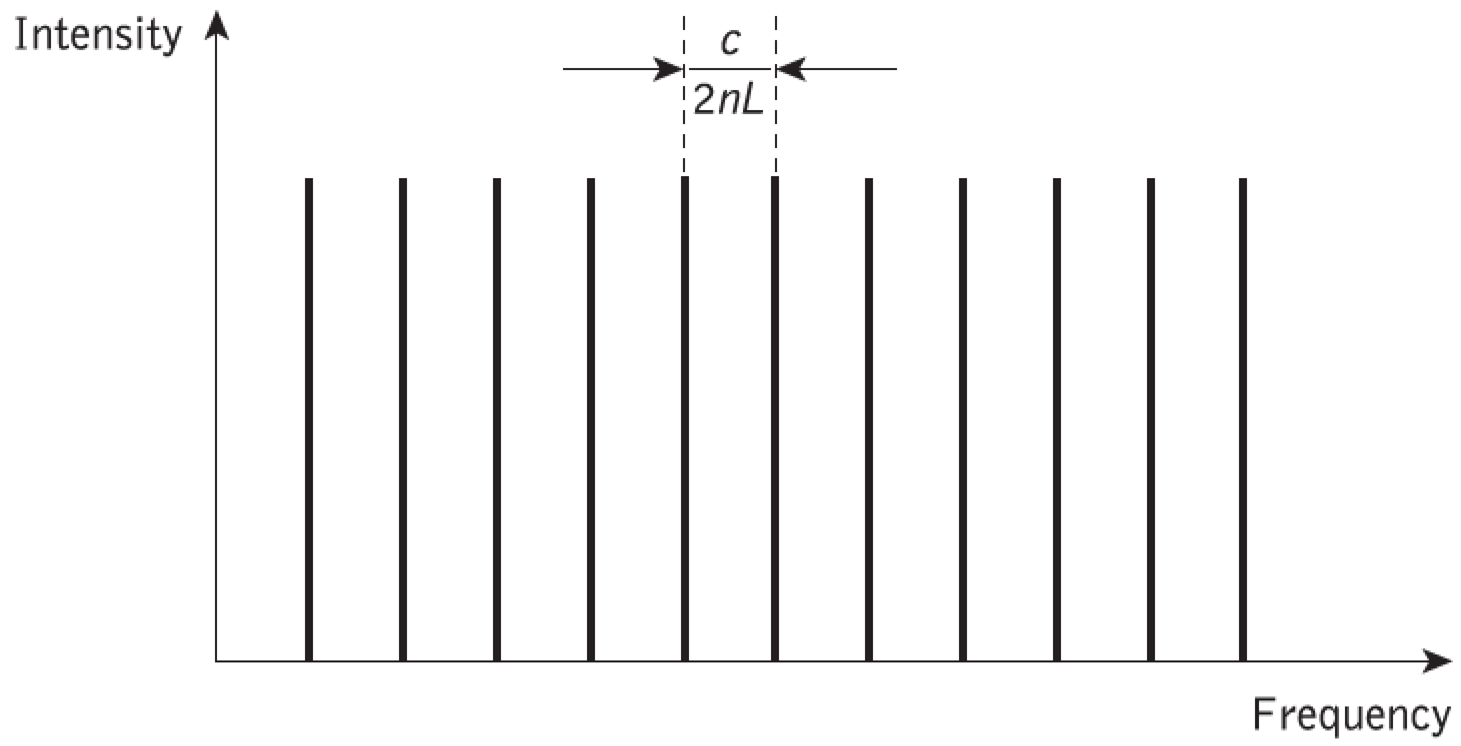
- When sufficient population inversion exists in the amplifying medium, the radiation builds up and becomes established as standing waves between the mirrors.
- These standing waves exist only at frequencies for which the distance between the mirrors is an integral number of half wavelengths. Thus when the optical spacing between the mirrors is *L*, the resonance condition along the axis of the cavity is

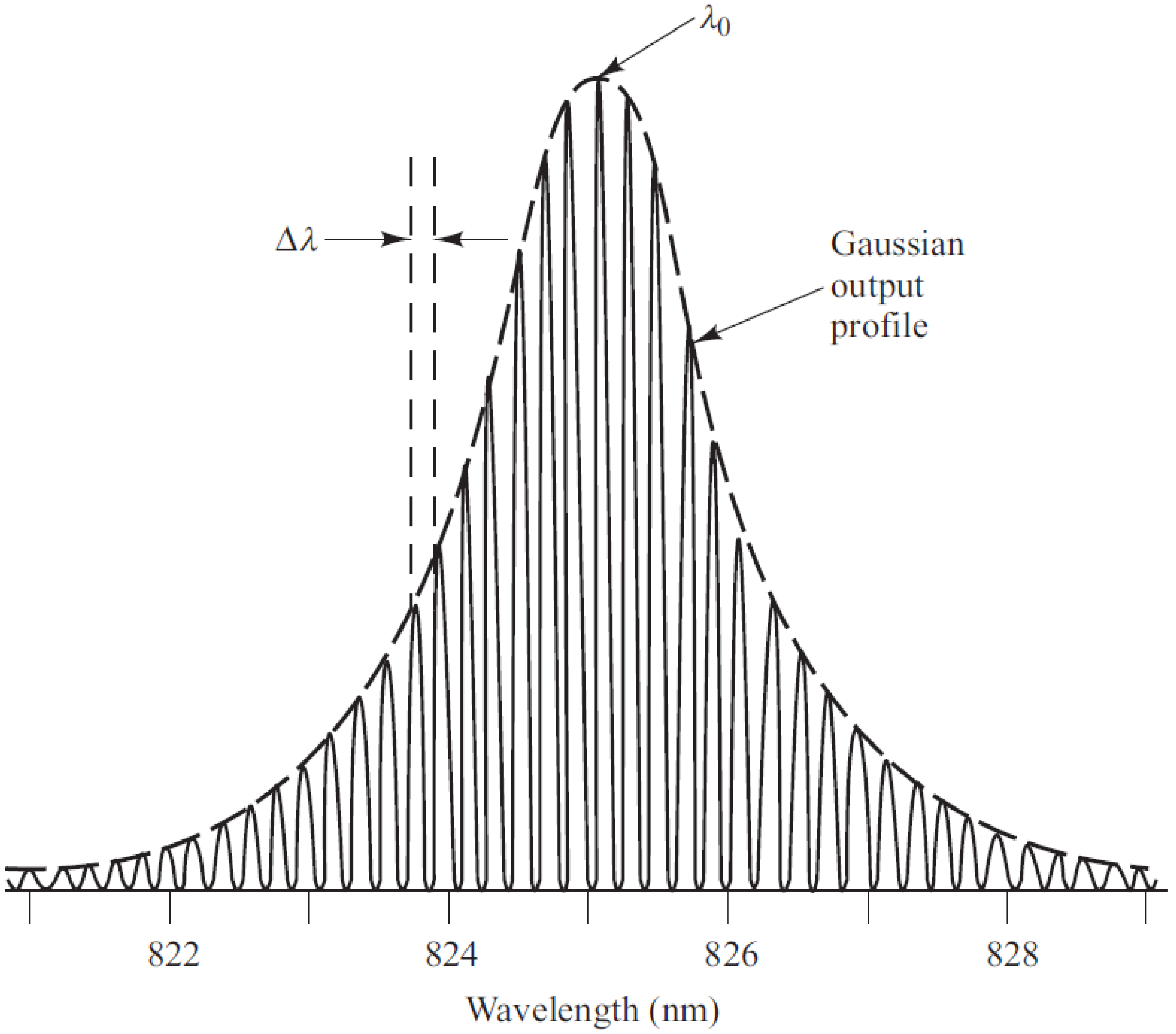
$$L = \frac{m\lambda}{2n}$$

- where λ is the emission wavelength, *n* is the refractive index of the amplifying medium and *m* is an integer.

$$f = \frac{mc}{2nL}$$

- The different frequencies of oscillation within the laser cavity are determined by the various integer values of *m* and each constitutes a resonance or mode.
- The modes are separated by a frequency interval $\delta f = \frac{c}{2nL}$ or $\delta\lambda = \frac{\lambda^2}{2nL}$


Intensity
$\frac{c}{2nL}$
Frequency

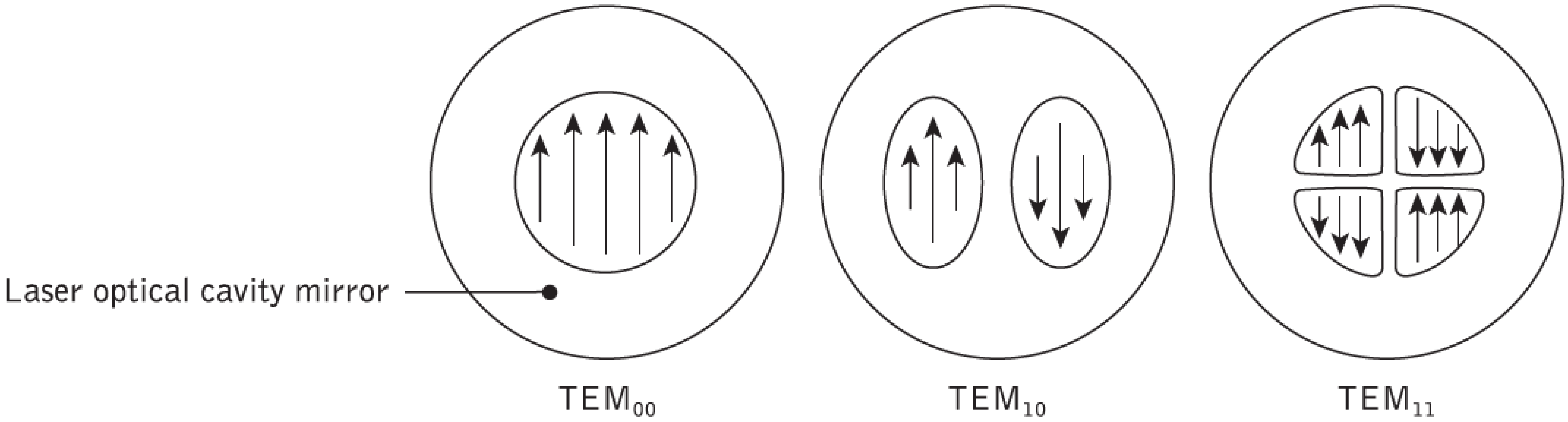


λ_0
$\Delta\lambda$
Gaussian
output
profile
822
824
826
828
Wavelength (nm)

Modes in Laser

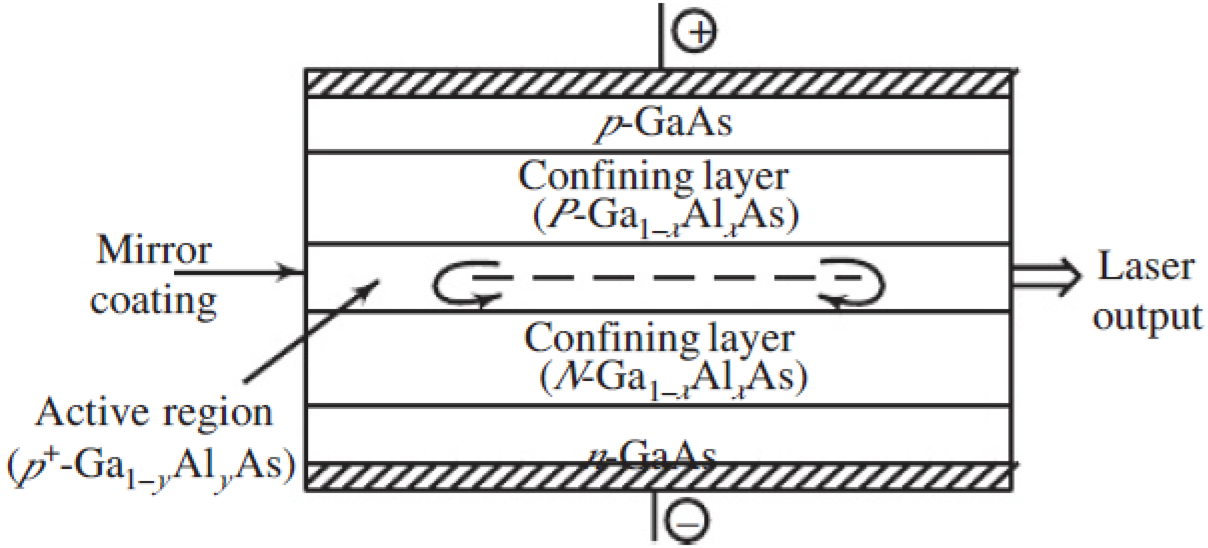
- The optical radiation within the resonance cavity of a laser diode sets up a pattern of electric and magnetic field lines called the modes of the cavity (sets of TE and TM modes).
- Each set of modes can be described in terms of the longitudinal, lateral, and transverse half-sinusoidal variations of the electromagnetic fields along the major axes of the cavity.
- The **longitudinal modes** are related to the **length of the cavity L** and determine the principal structure of the **frequency spectrum of the emitted optical radiation**. Since L is much larger than the lasing wavelength of approximately 1 mm, many longitudinal modes can exist.
- **Lateral modes** lie in the plane of the pn junction. These modes depend **on the side wall preparation and the width of the cavity**, and determine the **shape of the lateral profile of the laser beam**.
- **Transverse modes** are associated with the **electromagnetic field and beam profile in the direction perpendicular to the plane** of the pn junction. These modes are of great importance as they largely determine such **laser characteristics as the radiation and the threshold current density**.

- As the laser output consists of several modes is called a multimode laser. All these axial modes contribute to a single ‘**spot**’ of light in the output.
- The resonant modes may be formed in a direction transverse to the axis of the cavity. These are called transverse electromagnetic (TEM) modes e.g., TEM_{lm}. Here, *l* and *m* give the number of minima as the output beam is scanned horizontally and vertically, respectively



LASER STRUCTURE

- Basic requirements for efficient operation of laser diodes
  - transverse optical confinement and carrier confinement between heterojunction layers,
  - the current flow must be restricted laterally to a narrow stripe along the length of the laser.



HETEROSTRUCTURE LASER DIODES

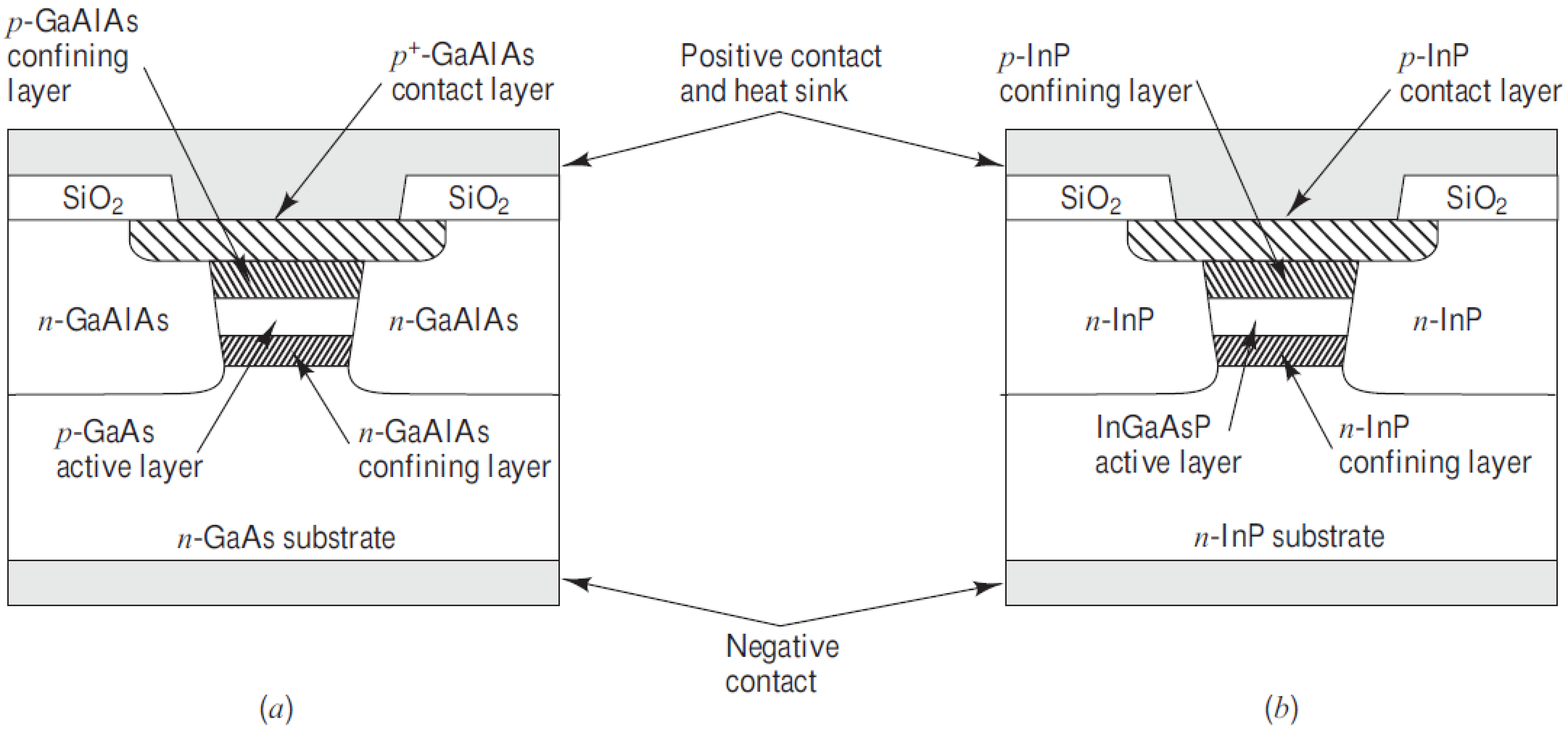
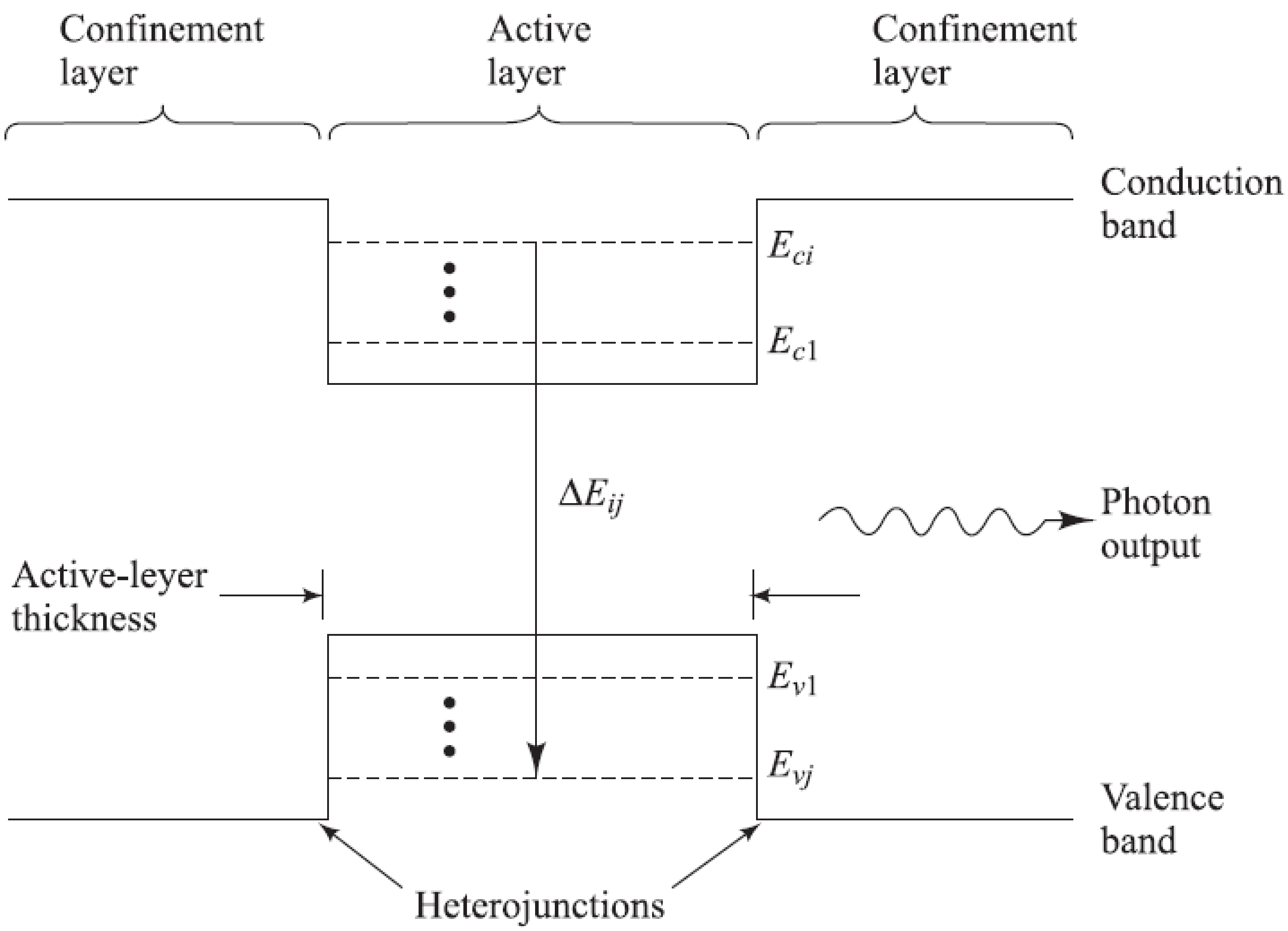
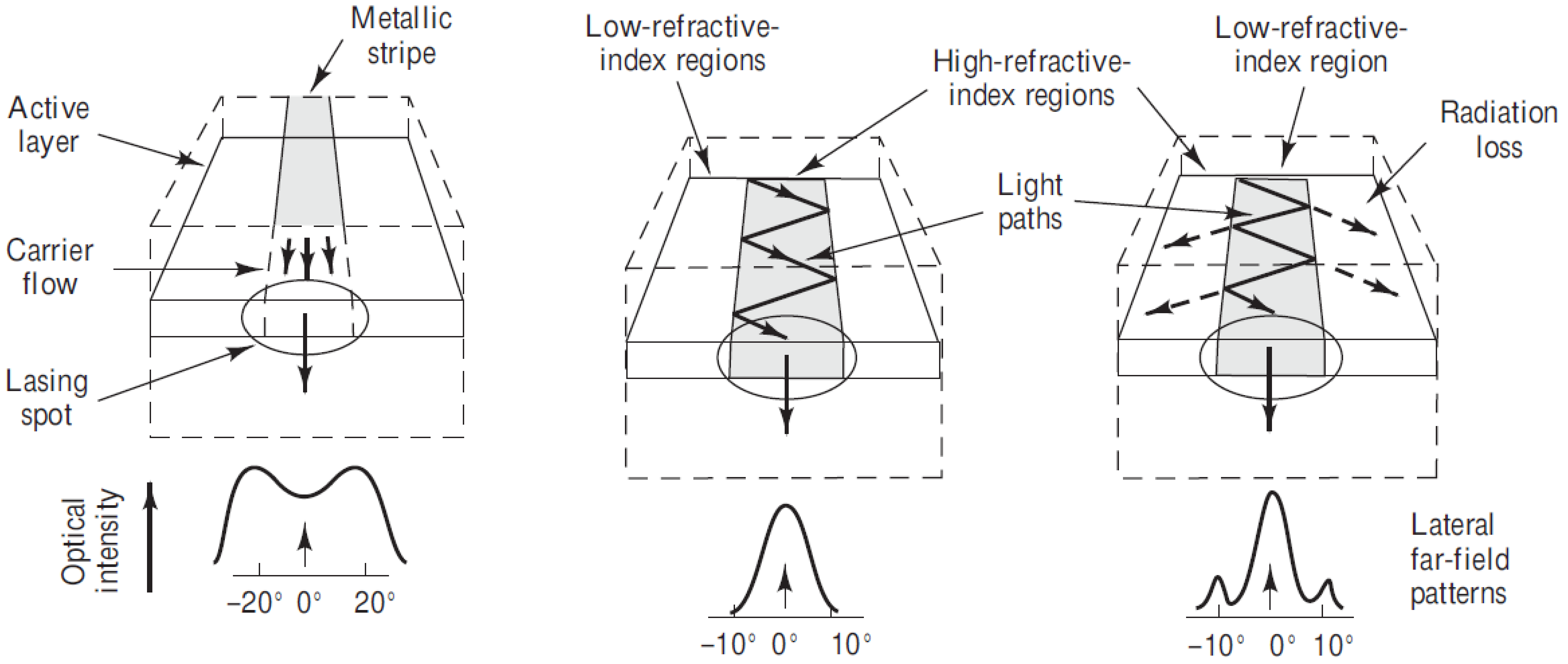


Fig: (a) Short-wavelength (800–900 nm) GaAlAs and (b) long-wavelength (1300–1600 nm) InGaAsP


Confinement layer
Active layer
Confinement layer
Conduction band
E_{ci}
E_{c1}
ΔE_{ij}
Photon output
Active-leyer thickness
E_{v1}
E_{vj}
Valence band
Heterojunctions



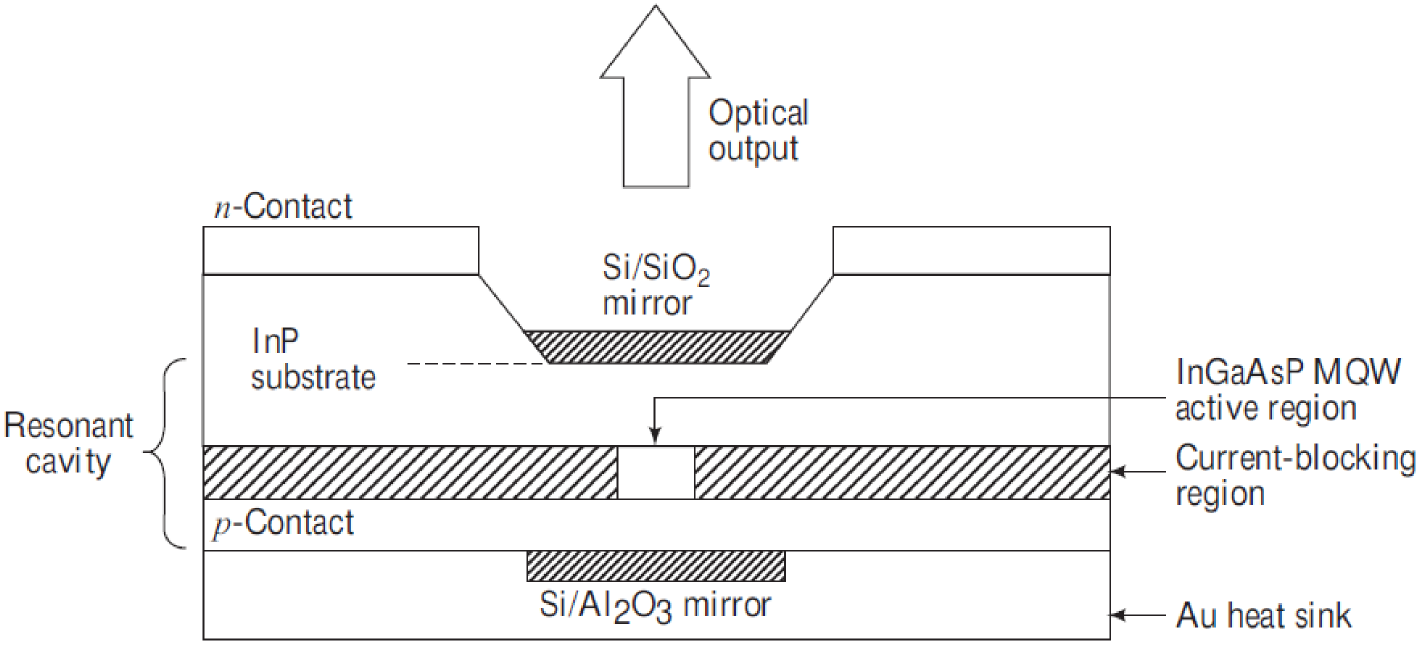
(a) in the gain-induced guide, electrons injected via a metallic stripe contact alter the index of refraction of the active layer;

(b) the positive index waveguide has a higher refractive index in the central portion of the active region;

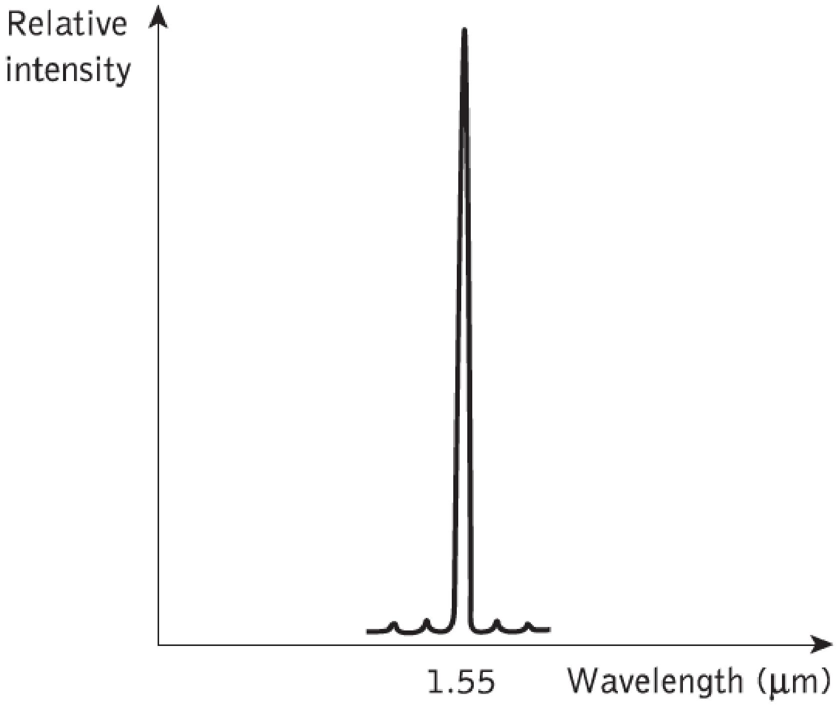
(c) the negative index waveguide has a lower refractive index in the central portion of the active region.

SINGLE-MODE LASERS

- For high-speed long-distance communications one needs single-mode lasers, which must
  - contain only a single longitudinal mode and a single transverse mode.
  - the spectral width of the optical emission is very narrow.
- Method to achieve single longitudinal mode:
  - to reduce the length L of the lasing cavity to the point where the frequency separation of the adjacent modes is larger than the laser transition line width;
- For example, consider a Fabry-Perot cavity,
  - all longitudinal modes have nearly equal losses and are spaced by about 1 nm in a 250-mm-long cavity at 1300 nm.
  - By reducing L from 250 mm to 25 mm, the mode spacing increases from 1 nm to 10 nm. However, these lengths make the device hard to handle, and they are limited to optical output powers of only a few milliwatts



Basic architecture of a vertical-cavity surface-emitting laser (VCSEL)



- Light emission is perpendicular to the semiconductor surface
- The active-region volume of these devices is very small, which leads to very low threshold currents (< 100 mA).

External quantum efficiency

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

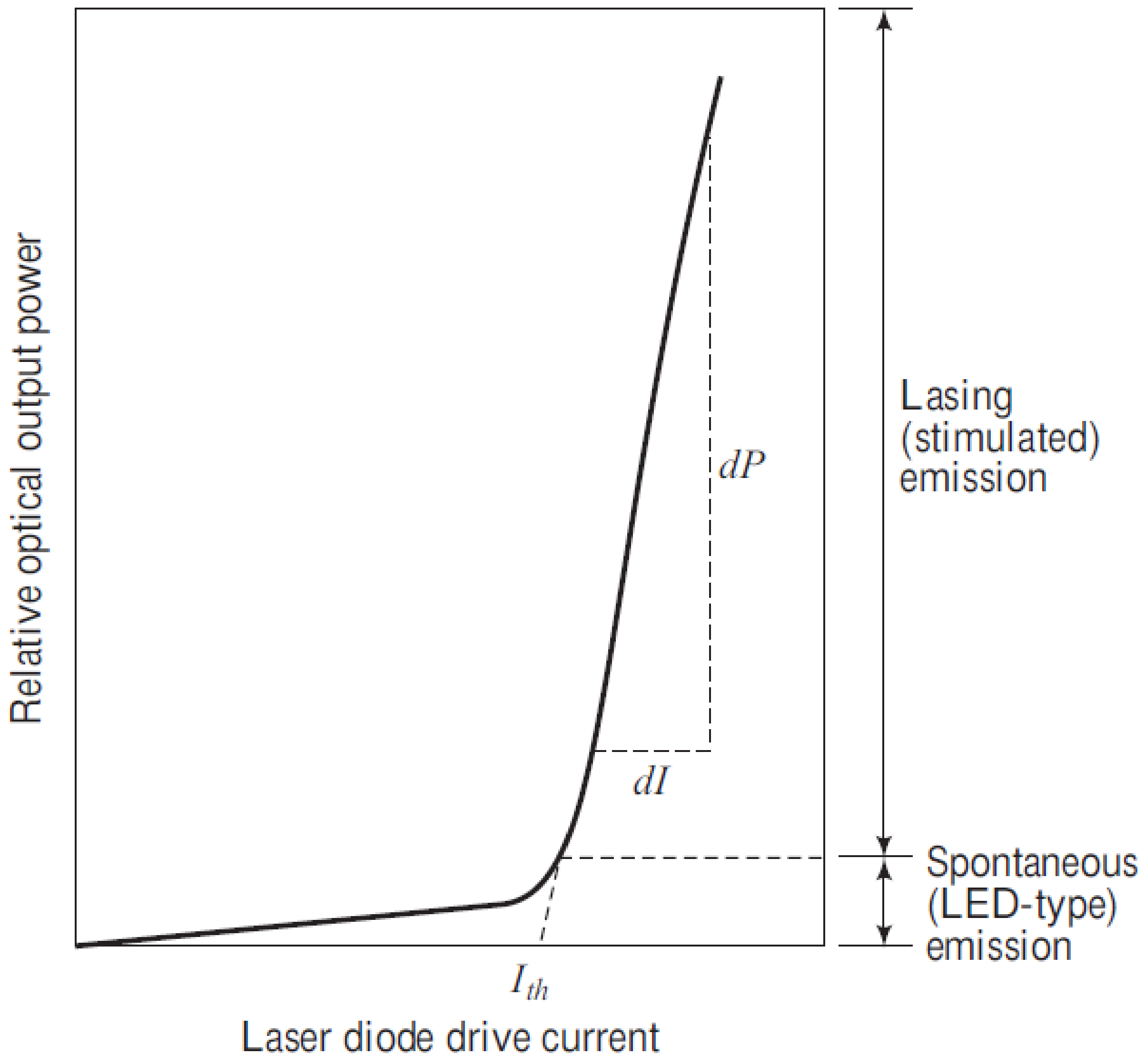
$$\eta_{ext} = \eta_{int} \frac{g_{th} - \alpha}{g_{th}}$$

- Typical values:

$$\eta_{int} \approx 60\ to\ 70\%; \qquad \eta_{ext} \approx 15\ to\ 40\%$$

- Experimentally, η_{ext} is calculated from the straight-line portion of the curve for the emitted optical power P versus drive current I

$$\eta_{ext} = \frac{q}{E_g} \frac{dP}{dI} = 0.8065\, \lambda\, (\mu m) \frac{dP\ (mW)}{dI\ (mA)}$$

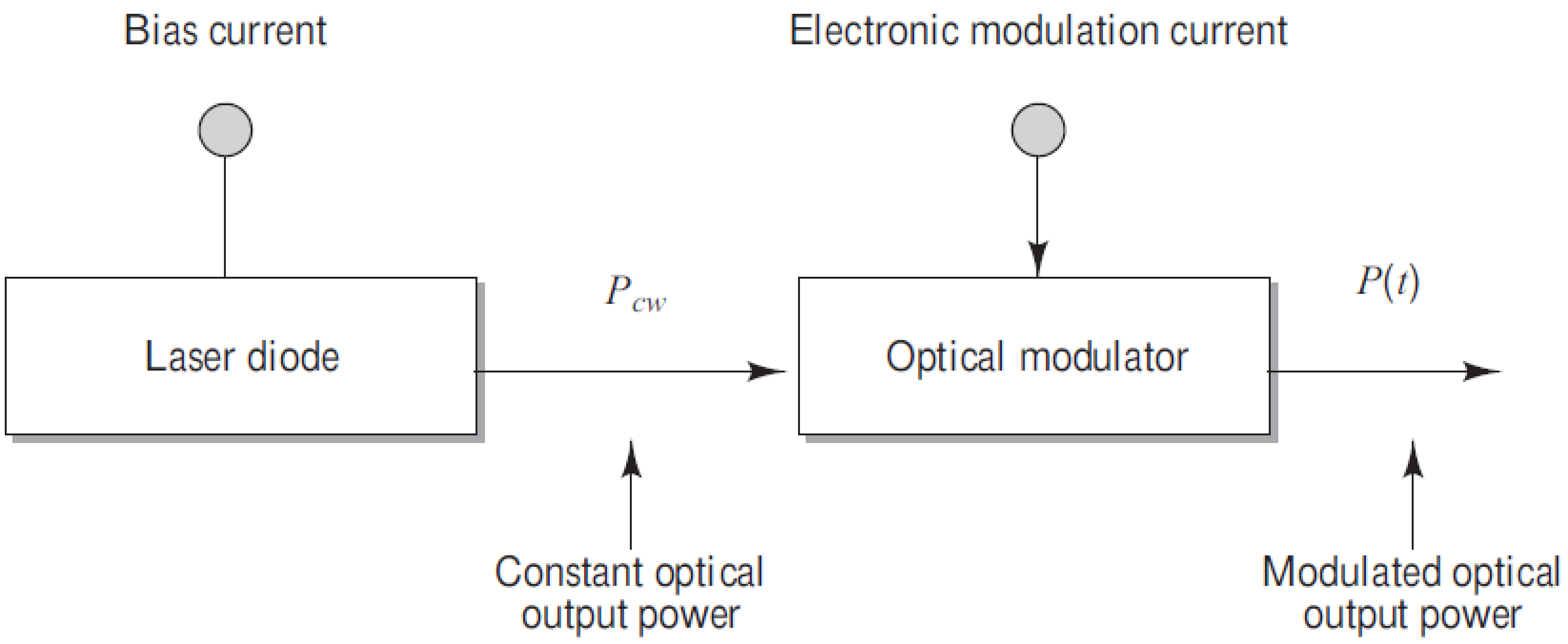

Relative optical output power
dP
dI
I_{th}
Laser diode drive current
Lasing
(stimulated)
emission
Spontaneous
(LED-type)
emission

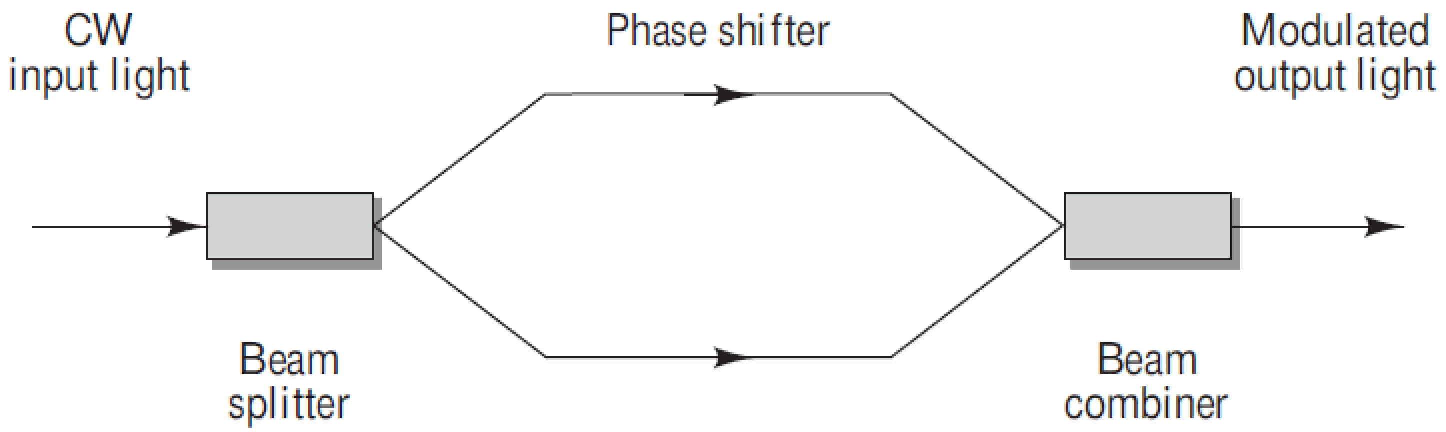
Modulation of Laser Diodes

- The process of putting information onto a light wave is called modulation.
- For data rates of less than approximately 10 Gb/s (typically 2.5 Gb/s), the process of imposing information on a laser-emitted light stream can be realized by **direct modulation**. This involves directly varying the laser drive current with the **electrically formatted information stream to produce a correspondingly varying optical output power**.
- The basic limitation on the direct modulation rate of laser diodes depends on the spontaneous and stimulated emission carrier lifetimes and the photon lifetime.
- When direct modulation is used in a laser transmitter, the process of turning the laser on and off with an electrical drive current produces a widening of the laser linewidth. This phenomenon is referred to as chirp and makes directly modulated lasers undesirable for operation at data rates greater than about 2.5 Gb/s.

Modulation of Laser Diodes

- For higher data rates one needs to use a device called an **external modulator** to temporally modify a steady optical power level emitted by the laser.
- A variety of external modulators are available commercially either as a separate device or as an integral part of the laser transmitter package.




CW
input light
Phase shifter
Modulated
output light
Beam
splitter
Beam
combiner

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 (PROBLEMS)

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Problem 1

An engineer has two $Ga_{1-x}Al_xAs$ LEDs: one has a bandgap energy of 1.540 eV and the other has x = 0.015.

(a) Find the aluminum mole fraction x and the emission wavelength for the first LED.

(b) Find the bandgap energy and the emission wavelength of the other LED.

Sol:

For LED1: E_g = 1.54 eV

For LED2; x = 0.015

(a)

$$E_g = 1.424 + 1.266\,x + 0.266\,x^2 = 1.54$$
$$x = 0.09$$

Emission wavelength $\lambda = \frac{hc}{E_g} = \frac{1.24}{1.54}\mu m = 805.2\, nm$

(a)

$$E_g = 1.424 + 1.266\,x + 0.266\,x^2$$
$$= 1.424 + 1.266\,(0.015) + 0.266\,(0.015)^2 = 1.62$$

Emission wavelength $\lambda = \frac{hc}{E_g} = \frac{1.24}{1.62}\mu m = 765.4\, nm$

PROBLEM 2

A double-heterojunction InGaAsP LED emitting at a peak wavelength of 1310 nm has radiative and nonradiative recombination times of 25 and 90 ns, respectively. The drive current is 35 mA.

(a) Find the internal quantum efficiency and the internal power level.

(b) If the refractive index of the light source material is n = 3.5, find the power emitted from the device.

Sol:

(a) the internal quantum efficiency

$$\eta_{int} = \frac{1}{1+\frac{\tau_{rr}}{\tau_{nr}}} = \frac{1}{1+\frac{25}{90}} = 0.783$$

the internal power level $P_{int} = \frac{\eta_{int} I}{q}\frac{hc}{\lambda}$

(b) LED emitted power $P_{ext} = \eta_{ext}\, P_{int} = \frac{\mathbf{1}}{\boldsymbol{n_s}\,(\boldsymbol{n_s}+\mathbf{1})^{\mathbf{2}}} P_{int}$

PROBLEM 3

A GaAs laser emitting at 800 nm has a 400 mm cavity length with a refractive index n = 3.6. If the gain g exceeds the total loss throughout the range 750 nm < λ < 850 nm, how many modes will exist in the laser?

Sol:

Given that λ = 800 nm; L = 400 mm; n = 3.6

The total number of modes $m = \frac{2nL}{\lambda} = \frac{2\times3.6\times400\times10^{-3}}{800\times10^{-9}} = 3.6 \times 10^6$

The number of modes within the range is

$$m_g = \frac{850 - 750}{\Delta\lambda}$$

Where the mode spacing $\delta\lambda = \frac{\lambda^2}{2nL} = 0.22\ nm; m_g \approx 455$

PROBLEM 4

(a) A GaAlAs laser diode has a 500-mm cavity length, which has an effective absorption coefficient of 10 cm^{-1}. For uncoated facets the reflectivities are 0.32 at each end. What is the optical gain at the lasing threshold?

(b) If one end of the laser is coated with a dielectric reflector so that its reflectivity is now 90 %, what is the optical gain at the lasing threshold?

(c) If the internal quantum efficiency is 0.65, what is the external quantum efficiency in cases (a) and (b)?

Sol:

Given that L = 500 mm; α=10 cm^{-1};

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

(a) $R_1 = R_2 = 0.32$**;** $g_{th} = 55.6$ cm^{-1}

(b) $R_1 = 0.9;\ R_2 = 0.32$**;** $g_{th} = 34.9$ cm^{-1}

(c) $\eta_{int} = 0.65; \eta_{ext} = \eta_{int} \frac{g_{th}-\alpha}{g_{th}}$

PROBLEM 5

For a DH ILD, with strong carrier confinement, the threshold gain coefficient, gth, to a good approximation, may be given by the relation $g_{th} = \beta J_{th}$, where β is a constant depending on the device configuration and J_{th} is the threshold current density for stimulated emission. Consider a GaAs laser with an optical cavity of length 250 mm and width 100 mm. At the normal operating temperature, the gain factor $\beta = 21 \times 10^{-3}$ A/cm³ and the effective absorption coefficient $\alpha = 10$ cm⁻¹.

(a) If the refractive index is 3.6, find the threshold current density and the threshold current I_{th}. Assume the laser end faces are uncoated and the current is restricted to the optical cavity.

(b) What is the threshold current if the laser cavity width is reduced to 10 mm?

Sol:

(a) The reflectivity at the GaAs-air interface is $R = R_1 = R_2 = \left(\frac{n-1}{n+1}\right)^2 = 0.32$

For laser structures that have strong carrier confinement, the threshold current density for stimulated emission J_{th} $J_{th} = \frac{g_{th}}{\beta}$

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

$$I_{th} = J_{th} \times area\ of\ the\ cavity$$

Similarly do for (b)

EXERCISE PROBLEMS

- A GaAs LED is forward-biased with a current of 120 mA and a voltage of 1.5 V. Each emitted photon possesses an energy of 1.43 eV, and the refractive index of GaAs is 3.7. The configuration of the LED is such that we may neglect back emission and self-absorption within the semiconductor. Assuming the internal quantum efficiency of the LED to be 60%, calculate

  (a) the internal power efficiency of the device and

  (b) the external power efficiency of the device. **(Ans: (a) 0.572 (b) 0.0276)**
- The longitudinal modes of a DH GaAs/GaAlAs Injected Laser Diode (ILD) operating at a wavelength of 850 nm are separated in frequency by 250 GHz. If the refractive index of the active region is 3.7, calculate the length of the optical cavity and the number of longitudinal modes emitted. **(Ans: 162 µm, 1410)**
- Calculate the maximum allowed length of the active region for the single-mode operation of a DH InGaAsP/InP ILD emitting at 1.3 µm. Assume that the refractive index of the active region is 3.5. **(Ans: 0.185 µm)**

EXERCISE PROBLEMS

- A DH GaAs/GaAlAs ILD has a cavity length of 0.5 mm, an effective loss coefficient α_{eff} of 1.5 mm^{-1}, a confinement factor Γ of 0.8, and uncoated facet reflectivities of 0.35. (a) Calculate the reduction that occurs in the threshold gain coefficient when the reflectivity of one of the facets is increased to 1. (b) In the latter case, if the internal quantum efficiency of stimulated emission is 0.80, calculate the differential quantum efficiency of the device.

TEXT BOOKS

- Gerd Keiser, Optical Fiber Communications, TMH India, Fourth Edition, 2010.
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COURSE: *OPTICAL COMMUNICATION* (EC317)

UNIT-III OPTICAL DETECTOR

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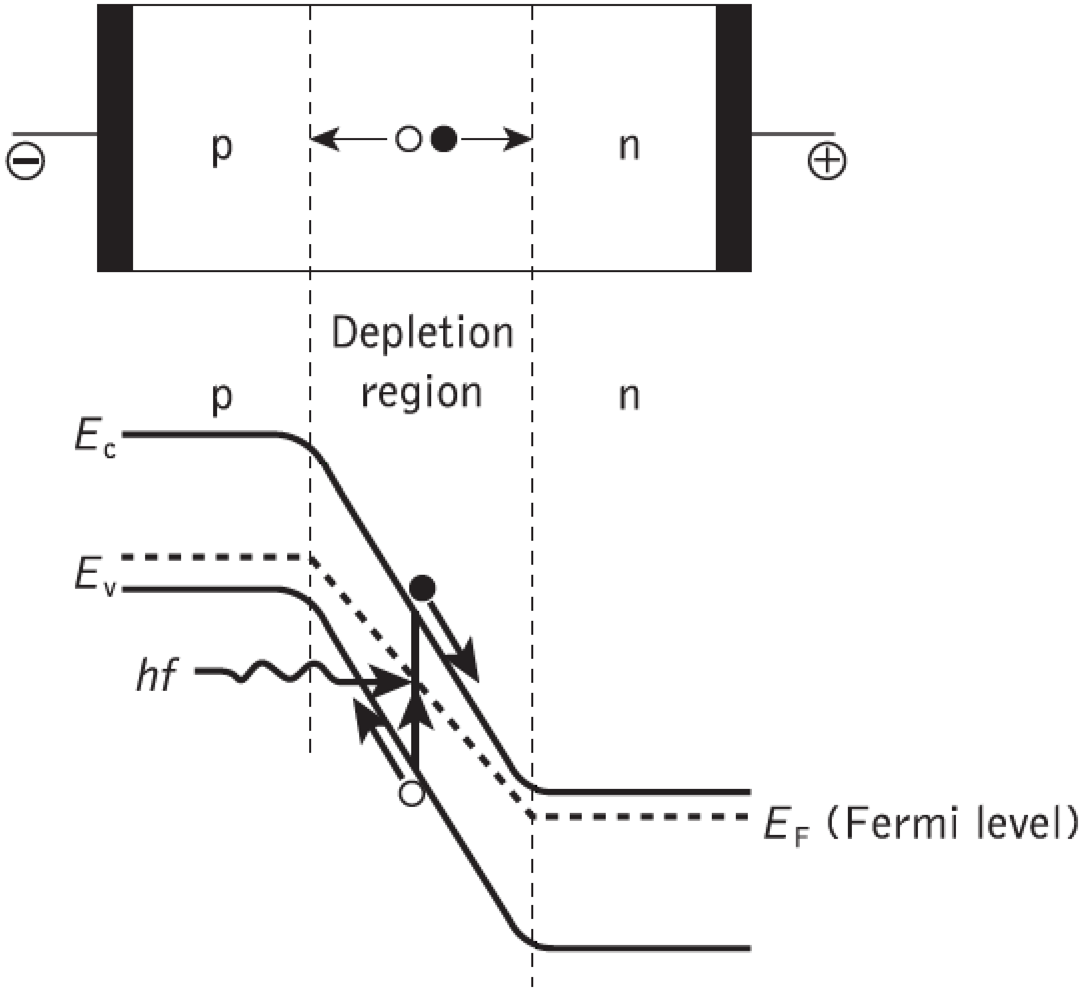
Requirements for optical detector

- High sensitivity at the operating wavelengths
- High fidelity
- Large electrical response to the received optical signal
- Short response time to obtain a suitable bandwidth
- Noise introduced by the detector should be minimum
- Stability of performance characteristics
- Small size
- Low bias voltages
- High reliability
- Low cost

Basic principle of optical detection

- Similar to LED and laser sources, a semiconductor p-n junction can be used for Optical detection
- When the device is reverse biased, an electric field developed across the p-n junction sweeps mobile carriers(holes and electrons) to their respective majority sides and a depletion region is created on either side of the junction.
- This barrier has the effect of **stopping the majority carriers crossing the junction** in the opposite direction to the field. However, the field accelerates minority carriers from both sides to the opposite side of the junction, forming the **reverse leakage current of the diode.**
- A photon incident in or near the depletion region of this device which has energy greater than or equal to the band gap energy E_g of the fabricated material (i.e. $hf \geq E_g$) will excite an electron from valance band into the conduction band. This process produce the photogeneration of an electron-hole pair.
- Carriers pairs generated near the junction are separated and drift under the influence of the electric field to produce a displacement current in the external circuit in excess of any reverse leakage current.

Basic photodiode operation



- The resulting flow of current is proportional to the number of incident photons. Such a reverse biased p-n junction acts as a photodetector.
- The depletion region must be sufficient thick to allow a large fraction of the incident light to be absorbed in order to achieve maximum carrier pair generation.
- Long carrier drift times in the depletion region restrict the speed of operation of the photodiode, so it is necessary to limit its width.
- Thus there is a trade-off between the number of photons absorbed (sensitivity) and the speed of response.

When discussing photo detectors there are four important parameters:

Responsivity:

This is the ratio of output current to input optical power. Hence this is the efficiency of the device.

Spectral Response Range:

This is the range of wavelengths over which the device will operate.

Response Time:

This is a measure of how quickly the detector can respond to variations in the input light intensity.

Noise Characteristics:

The level of noise produced in the device is critical to its operation at low levels of input light.

Optical Absorption Coefficient and Photocurrent

- The absorption of photons of a specific wavelength in a photodiode produces electron–hole pairs and thus a photocurrent depends on the absorption coefficient α of the semiconductor for that particular wavelength.
- Suppose P_{in} is the optical power level falling on the photodetector at x = 0 and P(x) is the power level at a distance x into the material.

$$P(x) = P_{in}e^{-\alpha x} \Rightarrow \frac{dP}{dx} = -\alpha\, P(x)$$

$$P_{abs} = \int_0^w -\alpha P_{in}e^{-\alpha x}\,dx = P_{in}(1 - e^{-\alpha w})$$

- The power absorbed by the semiconductor

$$P_{abs} = P_{in}(1 - R)(1 - e^{-\alpha w})$$

- The photo current $I_p = \frac{P_{in}(1-R)q}{hf}(1 - e^{-\alpha w})$

where q is the charge on an electron, R is the Fresnel reflection coefficient at the semiconductor–air interface and w is the width of the absorption region.

QUANTUM EFFICIENCY

- The quantum efficiency η is defined as the fraction of incident photons which are absorbed by the photodetector and generate electrons which are collected at the detector terminals

$$\eta = \frac{\text{number of electrons collected}}{\text{number of incident photons}} = \frac{r_e}{r_p}$$

- where r_p is the incident photon rate (photons per second)

  r_e is the electron rate (electrons per second)

$$r_e = \frac{I_p}{q} \; ; r_p = \frac{P_{in}\lambda}{hc}$$

RESPONSIVITY

- The responsivity $\mathcal{R}$ of a photodetector is defined as the output photocurrent per unit incident optical power.

$$\mathcal{R} = \frac{I_p}{P_{in}}$$

$$I_p = \mathrm{q}\, r_e$$

$$I_p = \eta\, \mathrm{q}\, r_p$$

$$r_p = \frac{incident\ power}{energy\ of\ the\ photon} = \frac{P_{in}\lambda}{hc}$$

$$I_p = \eta\, \mathrm{q} \frac{P_{in}\lambda}{hc}$$

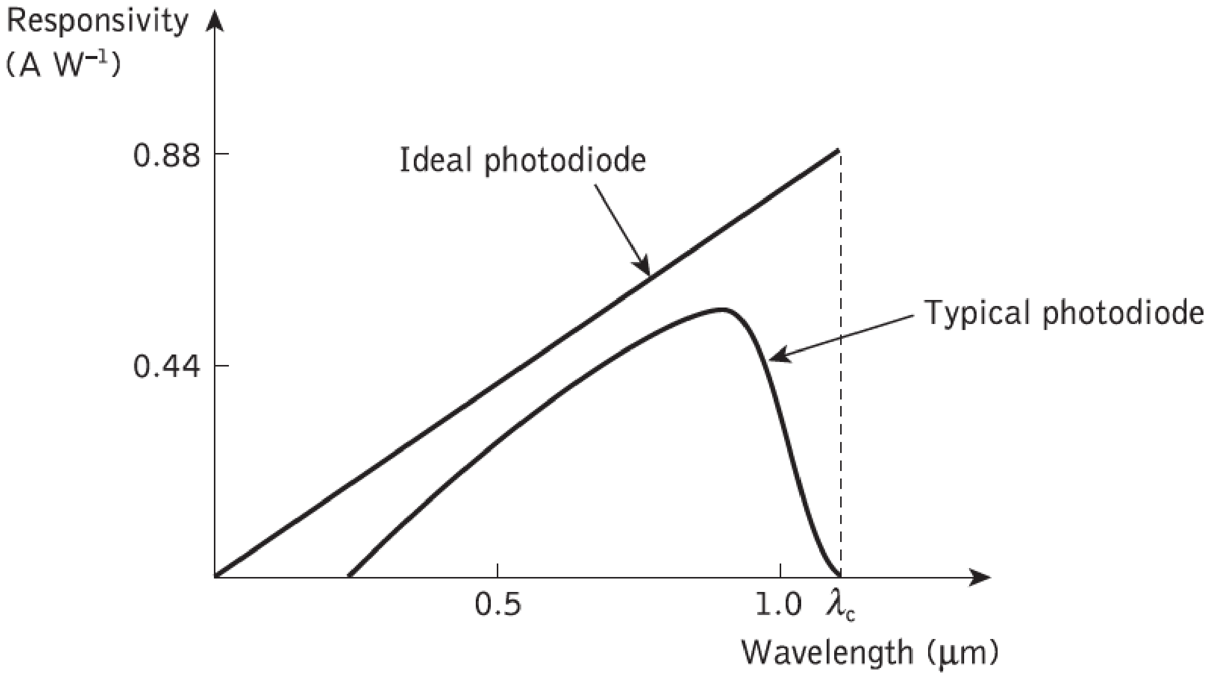
$$\mathcal{R} = \frac{I_p}{P_{in}} = \eta\, \frac{\mathrm{q}\lambda}{hc}$$

Cut-off wavelength

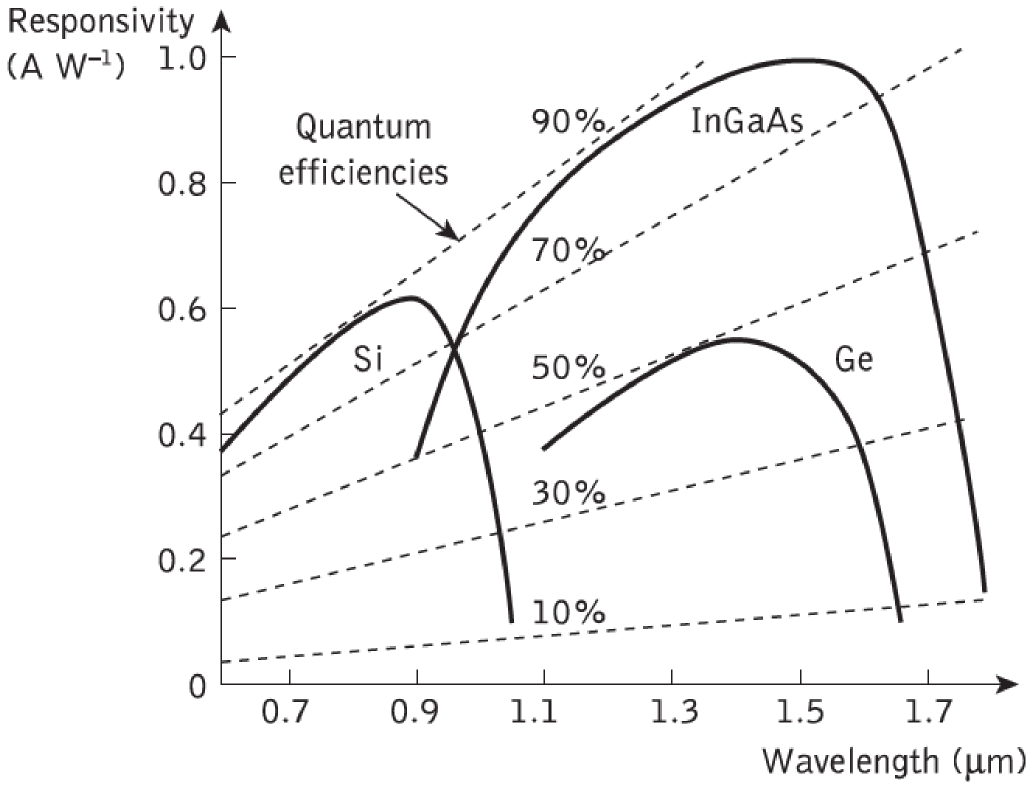
In an intrinsic semiconductor, the absorption of a photon is possible only when its energy is greater or equal to the band gap energy (E_g)

$$\frac{hc}{\lambda} \geq E_g$$

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



Responsivity
(A W⁻¹)
0.88
0.44
Ideal photodiode
Typical photodiode
0.5
1.0
λc
Wavelength (μm)



Responsivity
(A W⁻¹)
1.0
0.8
0.6
0.4
0.2
0
Quantum
efficiencies
90%
70%
50%
30%
10%
InGaAs
Si
Ge
0.7
0.9
1.1
1.3
1.5
1.7
Wavelength (μm)

Example problem

When 3×10^{11} photons each with a wavelength of 0.85 μm are incident on a photodiode, on average 1.2×10^{11} electrons are collected at the terminals of the device. Determine the quantum efficiency and the responsivity of the photodiode at 0.85 μm.

Example problem

A photodiode has a quantum efficiency of 65% when photons of energy 1.5×10^{-19} J are incident upon it. (a) At what wavelength is the photodiode operating? (b) Calculate the incident optical power required to obtain a photocurrent of 2.5 μA when the photodiode is operating as described above.

Semiconductor based photo detectors

- Two types of photodiodes are used
  - *PIN* photodiode
  - Avalanche photodiode (APD)

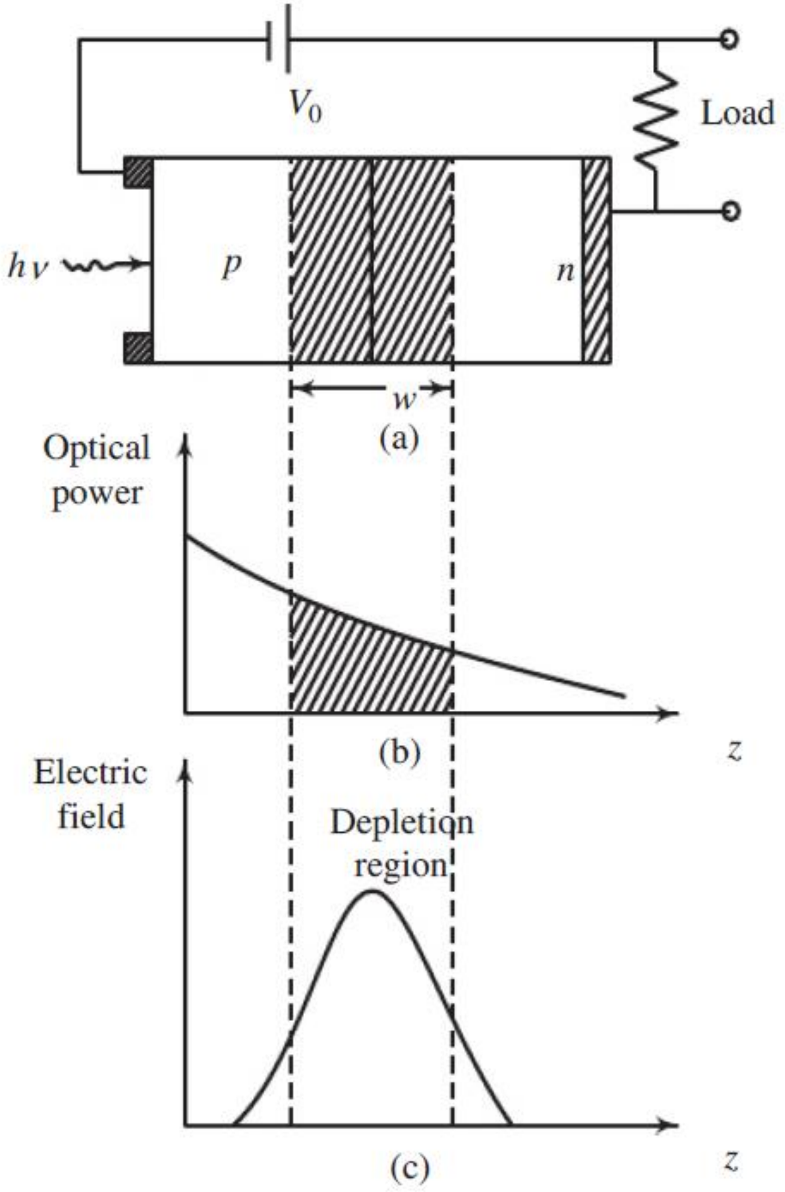
P-N photodiode

- the photons absorbed within the depletion region generate electron–hole pairs.
- Because of the induced electric field, electrons and holes generated inside this region get accelerated in opposite directions and thereby drift to the n -side and the p-side, respectively.
- The resulting flow of photocurrent constitutes the response of the photodiode to the incident optical power.
- The response time

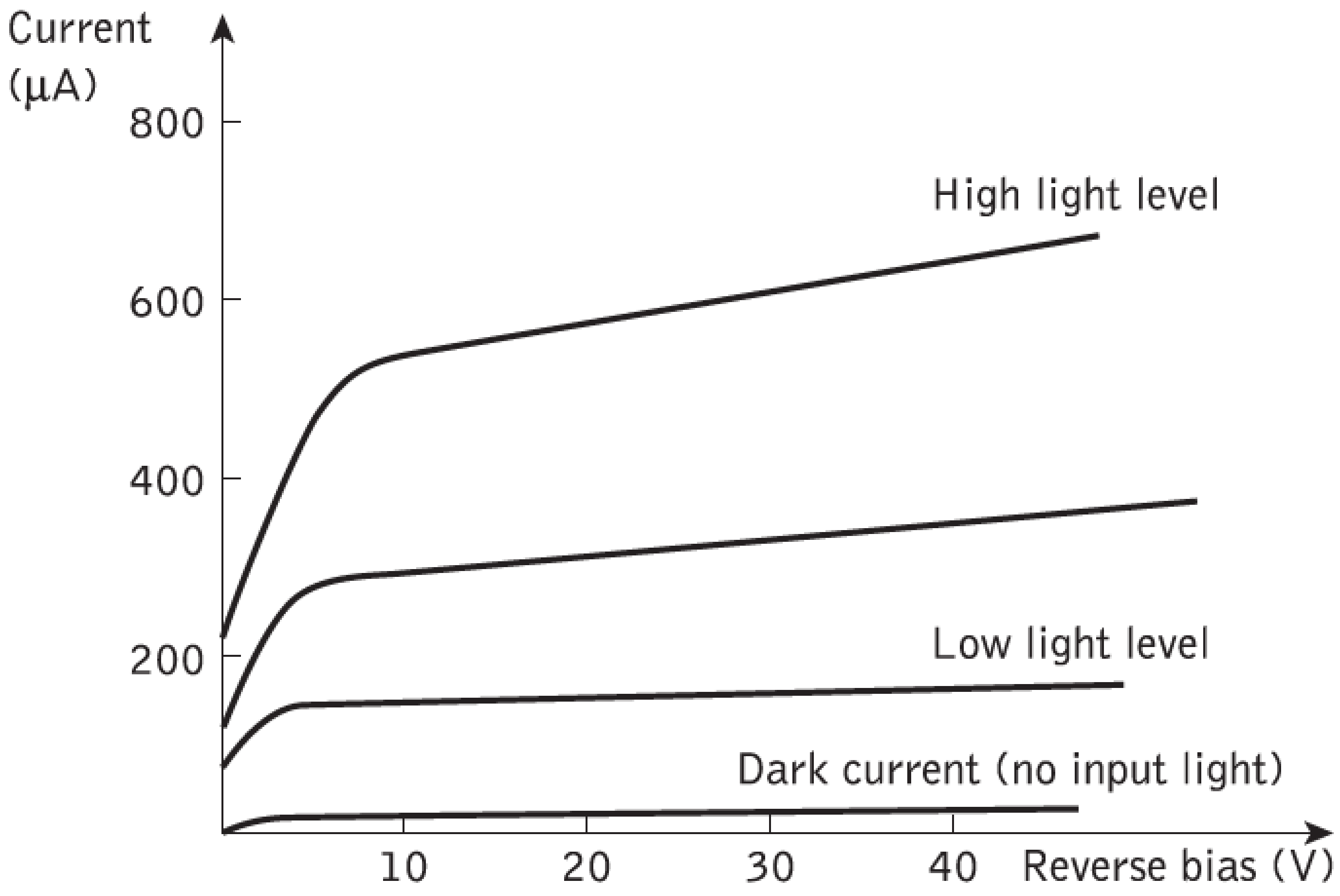
$$\tau_{drift} = \frac{w}{v_{drift}}; \tau_{diff} = \frac{d^2}{2\,D_c}$$

The depletion layer width w is

$$w = \sqrt{\frac{2\varepsilon}{q}(V_d + V_o)\left(\frac{1}{N_a} + \frac{1}{N_d}\right)}$$



P-N PHOTODIODE



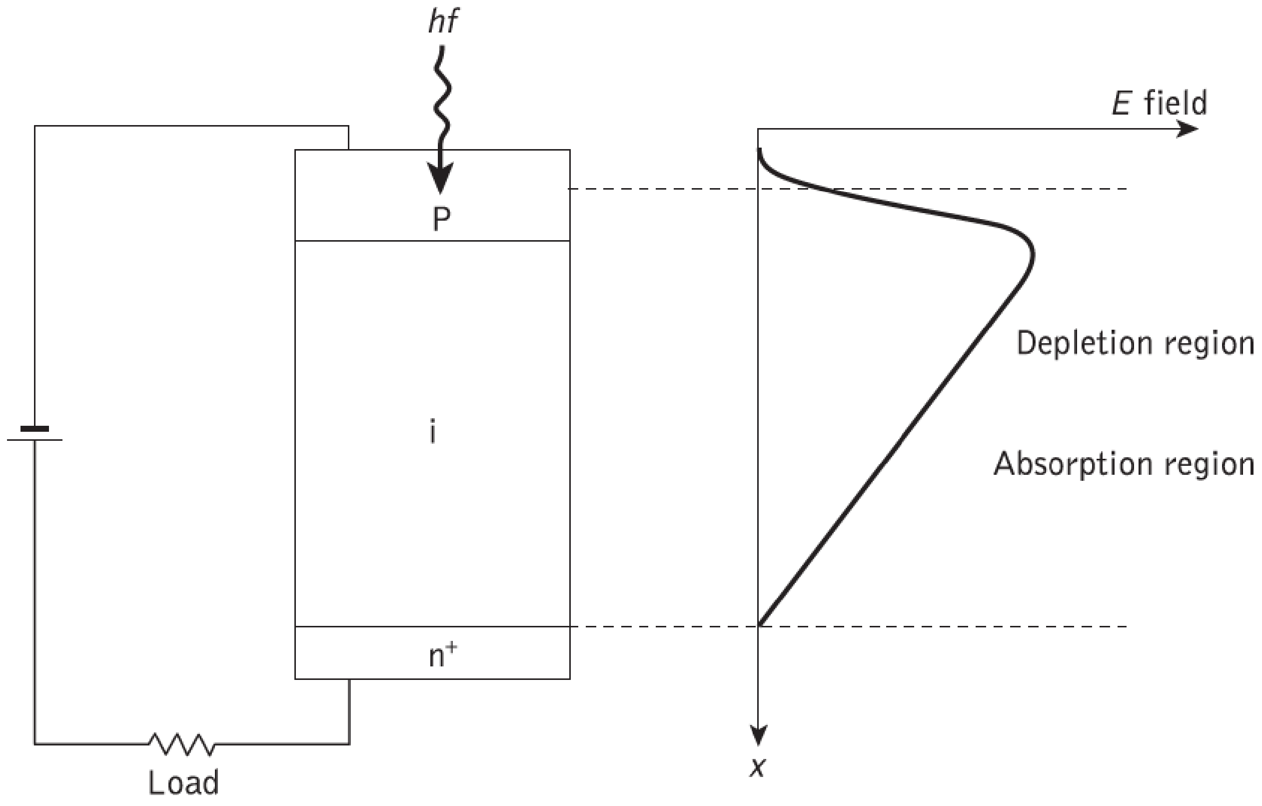
- The depletion region width in a *p–n* photodiode is normally **1 to 3 µm** and is optimized for the efficient detection of light at a given wavelength.
- For Si devices this is in the visible spectrum (0.4 to 0.7 µm) and for Ge in the near infrared (0.7 to 0.9 µm).

Drawbacks of P-N photodiode

- While the p-n diode produces current from incident light, two characteristics make it unsuitable for use in fiber optic applications.
  - the depletion region is relatively small and many of the absorbed photons do not produce an external current and so the received optical power must be fairly high to generate sufficient current.
  - the slow tail response makes the diode too slow and limits operations to the kHz range.

PIN photodiode

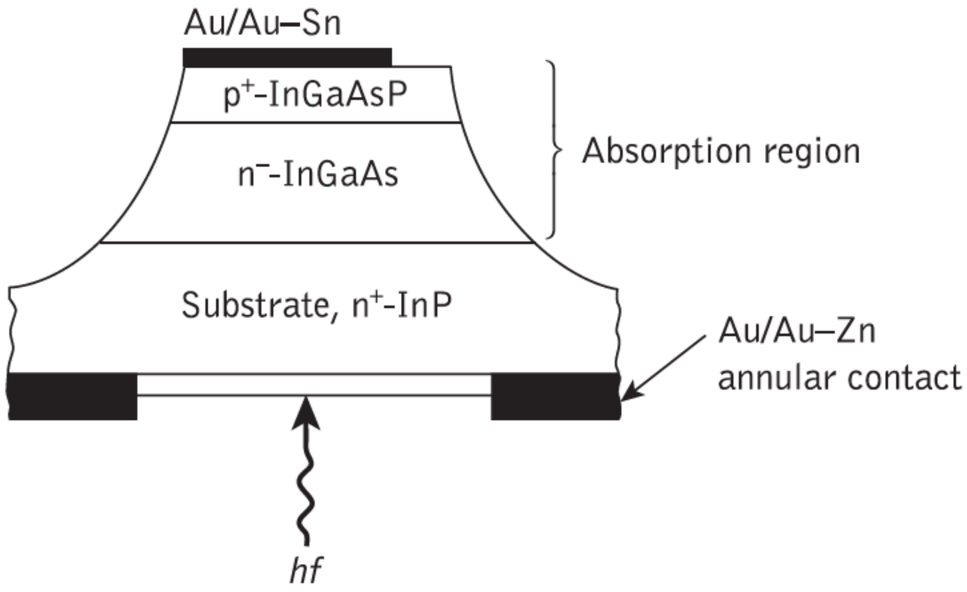
- A **wider depletion region** is necessary in order to **allow operation at longer wavelengths** where the light penetrates more deeply into the semiconductor material
- To achieve this, a layer of semiconductor, lightly doped that may be considered intrinsic, is inserted at the p-n junction. Such a structure is called a p -i-n photodiode
- This structure consists of the heavily doped p-type and n-type materials separated by a very lightly n-doped intrinsic material
- As the middle layer is intrinsic in nature, it offers **high resistance**, and hence most of the voltage drop occurs across it. Thus, a **strong electric field** exists across the middle i-region
- The inclusion of the intrinsic layer, increases the depletion region cross-sectional area, raises the maximum switching speed and the **photon capture area**. The result is more efficient production of external current and faster speed.

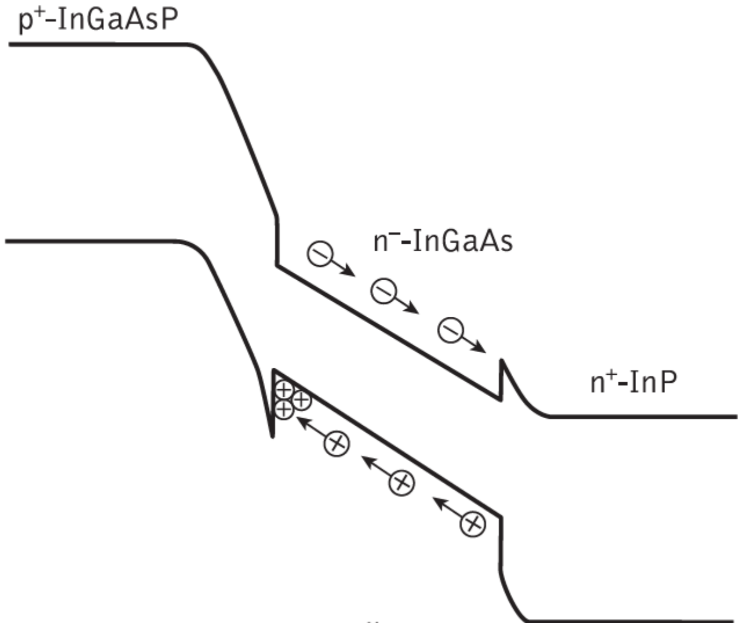


- A high electric field exists across the i-region results in the drift component of the photocurrent dominating the diffusion component.
- This gives rise to a current flow in an external circuit, with one electron for every carrier pair generated . This current is known as the photocurrent.

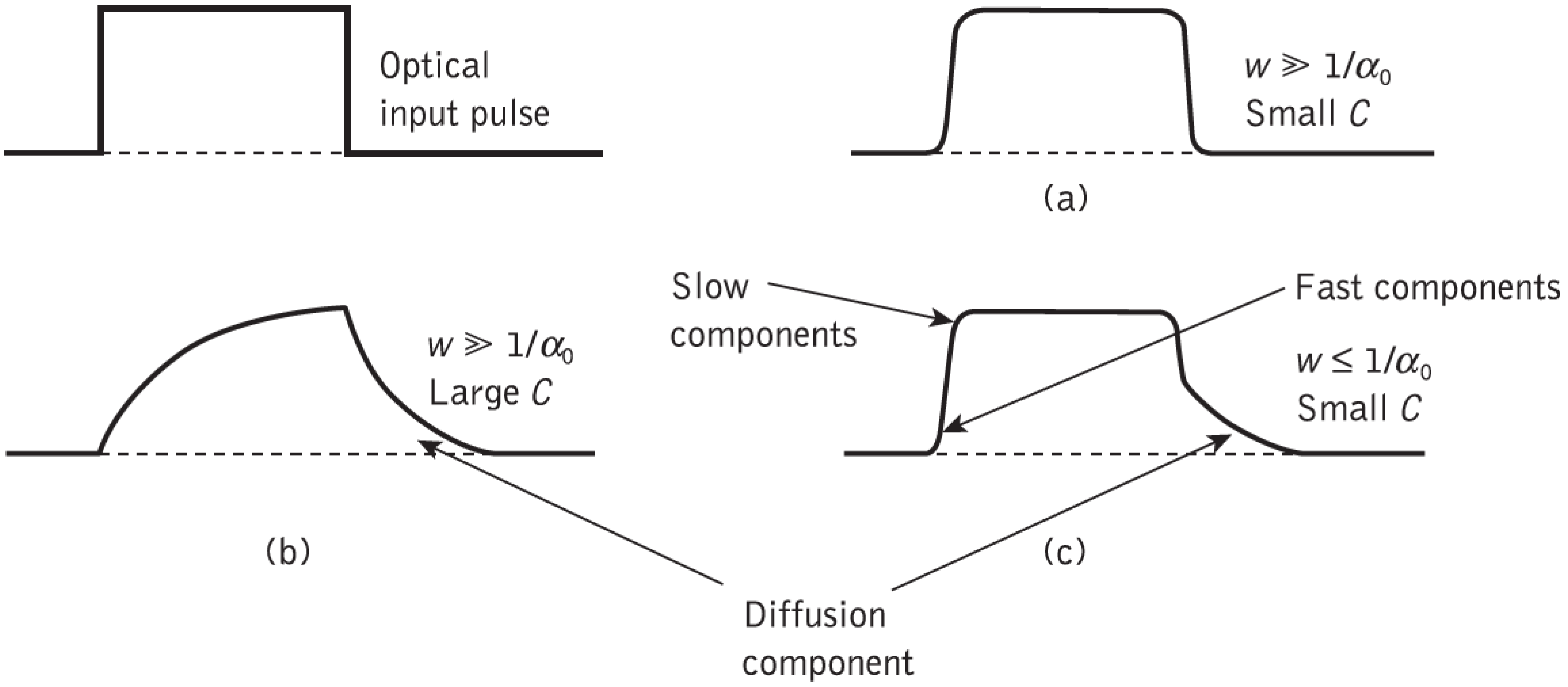
- A double heterostructure, improves the performance of the p-i-n photodiodes.
- Herein, the middle i-region of a material with lower band gap is sandwiched between p- and n-type materials of higher band gap, so that incident light is absorbed only within the i -region.
- the maximum photodiode 3 dB bandwidth

$$B_m = \frac{1}{2\pi\ \tau_{drift}}$$





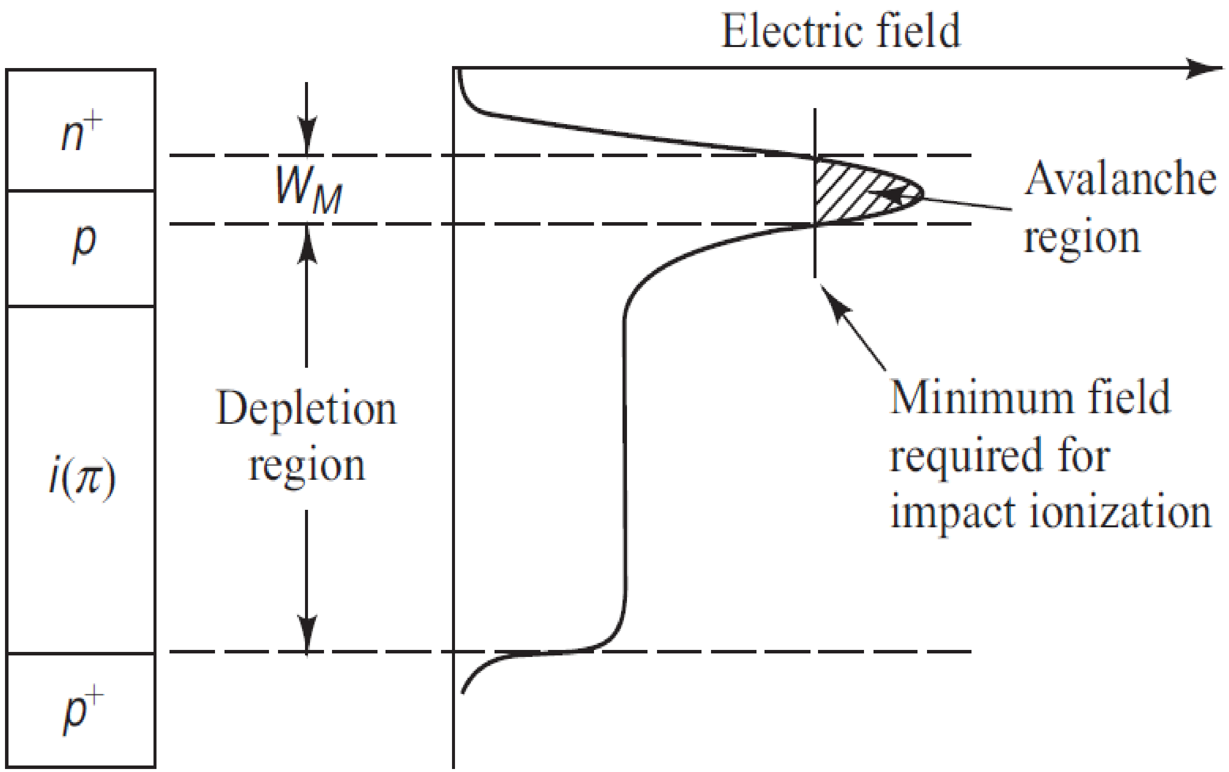
Photodiode responses to rectangular optical input pulses for various detector parameters



AVALANCHE PHOTODIODE(APD)

- Semiconductor photodiode with internal gain (internally multiply the primary signal photocurrent before it enters the input circuitry of the following amplifier)
- This increases receiver sensitivity
- In order for carrier multiplication, the photo carriers must traverse a region where a very high electric field is present.
- When the primary electron-hole pairs generated by incident photons pass through this region, they get accelerated and acquires so much kinetic energy that they ionize the bound electrons in the valance band upon collision and in the process create secondary electron-hole pair. This phenomenon is known as impact ionization.
- If the field is high enough, the secondary carrier pairs may also gain sufficient energy to create another new pairs. This is known as avalanche effect.

- A commonly used structure for achieving carrier multiplication with very little excess noise is the reach-through construction.
- The reach-through avalanche photodiode is composed of a lightly doped p-type intrinsic layer (called as π-layer) deposited on a p^+ substrate.



When the reverse bias voltage is increased the depletion layer widens across the p-region until it 'reaches through' to the nearly intrinsic (lightly doped) π-region.

P^+-π-p-n^+ reach trough structure

- The multiplication factor M of an APD is defined as

$$M = \frac{I_M}{I_P}$$

Where I_M is the average output current (after multiplication) and I_P is the primary photocurrent (before multiplication)

- Responsivity

$$\mathcal{R} = M\frac{\eta q}{hf}$$

Benefits and drawbacks of APD

- **Benefits:**
  - increase in sensitivity of between 5 and 15 dB over *p–i–n* photodiodes
- **Drawbacks :**
  - fabrication difficulties due to their more complex structure and hence increased cost;
  - the random nature of the gain mechanism which gives an additional noise contribution
  - the high bias voltages required
  - the variation of the gain (multiplication factor) with temperature for a silicon RAPD, thus temperature compensation is necessary to stabilize the operation of the device.

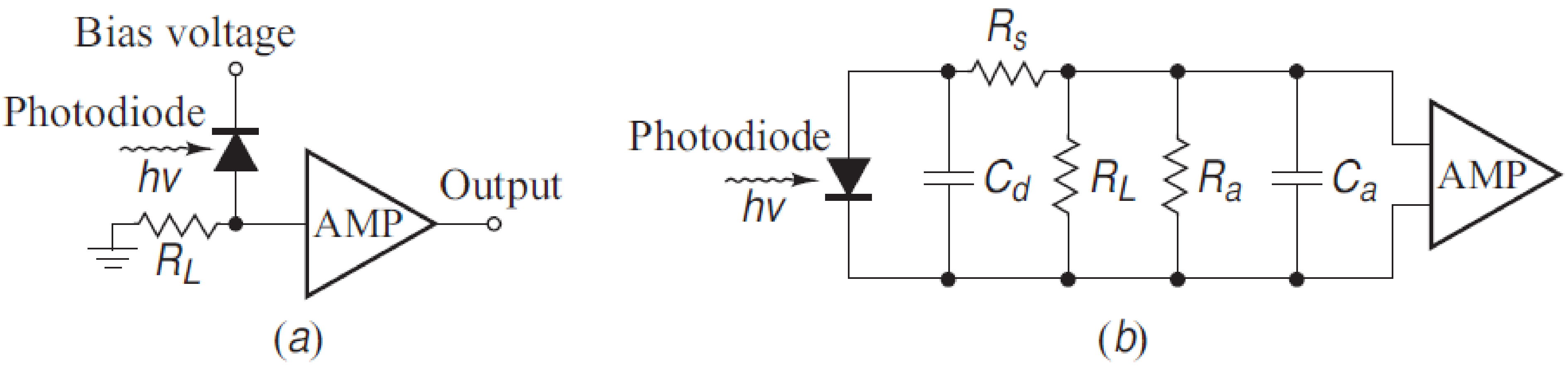
Noise considerations

- In optical comm. system, the photodiode is required to detect very weak signal.
- This is achieved by using the combination of photo-detector and its following amplification circuitry.

$$\frac{S}{N} = \frac{\text{Signal power from photocurrent}}{Photodetector\ noise\ power + amplifier\ noise\ power}$$

- To achieve high SNR,
  - Photo-detector must have a high quantum efficiency to generate a large signal power
  - Photo-detector and amplifier noise should be kept as low as possible

Noise considerations



(a) Simple model of a photodetector receiver, and (b) its equivalent circuit

Where R_s is series resistance, C_d is total capacitance of photodiode, R_L is the load resistance, R_a and C_a are the input resistance and capacitance of the amplifier

There are (i) quantum or shot noise, (ii) dark current noise, and (iii) thermal noise.

- **Quantum or shot noise:** It arises from the **random arrival of photons** at a photodetector

$$\langle {i_s}^2 \rangle = 2qI_p\, B_e\, M^2 F(M)$$

- **Dark current noise:** It is a **reverse leakage current** that continues to flow through the device when no light is incident on the photo-detector. Generally it arises from the electrons or holes which are thermally generated near the p-n junction.

$$\langle {i_d}^2 \rangle = 2qI_d\, B_e\, M^2 F(M)$$

Where I_P is the average photocurrent, B_e is the effective noise bandwidth, $F(M) \approx M^x$ is the noise figure associated with the random nature of the avalanche process. And $0 \le x \le 1$, x is depends on material , I_d is avg. primary dark current

- **Thermal noise:** Thermal (or Johnson) noise is a **random fluctuation in current due to the thermally induced random motion of electrons in a conductor**. The load resistance R_L adds such fluctuations to the current generated by the photodiode.

$$\langle {i_T}^2 \rangle = \frac{4k_B T}{R_L}\, B_e$$

The signal to noise ratio of an optical receiver can be written as

$$\frac{S}{N} = \frac{\langle i_p{}^2 \rangle M^2}{2q(I_p + I_d)M^2 B_e F(M) + \frac{4k_B T \Delta f}{R_L} + \langle i_{amp}{}^2 \rangle}$$

When p-n and p-i-n photodiodes are used in the receiver, M and F(M) become unity.

Table: Generic operating parameters of Si, Ge, and InGaAs pin photodiodes (Ref: 1)

Parameter	*Symbol*	*Unit*	*Si*	*Ge*	*InGaAs*
Wavelength range	λ	nm	400–1100	800–1650	1100–1700
Responsivity	$\mathscr{R}$	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
Modulation (bandwidth)	B_m	GHz	0.3–0.7	0.5–3	1–2
Bias voltage	V_B	V	5	5–10	5

Table: Generic operating parameters of Si, Ge, and InGaAs avalanche photodiodes (Ref: 1)

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	$M \cdot B_m$	GHz	100–400	2–10	20–250
Bias voltage	V_B	V	150–400	20–40	20–30

Some Example Problems

- The quantum efficiency of a particular silicon RAPD is 80% for the detection of radiation at a wavelength of 0.9 μm. When the incident optical power is 0.5 μW, the output current from the device (after avalanche gain) is 11 μA. Determine the multiplication factor of the photodiode under these conditions.
- If the photodiode capacitance is 3 pF, the amplifier capacitance is 4 pF, the load resistor is 1 kΩ, and the amplifier input resistance is 1 MΩ, then C_T = 7 pF and R_T = 1 kΩ, then find the bandwidth of the circuit.
- An InGaAs pin photodiode has the following parameters at a wave length of 1300 nm: $I_D = 4$ nA, $\eta = 0.90$, $R_L = 1000\ \Omega$, and the surface leakage current is negligible. The incident optical power is 300 nW (–35 dBm), and the receiver bandwidth is 20 MHz. Find the various noise terms of the receiver.

EXERCISE PROBLEMS

- A *p*–*n* photodiode has a quantum efficiency of 50% at a wavelength of 0.9 μm. Calculate: (a) its responsivity at 0.9 μm; (b) the received optical power if the mean photocurrent is 10^{-6} A; (c) the corresponding number of received photons at this wavelength.
- A *p*–*i*–*n* photodiode on average generates one electron–hole pair per three incident photons at a wavelength of 0.8 μm. Assuming all the electrons are collected calculate: (a) the quantum efficiency of the device; (b) its maximum possible bandgap energy; (c) the mean output photocurrent when the received optical power is 10^{-7} W.

Exercise Problems

- (a) The time taken for electrons to diffuse through a layer of *p*-type silicon is 28.8 ns. If the minority carrier diffusion coefficient is 3.4×10^{-3} m^2 /s, determine the thickness of the silicon layer.
- (b) Assuming the depletion layer width in a silicon photodiode corresponds to the layer thickness obtained in part (a) and that the maximum response time of the photodiode is 877 ps, estimate the carrier (hole) drift velocity.

Exercise problems

- A silicon *p–i–n* photodiode with an area of 1.5 mm^2 is to be used in conjunction with a load resistor of 100 Ω. If the requirement for the device is a fast response time, estimate the thickness of the intrinsic region that should be provided. It may be assumed that the permittivity for silicon is 1.04×10^{-10} F m^{-1} and that the electron saturation velocity is 10^7 m s^{-1}.
- An APD with a multiplication factor of 20 operates at a wavelength of 1.5 μm. Calculate the quantum efficiency and the output photocurrent from the device if its responsivity at this wavelength is 0.6 A W^{-1} and 10^{10} photons of wavelength 1.5 μm are incident upon it per second.

TEXT BOOKS

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

COURSE: *OPTICAL COMMUNICATION* (EC317)

UNIT-IV OPTICAL RECEIVER

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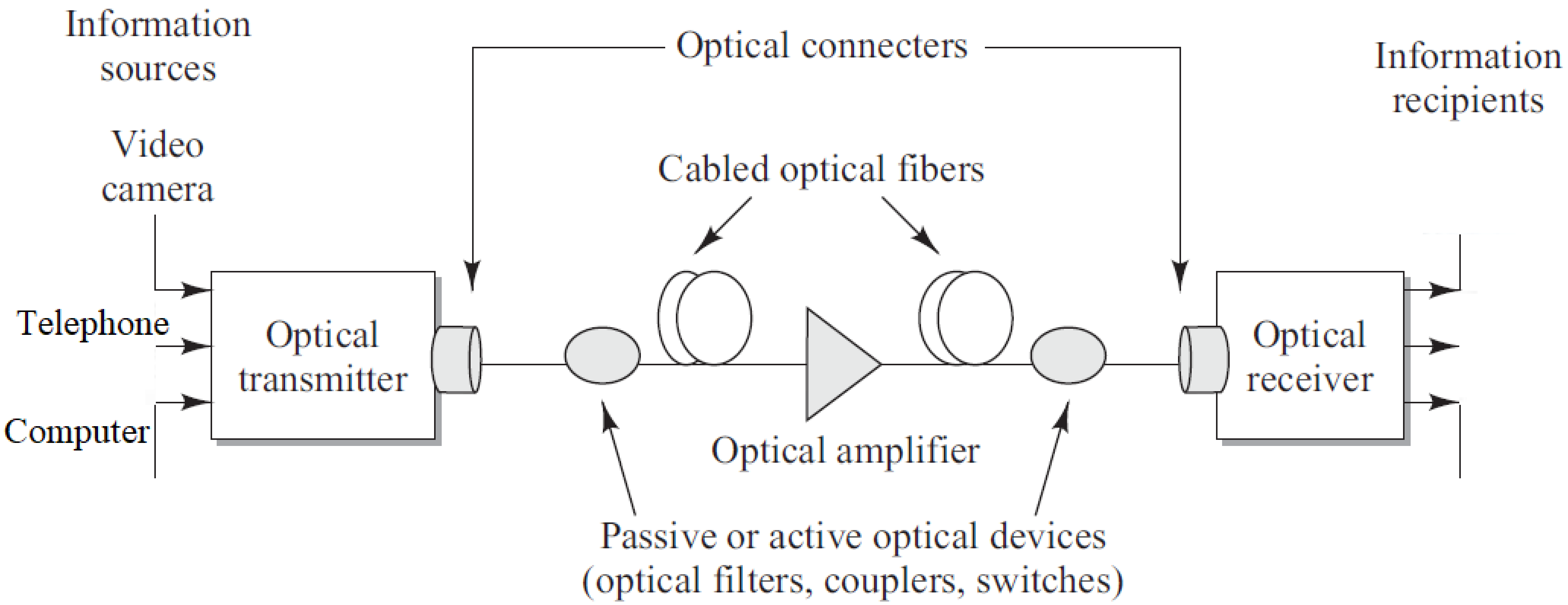
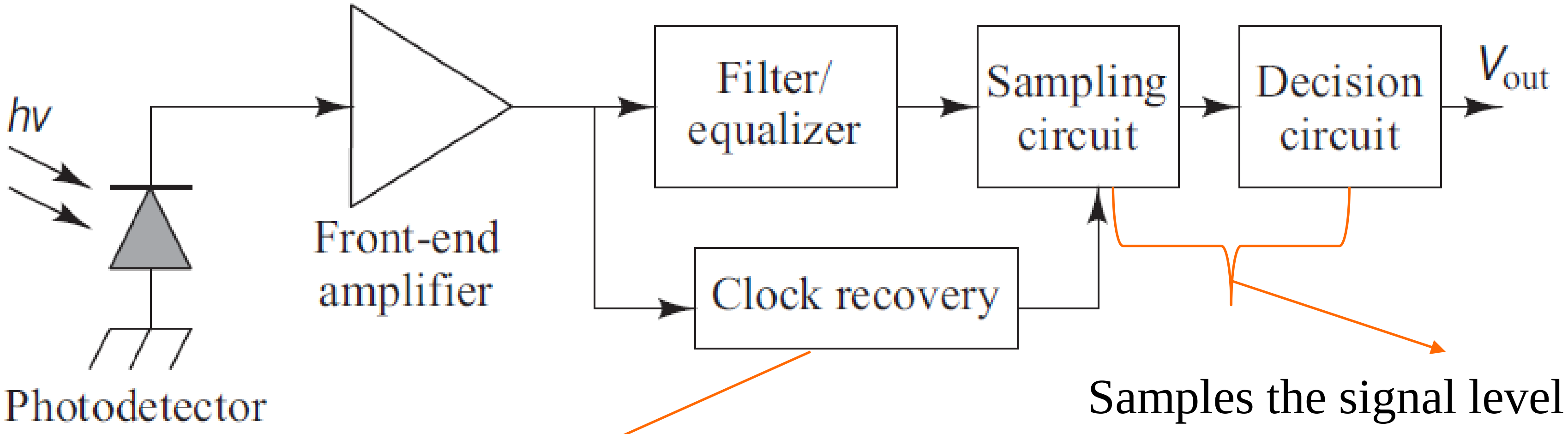
OPTICAL FIBER COMMUNICATION SYSTEM



Optical receiver

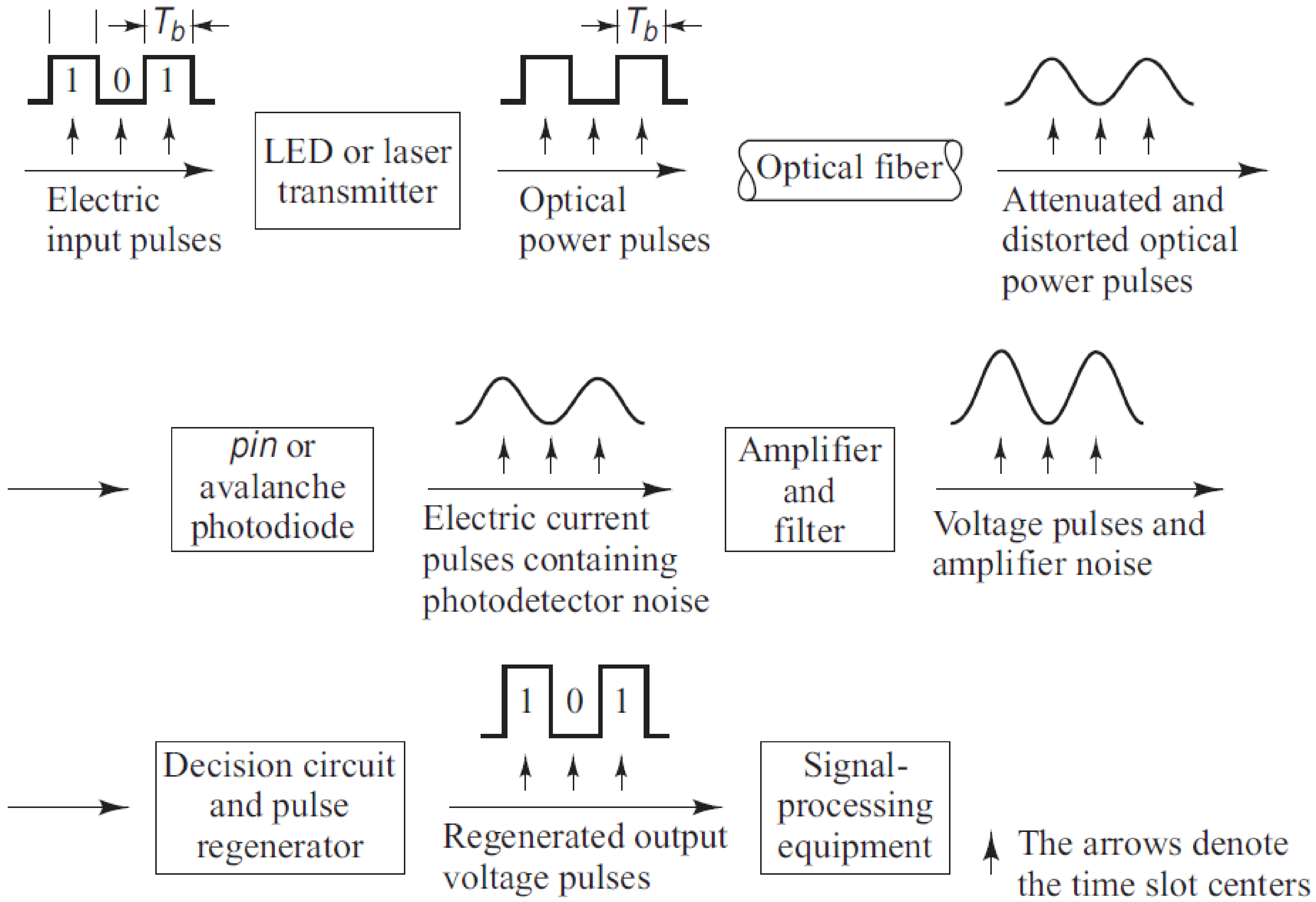
- **Basic function of the receiver**: able to detect weak, distorted signals and make decisions on what type of data was sent based on an amplified and reshaped version of this distorted signal.



provides the bit boundaries (start /end). The clock has a periodicity equal to the bit interval.

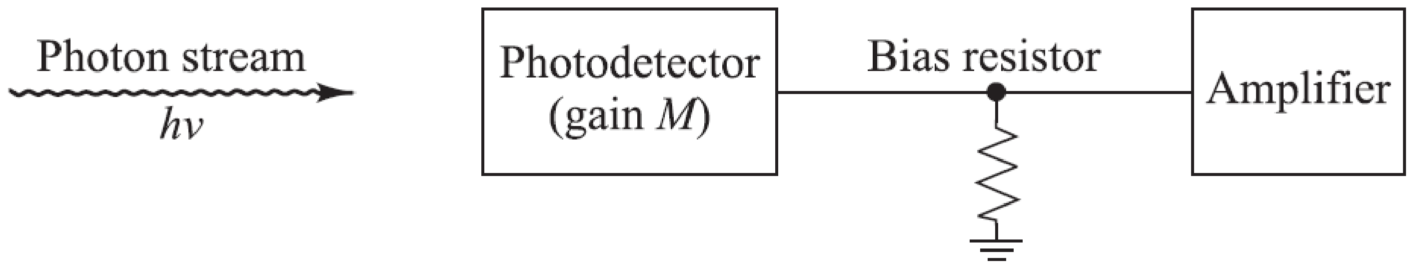
Samples the signal level at the midpoint of each time slot and compares it with a the threshold level (V_{Th}).

$$received\ bit = \begin{cases} 1;\ V_r > V_{th} \\ 0; V_r < V_{th} \end{cases}$$



T_b
1 0 1
Electric input pulses
LED or laser transmitter
T_b
Optical power pulses
Optical fiber
Attenuated and distorted optical power pulses
pin or avalanche photodiode
Electric current pulses containing photodetector noise
Amplifier and filter
Voltage pulses and amplifier noise
Decision circuit and pulse regenerator
1 0 1
Regenerated output voltage pulses
Signal-processing equipment
The arrows denote the time slot centers

Error Sources



- Photon detection quantum noise (Poisson fluctuation)

$$\langle i_s{}^2 \rangle = 2qI_p\, B_e$$

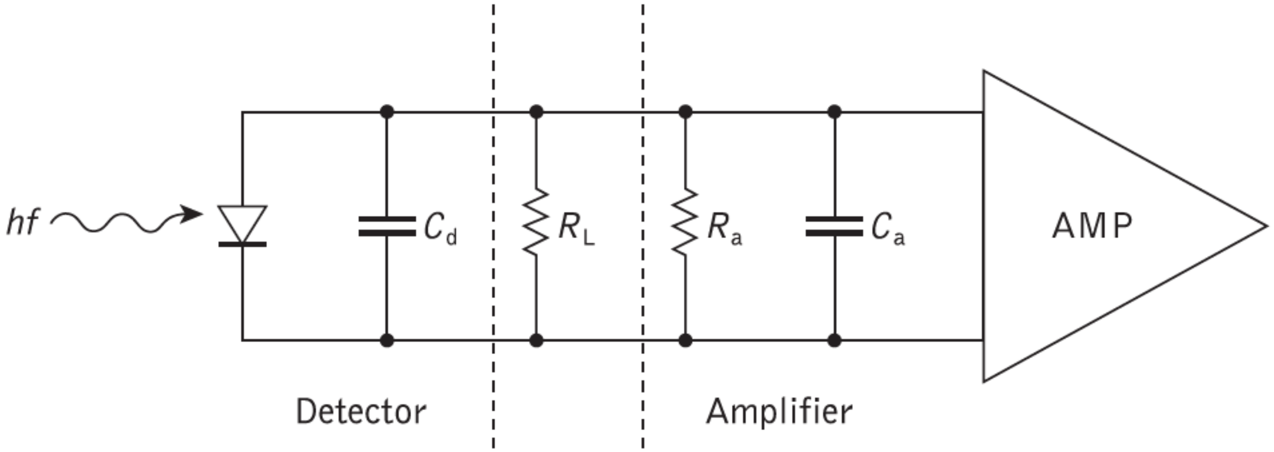
- Dark current
- Statistical gain fluctuation (for an APD)

$$\langle i_d{}^2 \rangle = 2qI_d\, B_e$$

- Thermal noise

$$\langle i_T{}^2 \rangle = \frac{4k_BT}{R_L}\, B_e$$

- Amplifier noise



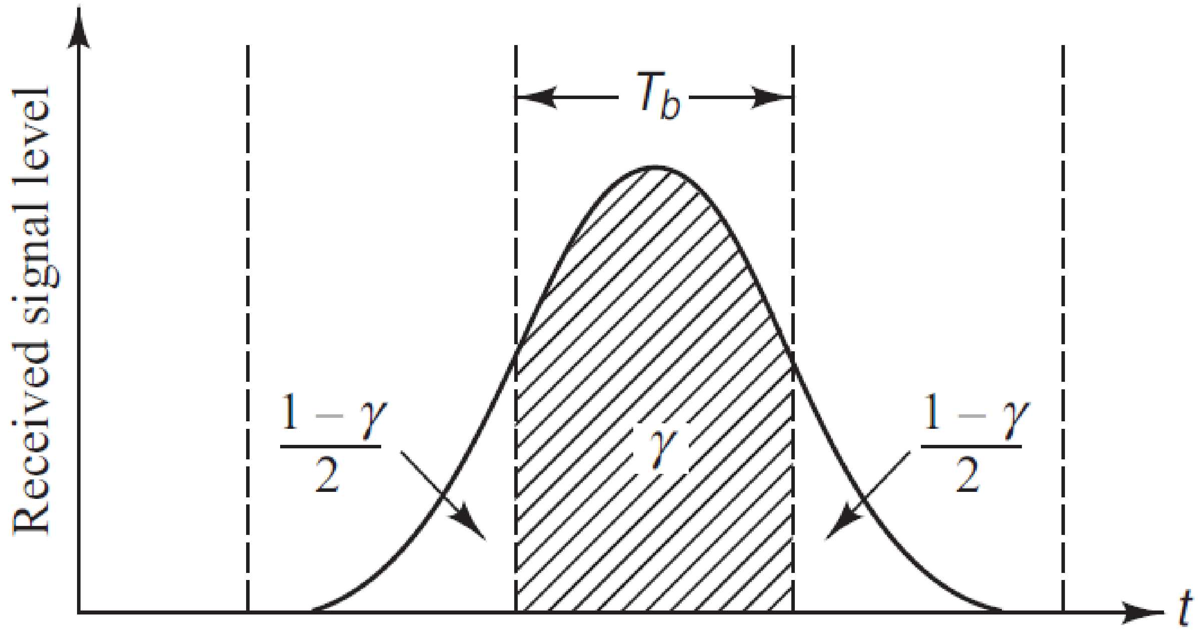
- For a detector with a mean avalanche gain M and an ionization rate ratio k, the excess noise factor F(M) for electron injection is

$$F(M) = kM + \left(2 - \frac{1}{M}\right)(1-k)$$

$= M^x$; approximated empirical expression

Error Sources: Inter-symbol interference (ISI)

- Which results from pulse spreading in the optical fiber.
- When a pulse is transmitted in a given time slot, most of the pulse energy will arrive in the corresponding time slot at the receiver



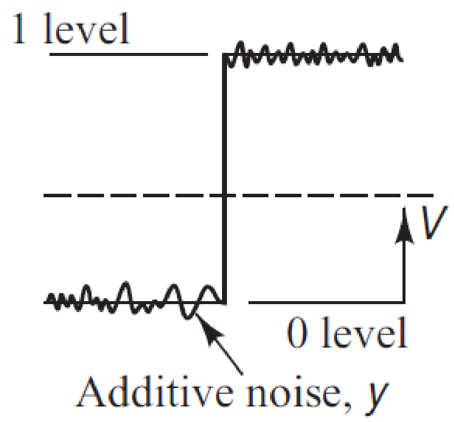
Probability of Error/ Bit Error Rate (BER)

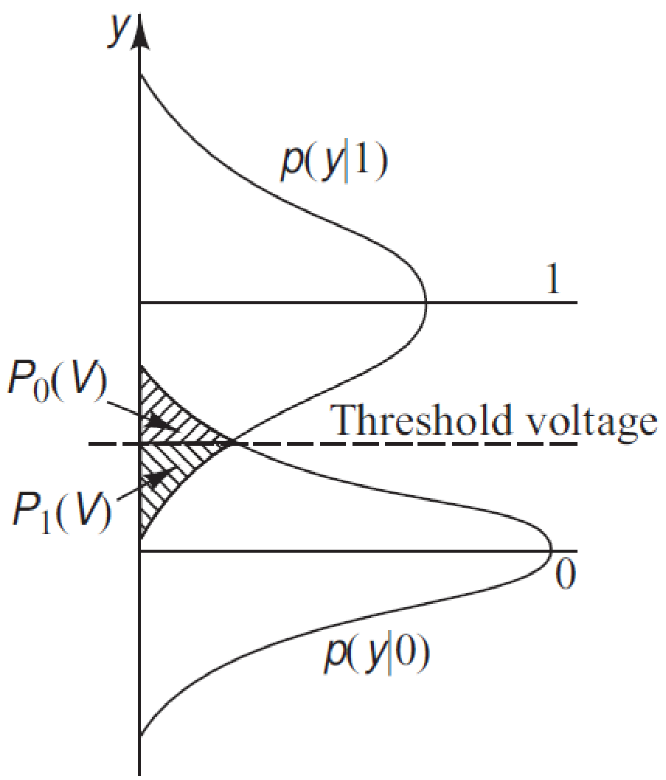
- The performance of the optical receiver with digital data (in the form of bits binary 1 and 0) can defined in terms of BER
- One of the simplest techniques for sending binary data is amplitude-shift keying (ASK) or on-off keying (OOK), wherein a voltage level is switched between two values, which are usually on or off.
- That is a voltage pulse of amplitude V relative to the zero voltage level when a binary 1 occurs and a zero-voltage-level space when a binary 0 occurs.
- The BER is defined as

$$BER = \frac{number\ of\ errors\ (N_e)}{Total\ number\ of\ bits\ (N_T)}$$

PROBABILITY OF ERROR/ BIT ERROR RATE (BER)

- Assume that the overall noise of the system be Gaussian noise which is additive in nature.
- The introduction of noise into the detected signal causes the photo-current to fluctuate about its mean level in the two logic levels (0 and 1)
- The variance for the logic ‘0’ is narrower than that for the logic ‘1’ because the logic ‘1’ level involves shot noise which is Poisson distribution but the logic ‘0’ involves only dark-current noise and thermal noise which are Gaussian in nature.





PROBABILITY OF ERROR/ BIT ERROR RATE (BER)

- Let us assume the photo-current (or voltage) corresponding to the threshold level be denoted by 'I_{th}' (or 'V_{th}').
- Bit error occurs, if a '0' was transmitted by the source but, due to noise and other factors, the detected bit would be '1' (the detected signal level exceeds the threshold level). Similarly, if a '1' was transmitted by the source and the detected signal level drops below threshold level, the detected bit is assigned '0'.
- BER is the probability of occurrence of bit errors in the transmission

$$BER = P_e = P(1/0)P(0) + P(0/1)P(1)$$

If the probabilities of 0 and 1 pulses are equally likely P(0) = P(1) = 1/2

$$BER = \frac{1}{2}(P(1/0) + P(0/1))$$

Where

$$P(1/0) = \frac{1}{\sqrt{2\pi}\sigma_0}\int_{I_{th}}^{\infty} e^{-\frac{(I-I_0)^2}{2\sigma_0{}^2}} dI \text{ and } P(0/1) = \frac{1}{\sqrt{2\pi}\sigma_1}\int_{-\infty}^{I_{th}} e^{-\frac{(I_1-I)^2}{2\sigma_1{}^2}} dI$$

PROBABILITY OF ERROR/ BIT ERROR RATE (BER)

Where

$$P(1/0) = \frac{1}{\sqrt{2\pi}\sigma_0} \int_{I_{th}}^{\infty} e^{-\frac{(I-I_o)^2}{2\sigma_0{}^2}} dI$$

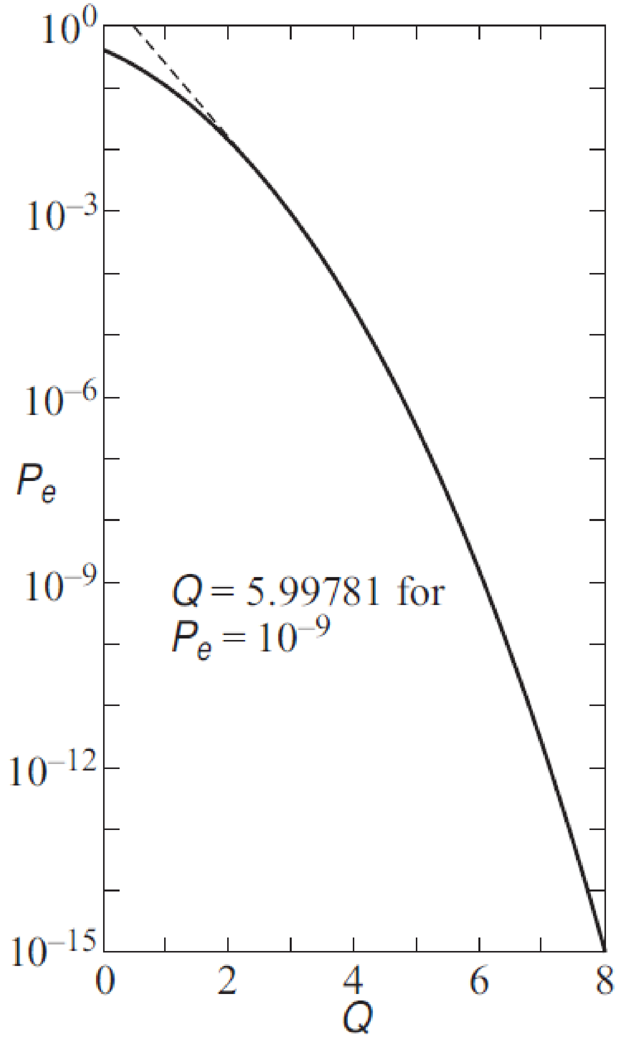
$$= \frac{1}{\sqrt{\pi}} \int_{Q/\sqrt{2}}^{\infty} e^{-x^2} dx\,; \quad where\ Q = \frac{I_{th} - I_0}{\sigma_0} = \frac{I_1 - I_{th}}{\sigma_1} = \frac{I_1 - I_0}{\sigma_0 + \sigma_1}$$

The above expression is like a complementary error function

The error function is defined as

$$\mathrm{erf}(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-y^2} dx$$

$$BER = \frac{1}{2}\mathrm{erfc}\left(Q/\sqrt{2}\right)$$



10^0
10^{-3}
10^{-6}
10^{-9}
10^{-12}
10^{-15}
P_e
$Q = 5.99781$ for
$P_e = 10^{-9}$
0
2
4
6
8
Q

Receiver Sensitivity

- Optical communication systems use a BER value to specify the performance requirements for a particular transmission link application
- To achieve a desired BER at a given data rate, a specific minimum average optical power level must arrive at the photodetector. The value of this minimum power level is called the receiver sensitivity (i.e., an average optical power (P_{avg}) in dBm incident on the photodetector).
- The average power received is

$$P_{avg} = \frac{P_1 + P_0}{2}$$

Where P_1 is the average incident power onto the photo-detector when logic '1' is received and 'P_0' is the average power incident onto the detector when logic '0' is received.

Receiver Sensitivity

- For the logic '0' reception, there is no incident power and the thermal noise component dominates the noise component in the output signal of the photo-detector. So, the total variance in the '0' level (denoted by σ_0^2) is given by: $\sigma_0{}^2 = \sigma_T{}^2 = \frac{4k_BTB}{R_L}$
- For the logic '1', the noise component is composed of shot noise and thermal noise. Therefore, the total noise variance (σ_1^2) is $\sigma_1{}^2 = \sigma_s{}^2 + \sigma_T{}^2$

$$\sigma_s{}^2 = 2qI_1B = 2q\mathcal{R}P_1B$$

- The Q-parameter for the photo-detector is $Q = \frac{I_1 - I_0}{\sigma_0 + \sigma_1}$
- Assume there is no optical power in a zero pulse, $P_{avg} = \frac{P_1}{2}$ and $Q = \frac{I_1}{\sigma_0 + \sigma_1}$

$$Q = \frac{2\mathcal{R}P_{avg}}{\sigma_T + (\sigma_s{}^2 + \sigma_T{}^2)^{1/2}}$$

$$P_{sensivity} = P_{avg} = \frac{Q}{2\mathcal{R}}\left(\sigma_T + (\sigma_s{}^2 + \sigma_T{}^2)^{\frac{1}{2}}\right)$$

Receiver Sensitivity

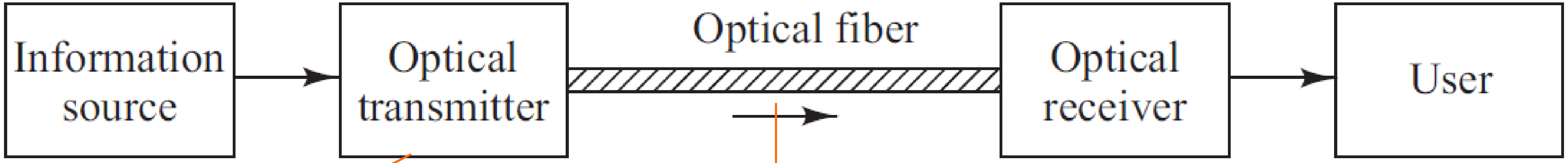
- Substitute ${\sigma_s}^2 = 4q\mathcal{R}BP_{sensitivity}$ and ${\sigma_T}^2 = \frac{4k_BTB}{R_L}$; and solve for $P_{sensitivity}$

$$P_{sensivity} = \frac{Q}{2\mathcal{R}}\left(\frac{qBQ}{2} + \left(\frac{4k_BTB}{R_L}\right)^{1/2}\right)$$

POINT-POINT OPTICAL LINK

The following key system requirements are needed in analyzing a link:

- The desired (or possible) transmission distance
- The data rate or channel bandwidth
- The bit-error rate (BER)



LED or laser diode optical source

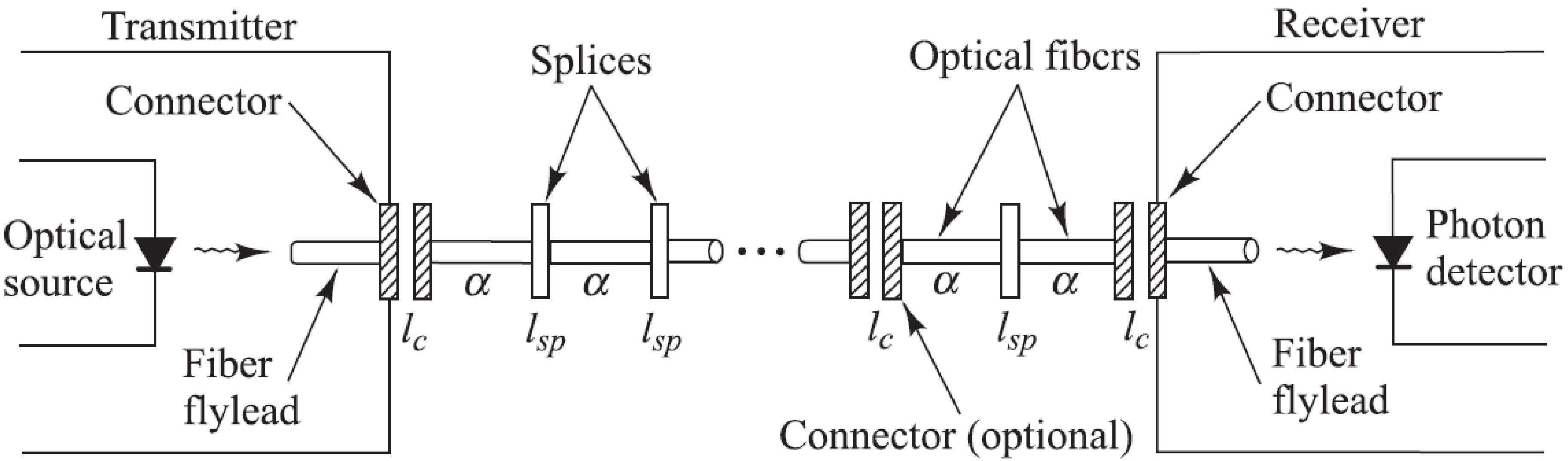
- Emission wavelength
- Spectral line width
- Output power
- Effective radiating area
- Emission pattern
- Number of emitting modes

- Multimode or single-mode
- Core size, refractive index profile
- Numerical aperture or mode-field diameter
- Bandwidth or dispersion, Attenuation

PIN or Avalanche photodiode

- Responsivity
- Operating wavelength
- Speed
- Sensitivity

Link Power Budget



Optical power loss model for a point-to-point link. The losses occur at connectors (l_c), at splices (l_{sp}), and in the fiber (α).

The maximum allowable loss $\alpha_{max} = P_t - P_r = \alpha_{fiber} + \alpha_{splices} + \alpha_{connectors} + \alpha_{system}$

POWER LAUNCHING AND COUPLING

- A measure of the amount of optical power emitted from a source that can be coupled into a fiber is usually given by the coupling efficiency η_C defined as

$$\eta_C = \frac{P_{CF}}{P_{ES}}$$

where, P_{CF} is the power coupled into the fiber and P_{ES} is the power emitted from the light source.

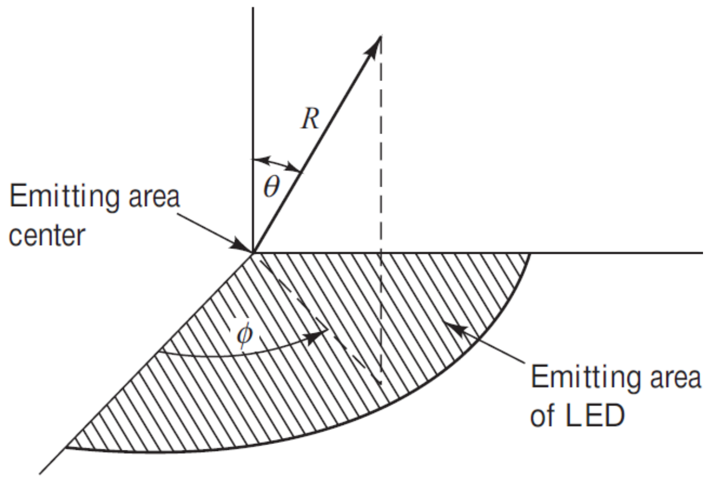
- The launching or coupling efficiency depends on the type of fiber that is attached to the source and on the coupling process

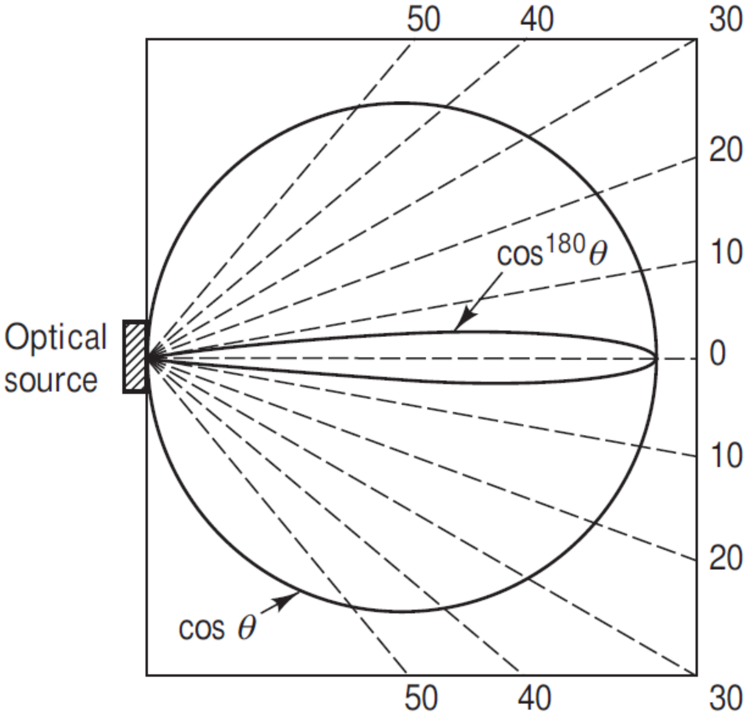
SOURCE-TO-FIBER POWER LAUNCHING

- The optical power that can be coupled into a fiber depends on the radiance (i.e., on the spatial distribution of the optical power).
- Radiance is the **optical power radiated into a unit solid angle per unit emitting surface area** (watts per square centimeter per steradian).
- The radiance may be a function of both θ and ϕ, and can also vary from point to point on the emitting surface.
- The power delivered at an angle θ, measured relative to a normal to the emitting surface

$$B(\theta, \phi) = B_0 \cos \theta$$

where B_0 is the radiance along the normal to the radiating surface.





Total optical power emitted from source

the total optical power P_s that is emitted from the source of area A_s

$$P_s = A_s \int_0^{2\pi} \int_0^{\pi/2} B(\theta, \phi) \sin\theta \ d\theta \ d\phi$$

$$= (\pi {r_s}^2) 2\pi B_0 \int_0^{\pi/2} \cos\theta \sin\theta \ d\theta$$

$$= \pi^2 {r_s}^2 B_0 [sin^2(\theta)]_0^{\pi/2}$$

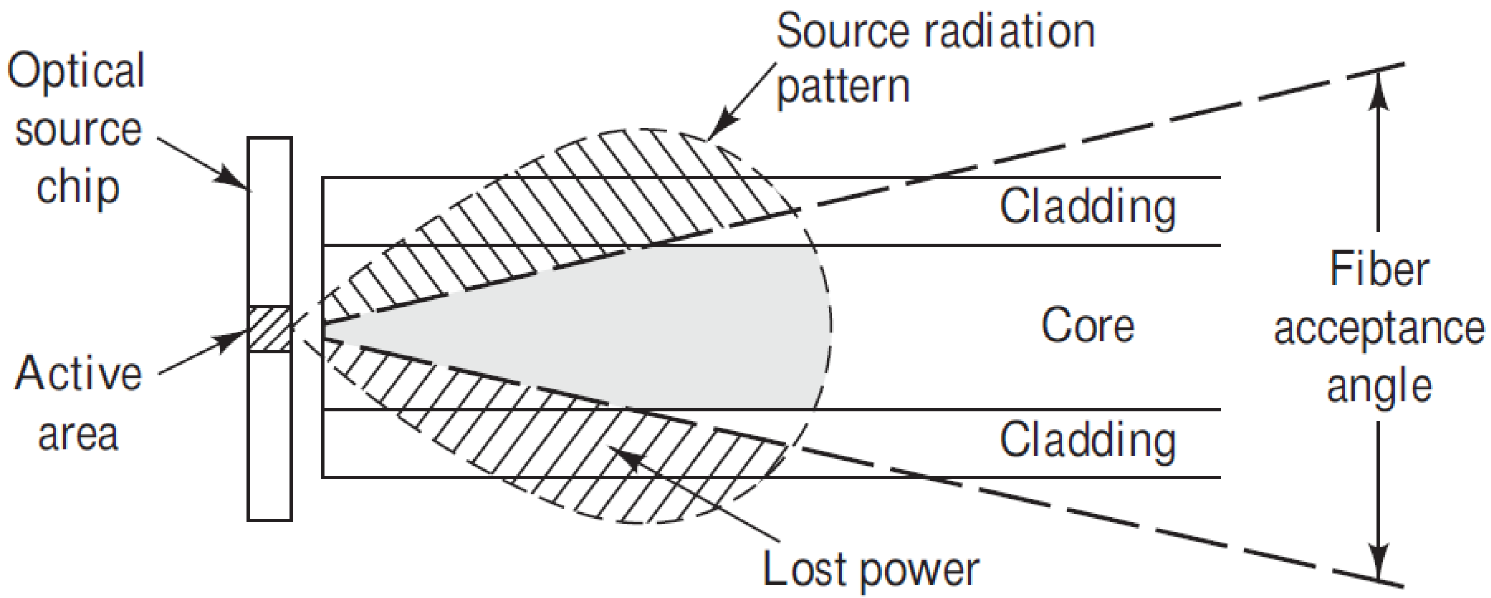
$$P_s = \pi^2 {r_s}^2 B_0$$

POWER-COUPLING CALCULATION

- Consider the fiber end face is centered over the emitting surface of the source and is positioned as close to it as possible.
- The coupled power can be found using the relationship

$$P_{C,LED} = \iint B(A_s, \Omega_s)\, dA_s \; d\Omega_s$$

where A_s and Ω_s are the area and solid emission angle of the source, respectively



Power-Coupling Calculation

$$P_{C,LED} = \int_0^{r_m}\int_0^{2\pi}\left(\int_0^{2\pi}\int_0^{\theta_A} B(\theta,\phi)\sin\theta\ d\theta\ d\phi\right) r\ d\theta_s\ dr$$

where θ_A is the acceptance angle of the fiber, $rdr\ d\theta_s$ is the emitting-point source of incremental area.

- If the source radius r_s < a (fiber-core radius), then the upper integration limit $r_m = r_s$; for source areas larger than the fiber-core area, r_m = a.

$$P_{C,LED} = \int_0^{r_s}\int_0^{2\pi} 2\pi B_0\left(\int_0^{\theta_A}\cos\theta\sin\theta\ d\theta\right) r\ d\theta_s\ dr$$

$$= \pi B_0 sin^2(\theta_A)\int_0^{r_s}\int_0^{2\pi} r\ d\theta_s\ dr = 2\pi^2 B_0 NA^2\int_0^{r_s} r\ dr$$

$$P_{C,LED} = \pi^2 {r_s}^2 B_0 NA^2 = 2\pi^2 {r_s}^2 B_0 {n_1}^2\Delta$$

$$P_{C,LED} = P_s\ NA^2$$

COUPLED POWER

- The power coupled from a surface LED source into step-index fiber

$$P_{LED,step} = \begin{cases} P_s\, NA^2; for\ r_s \le a \\ \left(\dfrac{a}{r_s}\right)^2 P_s\, NA^2; for\ r_s > a \end{cases}$$

- The power coupled from a surface-emitting LED into a graded-index fiber becomes (for $r_s < a$)

$$P_{LED,grad} = 2\pi^2 B_0 \int_0^{r_s} [n^2(r) - {n_2}^2]\, r\, dr$$

$$= 2\pi^2 {r_s}^2 B_0 {n_1}^2 \Delta \left(1 - \frac{2}{\alpha+2}\left(\frac{r_s}{a}\right)^{\alpha}\right)$$

$$= 2\, P_s {n_1}^2 \Delta \left(1 - \frac{2}{\alpha+2}\left(\frac{r_s}{a}\right)^{\alpha}\right)$$

Coupled Power for perfect coupling conditions

- For perfect coupling conditions between the source and the fiber, the power coupled into the fiber depends on Fresnel reflection or the reflectivity at the fiber-core end face (R)

$$P_{coupled} = (1 - R)P_{emitted}$$

Where

$$R = \left(\frac{n_1 - n}{n_1 + n}\right)^2$$

Here, n and n_1 are the refractive indices of the medium and fiber respectively

$$\text{Coupling loss} = -10\ \log_{10}\left(\frac{P_{Coupled}}{P_{Emitted}}\right)$$

PROBLEMS

- Consider an LED that has a circular emitting area of radius 35 mm and a Lambertian emission pattern with 150 W/(cm^2/sr) axial radiance at a given drive current. Compare the optical powers coupled into two step-index fibers, one of which has a core radius of 25 mm with NA = 0.20 and the other which has a core radius of 50 mm with NA = 0.20.
- A GaAs optical source with a refractive index of 3.6 is coupled to a silica fiber that has a refractive index of 1.48. What is the power loss between the source and the fiber? (Assume perfectly coupled)

OPTICAL FIBER CONNECTIONS AND THEIR LOSSES

- Any fiber optic system installation is requirement to interconnect fibers in a low loss manner.
- Interconnections occur
    - At the optical source
    - At the photo-detector
    - At the intermediate points within a cable where two fibers are joined
- The fiber to fiber connections may be achieved in two ways
- Splice: permanent joints b/w two fibers (it is analogous to the electrical soldering of two metallic wires)
- Connectors: demountable joints (analogous to a plug in socket arrangement)

- The losses due to fiber connections depends on parameters
  - The input power distribution to the joints
  - The length of the fiber b/w the source and joints
  - The geometrical and waveguide characteristics of the two fiber ends at the joint
  - the fiber end face qualities
- The optical power that can be coupled from one fiber to other is limited by the number of modes that can propagate in each fiber.

- For a G.I fiber , the total number of modes is estimated by

$$M = k^2 \int_0^a [n^2(r) - {n_2}^2] \, r \, dr$$

$$M = k^2 \int_0^a NA^2(r) \, r \, dr = k^2 NA^2(0) \int_0^a \left(1 - \left(\frac{r}{a}\right)^\alpha\right) r \, dr$$

$$M = \frac{\alpha}{\alpha + 2} \left(\frac{2\pi a n_1}{\lambda}\right)^2 \Delta$$

- The two fibers that are joined will have
  - Varying degree of differences in their radii ‘a’
  - Axial numerical aperture (NA(0))
  - Index profiles ‘α’

- The fraction of power coupled from one fiber to other is proportional to the common mode volume
- The fiber to fiber coupling efficiency is given by

$$\eta_F = \frac{M_{comm}}{M_E}$$

Where M_E is the number of modes in the emitting fiber

- The fiber to fiber coupling loss is given by

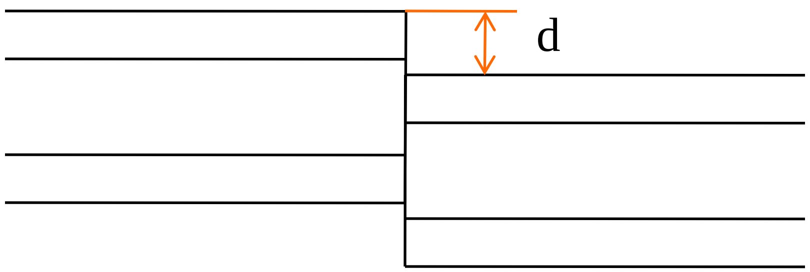
$$L_F = -10\log(\eta_F)$$

- The loss at the joint b/w multimode fibers depends on the power distribution among the modes in the fiber

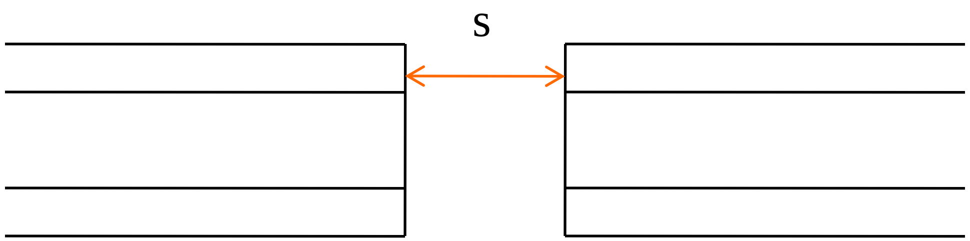
- When all modes in a fiber are equally excited, in this case for receiving fiber to accept all the optical power emitted by the first fiber
  - There must be perfect mechanical alignment b/w the two optical fibers
  - Their geometric and waveguide characteristics must match precisely
- If steady state modal equilibrium has been established in emitting fiber, most of the energy is concentrated in the lower order fiber modes (the optical power is concentrated near the center of the fiber core)
- In this case, NA of the receiving fiber is larger than the equilibrium NA of the emitting fiber
- Hence, slight mechanical misalignments do not contribute significantly to joint loss.

MECHANICAL MISALIGNMENT

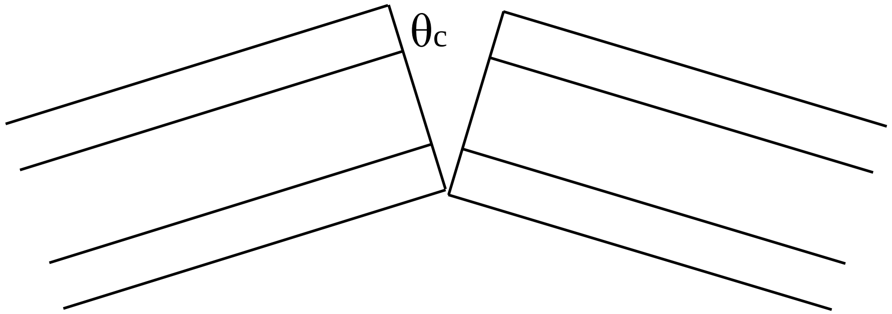
- Radiation losses results from mechanical misalignments because the radiation cone of the emitting fiber does not match the acceptance cone of the receiving fiber.
- There are three fundamental types of misalignment b/w the fibers
  - Axial displacement or lateral displacement occurs when the axes of the two fibers are separated by some distance
  - Longitudinal separation occurs when the fibers have the same axis but have a gap between their end faces
  - Angular misalignment occurs when the two axes form an angle so that the fiber end faces are no longer parallel



Lateral (axial) displacement



Longitudinal separation

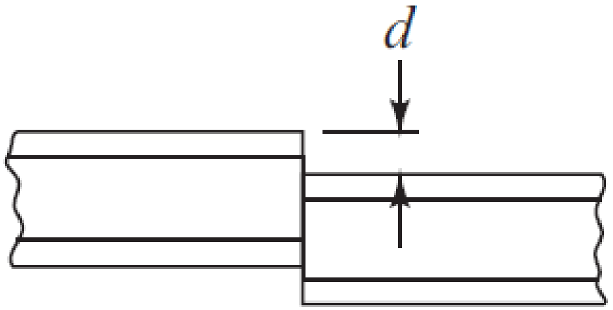


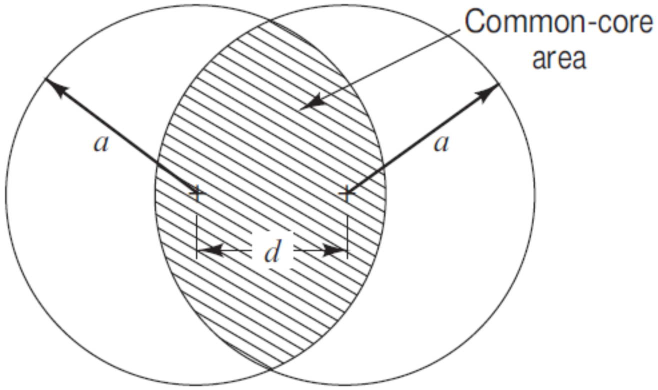
Angular misalignment

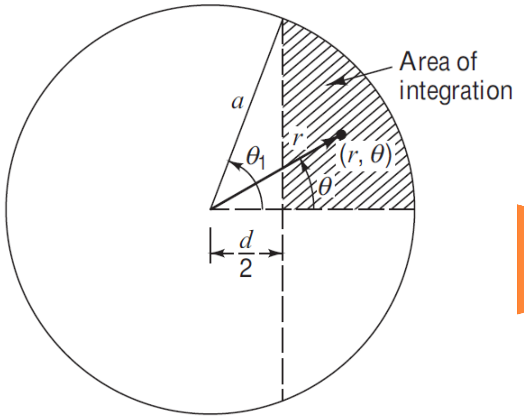
AXIAL DISPLACEMENT

- In practice, the most common misalignment occurring is axial displacement. Which causes the greatest power loss.
- It reduces the overlap area of the two fiber core end faces
- Reduces the amount of optical power that can be coupled from one fiber into other.
- Let us consider two identical S.I fibers of radii ‘a’ and assume there is uniform modal power distribution in the emitting fiber.
- In this case the optical power coupled is simply proportional to the common area of the two fibers

$$\eta_L = \frac{A_{comm}}{\pi a^2} = \frac{2}{\pi}\cos^{-1}\left(\frac{d}{2a}\right) - \frac{d}{2\pi}\sqrt{1-\left(\frac{d}{2a}\right)^2}$$







AXIAL DISPLACEMENT(CONT…)

- In G.I fiber the NA varies across the fiber end face
- The total power coupled into the receiving fiber is limited by the NA of the transmitting or receiving fiber
- The optical power density p(r) at a point ‘r’ on the fiber end is proportional to the square of the local NA at that point

$$p(r) = p(0)\frac{NA^2\,(r)}{NA^2\,(0)}$$

- For an arbitrary index profile

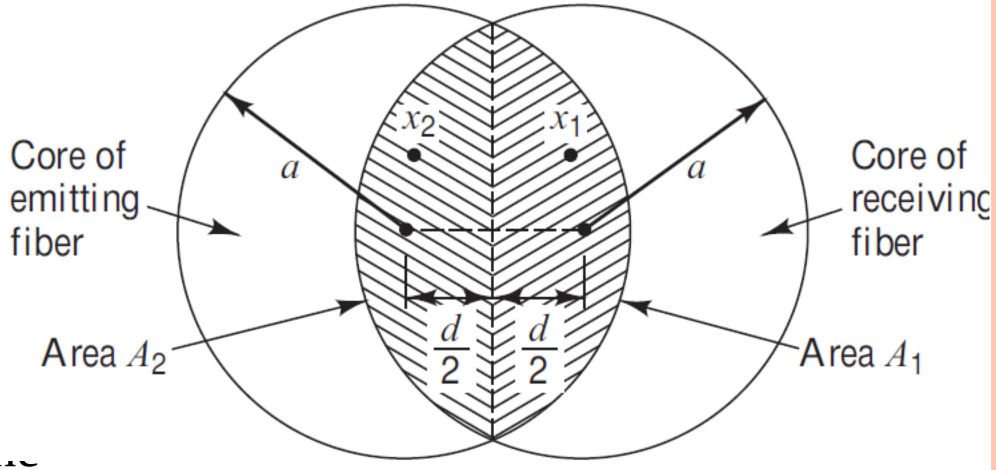
$$p(r) = p(0)\left(1 - \left(\frac{r}{a}\right)^{\alpha}\right)$$

- The total power P in the fiber is

$$P = \int_0^{2\pi}\int_0^{a} p(r)\, r\, d\theta dr$$

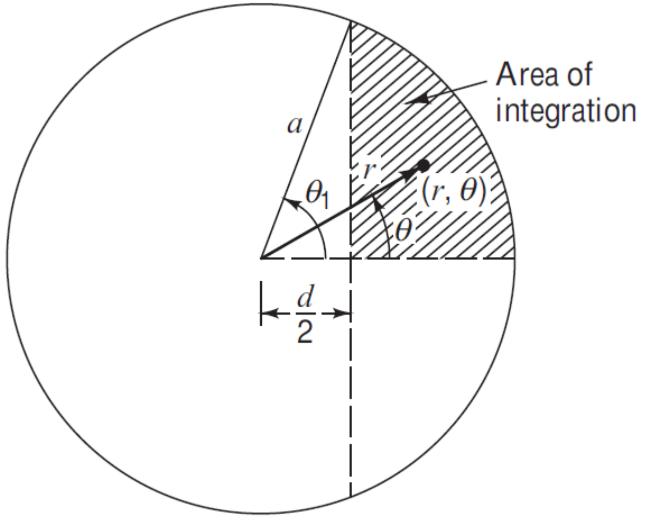
POWER COUPLED INTO THE RECEIVING FIBER

- Consider the power transmitted across the butt joint of the tw parabolic graded-index fibers with an axial offset d,
- The overlap region must be considered separately for the area A_1 and A_2.
- In area A_1 the numerical aperture is limited by that of the emitting fiber, whereas in area A_2 the numerical aperture of the receiving fiber is smaller than that of the emitting fiber.
- The received power P_1 in area A_1 is



$$P_1 = p(0)\int_{r_1}^{a}\int_{0}^{\theta_1}\left(1-\left(\frac{r}{a}\right)^2\right) r\, d\theta dr$$

$$= \frac{a^2}{2}\, p(0)\left(\cos^{-1}\left(\frac{d}{2a}\right) - \frac{d}{2\pi}\sqrt{1-\left(\frac{d}{2a}\right)^2}\right)\frac{d}{6a}\left(5-\frac{d^2}{2a^2}\right)$$



AXIAL DISPLACEMENT(CONT…)

- The total power P in the emitting fiber is

$$P = \frac{\pi a^2}{2}\, p(0)$$

- When the axial misalignment 'd' is small compared with the core radius 'a', then the total power accepted by the receiving fiber is

$$P_T \cong P\left(1 - \frac{8d}{3\pi a}\right)$$

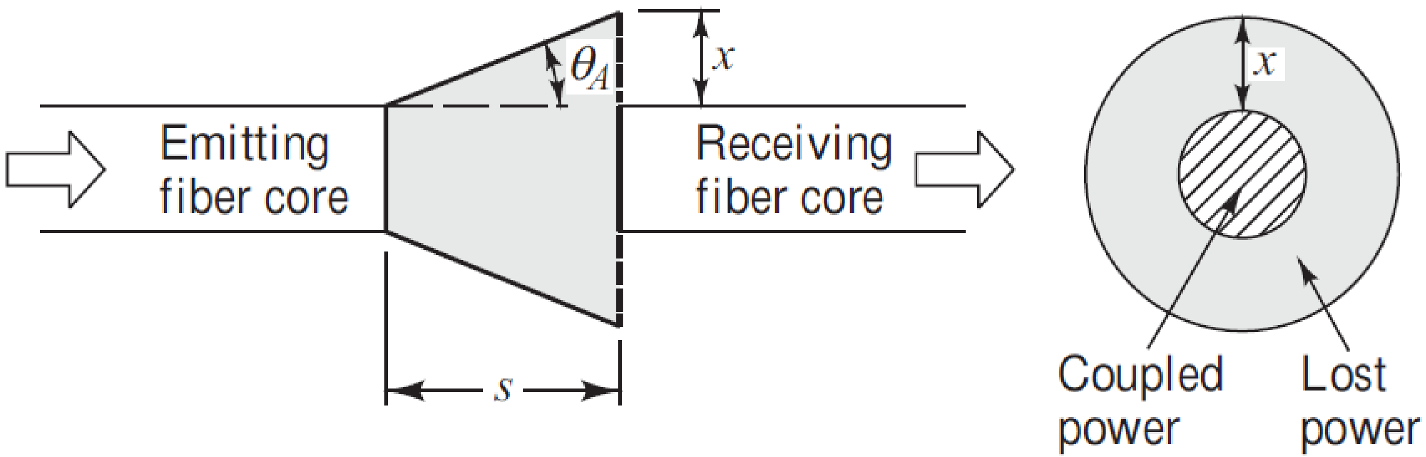
- The coupling loss is

$$L_F = -10\log\left(\frac{P_T}{P}\right)$$

LONGITUDINAL SEPARATION

- All the higher mode optical power emitted in the ring of the width 'x' will not be intercepted by the receiving fiber
- For S.I fiber, the loss is

$$L_F = -10\log\left(\frac{a}{a + s\tan\theta_A}\right)^2$$



ANGULAR MISALIGNMENT

- In this case, the optical power that leaves the emitting fiber outside of the solid acceptance angle of the receiving power
- For two S.I fibers that have an angular misalignment ‘θ’ , the power loss at the joint is

$$L_F = -10\log\left(\cos\theta\left\{\frac{1}{2}-\frac{1}{\pi}\left(p(1-p^2)^{1/2}-\sin^{-1}(p)\right)-q\left[\frac{1}{\pi}\left(y(1-y^2)^{1/2}+\sin^{-1}(y)\right)+\frac{1}{2}\right]\right\}\right)$$

$$p = \frac{\cos\theta_c\,(1-\cos\theta)}{\sin\theta_c\sin\theta}$$

$$q = \frac{\cos^3\theta_c}{(\cos^2\theta_c-\sin^2\theta)^{3/2}}$$

$$y = \frac{\cos^2\theta_c\,(1-\cos\theta)-\sin^2\theta}{\sin\theta_c\cos\theta_c\sin\theta}$$

FIBER RELATED LOSSES

- Difference in the geometrical and waveguide characteristics will effect on fiber to fiber coupling losses
- These are variations in **core diameter, numerical aperture** and **refractive index profile**
- If the radii are not equal but axial NA and index profiles are equal, the coupling loss is

$$L_F(a) = \begin{cases} -10\ \log_{10}\left(\dfrac{{a_R}^2}{{a_E}^2}\right); & for\ a_R < a_E \\ 0; & for\ a_R \geq a_E \end{cases}$$

- If the radii and the index profiles of the two coupled fibers are identical but their axial numerical apertures are different, then

$$L_F(NA) = \begin{cases} -10\ \log_{10}\left(\dfrac{{NA_R}^2(0)}{{NA_E}^2\ (0)}\right); & for\ NA_R(0) < NA_E(0) \\ 0; & for NA_R(0) \geq NA_E(0) \end{cases}$$

FIBER RELATED LOSSES

- If the radii and axial NAs are equal but index profiles are different, the coupling loss is

$$L_F(a) = \begin{cases} -10\ \log_{10}\left(\dfrac{\alpha_R(\alpha_E+2)}{\alpha_E(\alpha_R+2)}\right); & for\ \alpha_R < \alpha_E \\ 0; & for\ \alpha_R \geq \alpha_E \end{cases}$$

TEXT BOOKS

1. Gerd Keiser, Optical Fiber Communications, TMH India, Fourth Edition, 2010.
2. Senior John M., Optical Fiber Communications, Pearson Education India, Third Edition, 2009.

COURSE: *OPTICAL COMMUNICATION* (EC317)

UNIT-V OPTICAL NETWORKS

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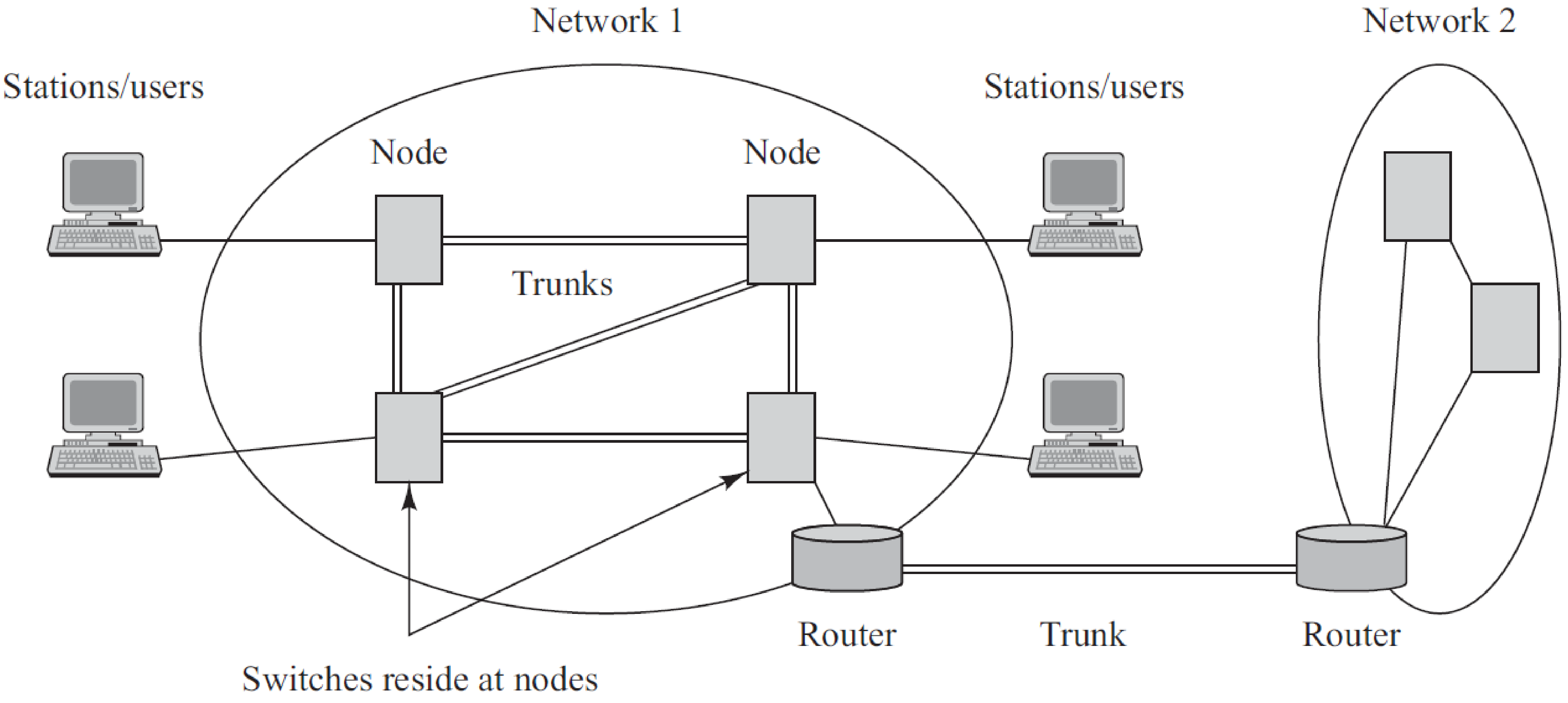
INTRODUCTION

- Telephone companies and community access television (CATV) providers are competing to offer subscribers the triple play services of voice, video, and high-speed data access.
- Both telephone and CATV networks have relied on copper cables to connect through the last mile to their subscribers, but a coaxial cable of the CATV companies has superior bandwidth capabilities relative to the twisted pair
- The main characteristics of optical fibers compared to other transmission mediums- wide bandwidth in the 1,550 nm range with a very low attenuation around 0.2 dB/km
- This bandwidth enables transmission bit rates up to the Gbps range on point-to-point fiber links of a few tens of km

NETWORK


Network 1
Network 2
Stations/users
Stations/users
Node
Node
Trunks
Router
Trunk
Router
Switches reside at nodes

General Network terminology

- **Stations:** Devices that network subscribers use to communicate are called stations. These may be computers, monitoring equipment, telephones, fax machines, or other telecommunication equipment.
- **Networks:** To establish connections between these stations, transmission paths run between them to form a collection of interconnected stations called a network.
- **Node:** Within this network, a node is a point where one or more communication lines terminate and/or where stations are connected. Stations also can be connected directly to a transmission line.
- **Trunk:** The term trunk normally refers to a transmission line that runs between nodes or networks and supports large traffic loads.
- **Topology:** The topology is the logical manner in which nodes are linked together by information transmitting channels to form a network (bus, ring, star, mesh etc.)
- **Switching and routing:** The transfer of information from source to destination through a series of intermediate nodes is called switching, and the selection of a suitable path through a network is referred to as routing.

OPTICAL NETWORK

- A telecommunications network with **optical fiber as the primary transmission medium**, which is designed to take advantage of the unique characteristics of optical fibers.

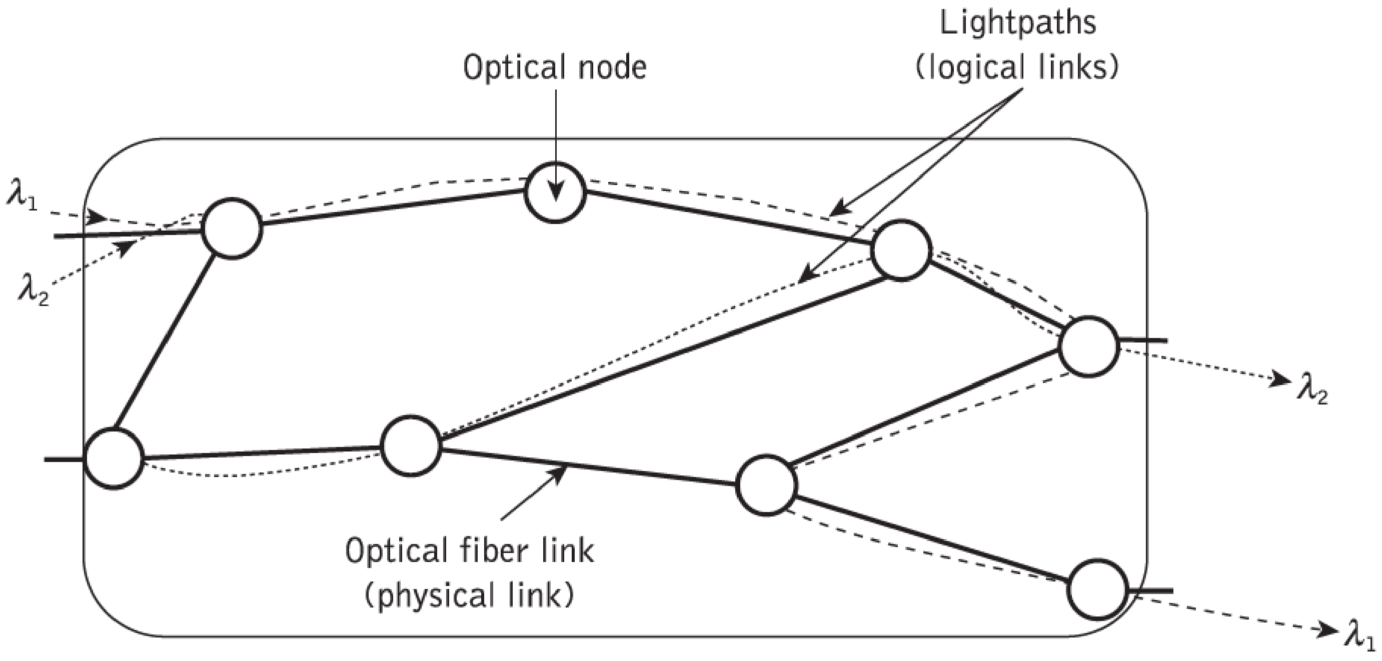
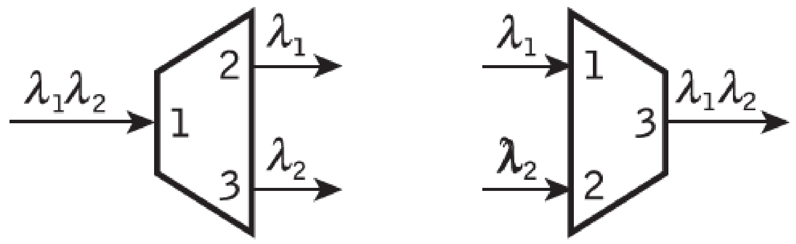
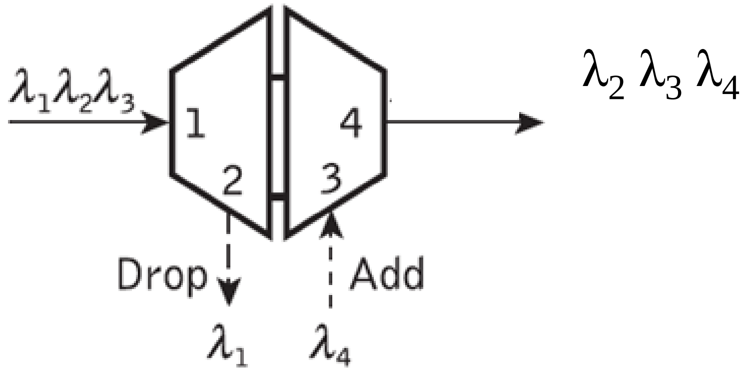


Fig: Optical network structure

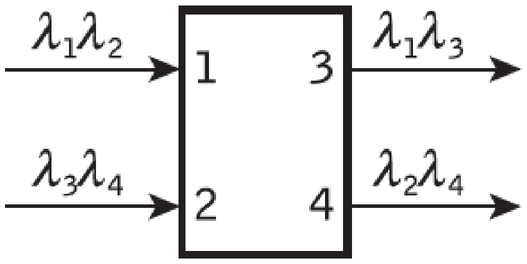
OPTICAL NETWORKING NODE ELEMENTS



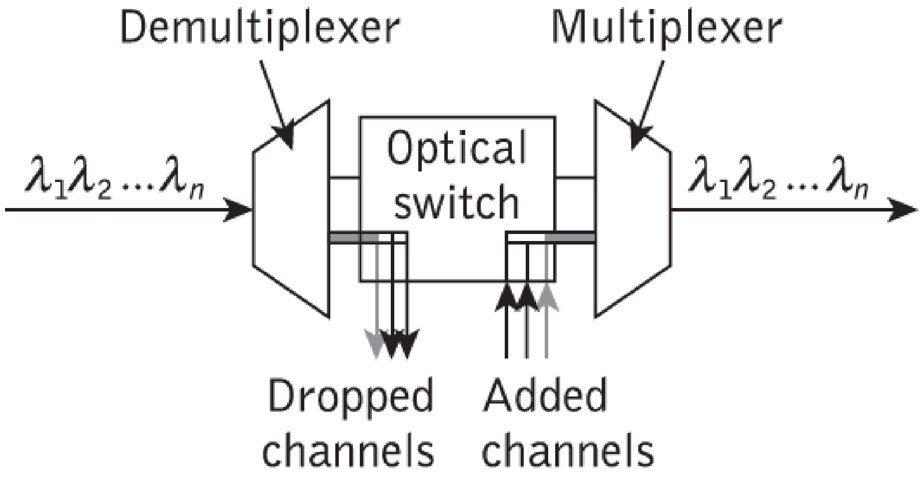
(a) wavelength demultiplexer and multiplexer



(b) optical add/drop multiplexer

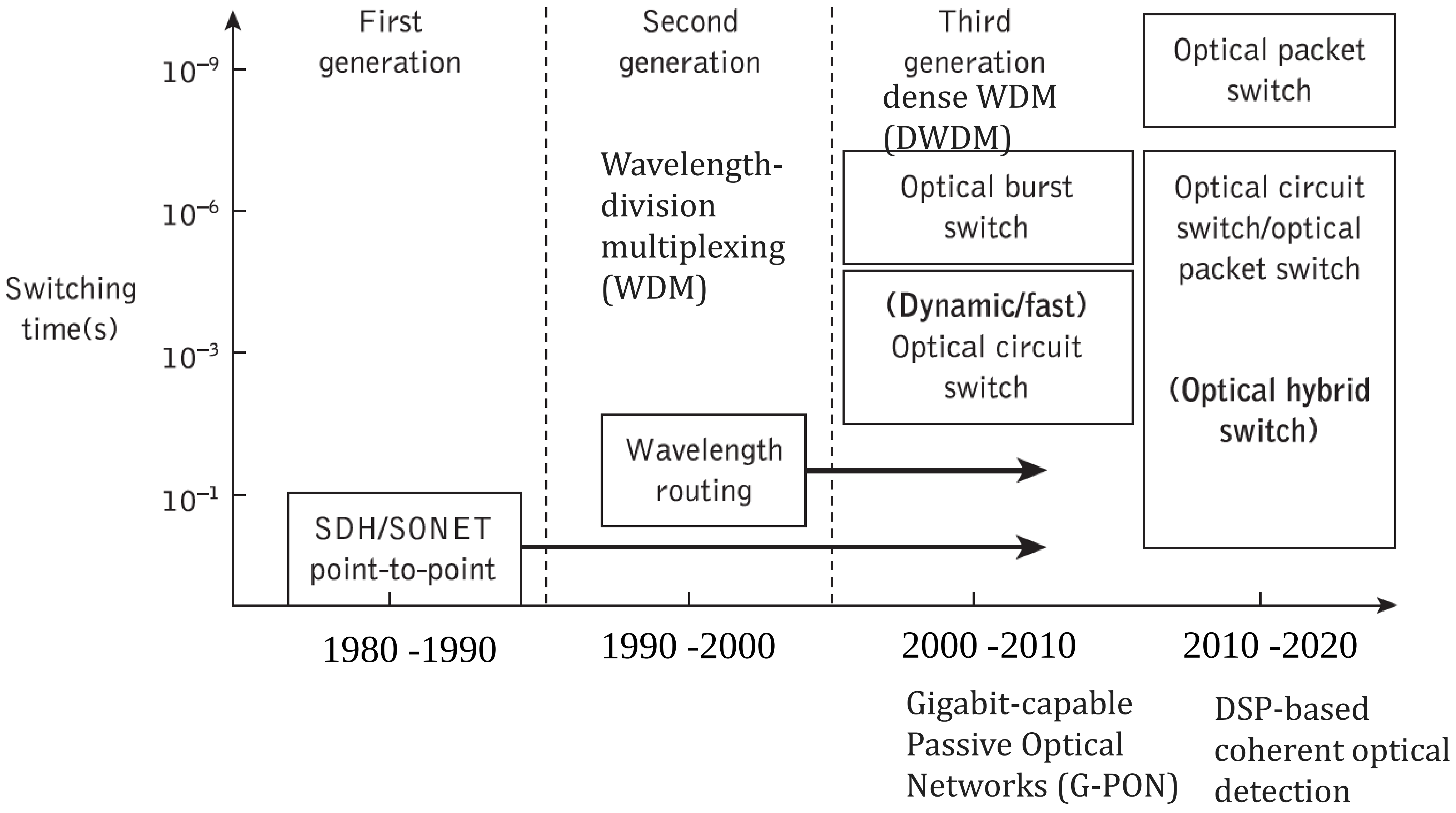


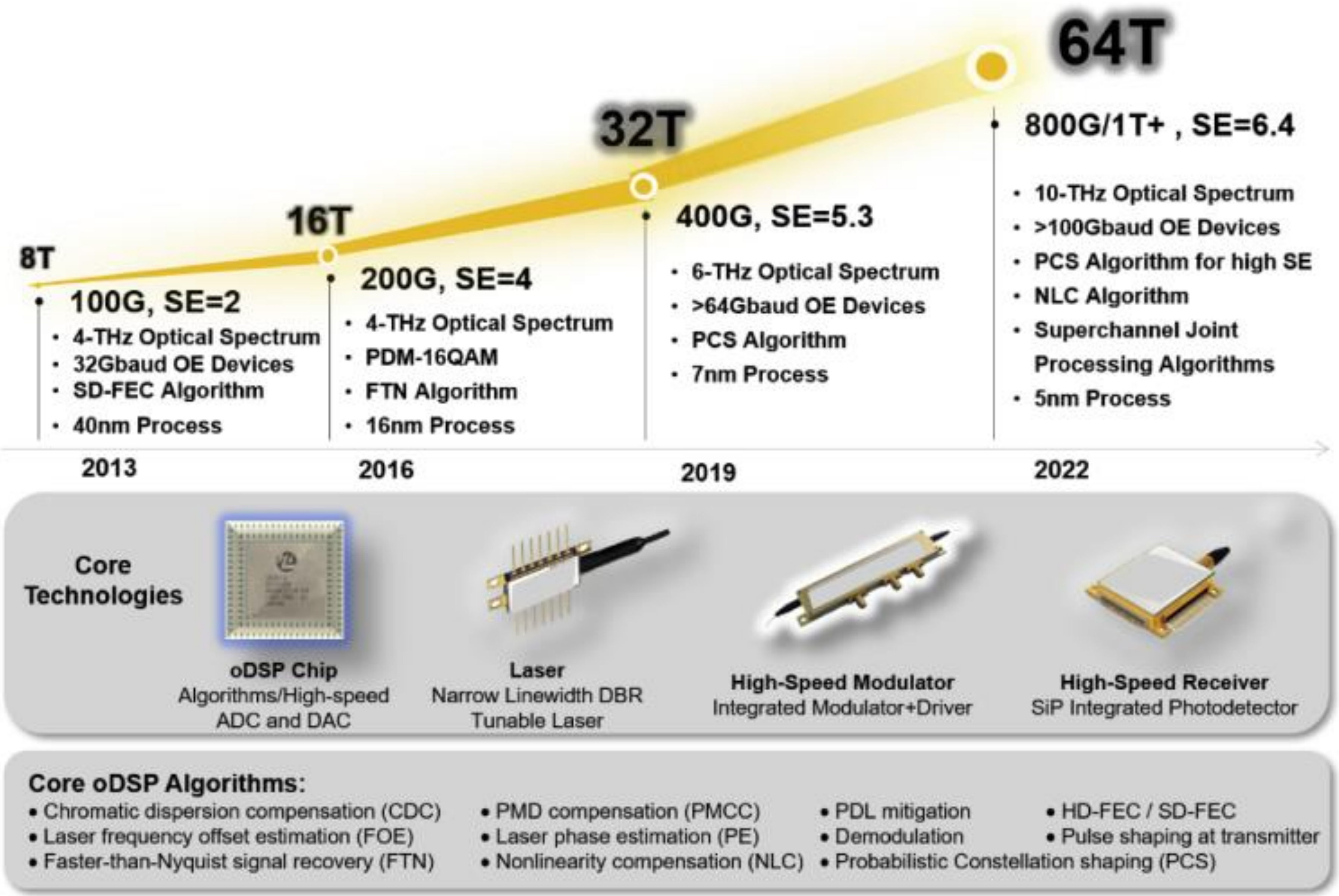
(c) 2x2 optical switch



(d) reconfigurable optical add/drop multiplexer

Optical fiber network evolution





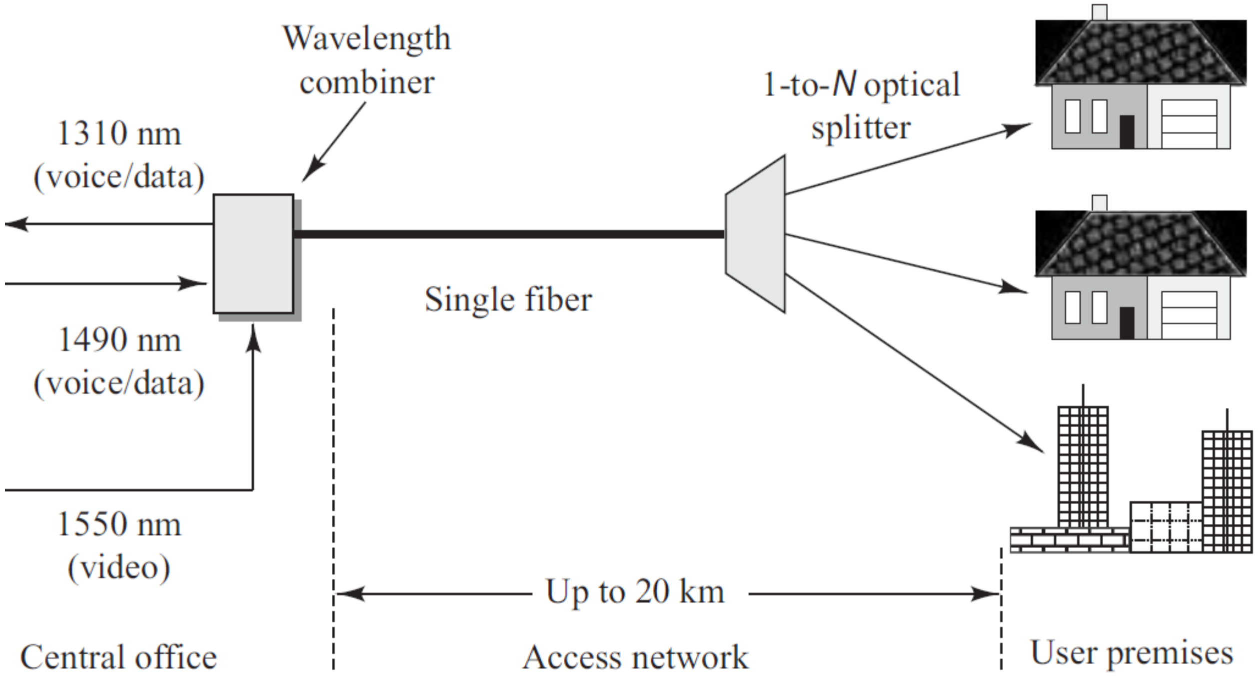
Probabilistic constellation shaping (PCS)

nonlinearity compensation (NLC)

Ref: Liu, X. (2019). Evolution of Fiber-Optic Transmission and Networking toward the 5G Era. *IScience*, *22*, 489-506. https://doi.org/10.1016/j.isci.2019.11.026

Passive Optical Networks (PON)

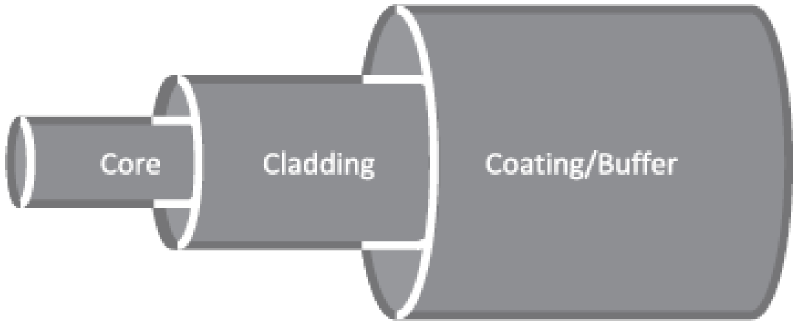
- A **passive optical network** (**PON**) is a optical fiber telecommunication technology used to deliver broadband services to the subscriber
- As the name implies, there is no active component between the central office and the user premises.
- Both ITU and IEEE have standardized solutions for PONs operating at Gbps line rates
- The application of PON technology for providing broadband connectivity in the access network to homes, multiple-occupancy units, and small businesses commonly is called fi ber-to-the-x (FTTx).
- Basic Optical Access Network Components: Optical Fiber, Optical Power Splitter, Wavelength Routing Devices



Architecture of a typical passive optical network

Optical Fiber Structure

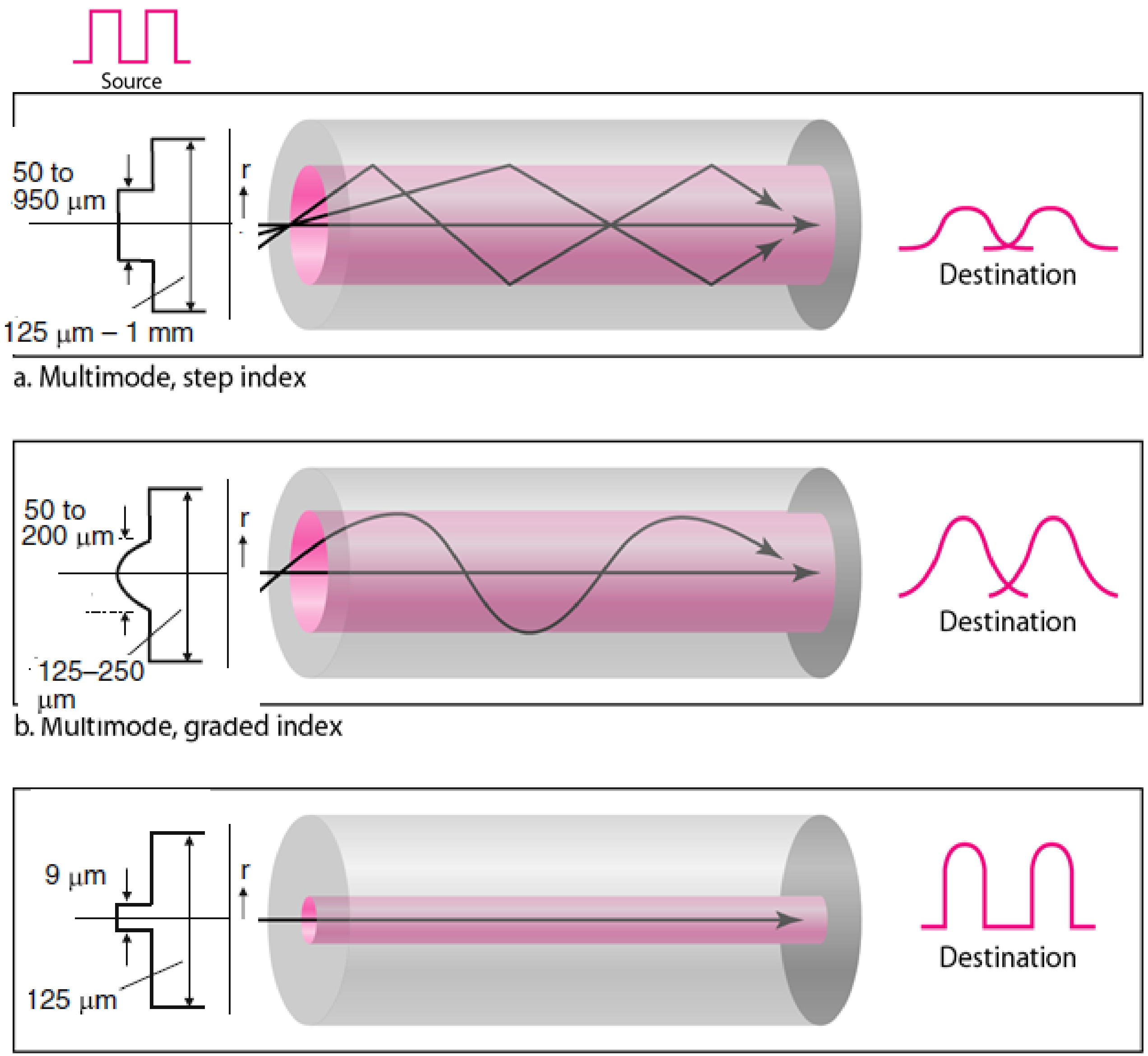
- Optical fiber used in optical communications consists of a cylindrical dielectric core surrounded by dielectric cladding.



Optical fiber structure.

- 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
- Used to transmits signals in the form of light.

Propagation of Light



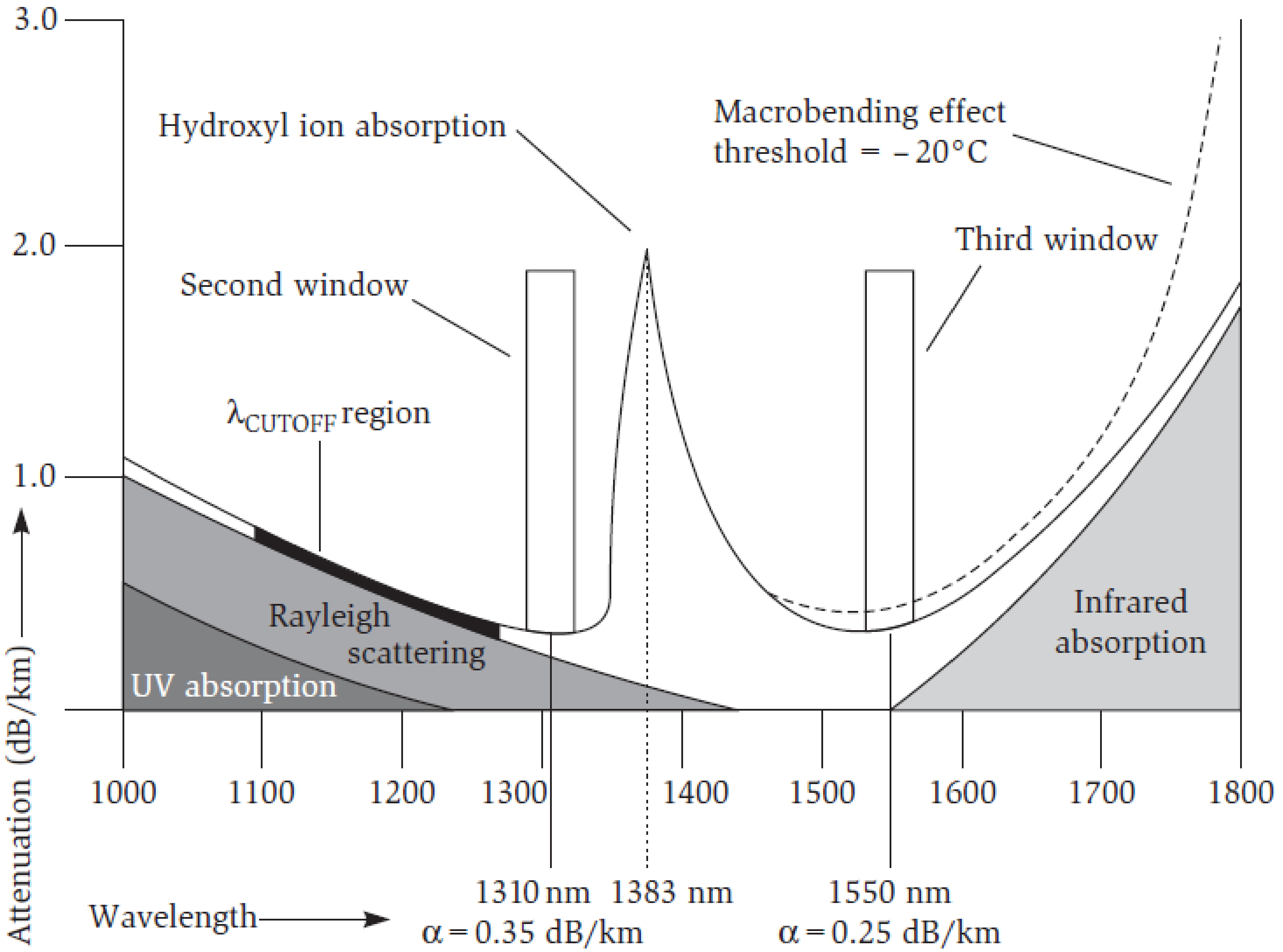
a. Multimode, step index

b. Multimode, graded index

c. Single mode

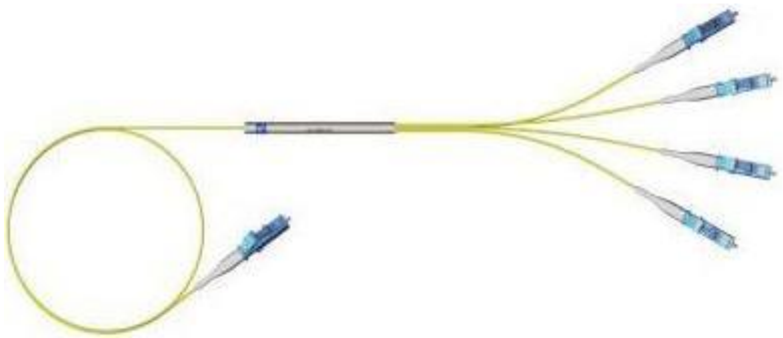
- Density of the core remains constant from center to the edge
- Density of the core is highest at the center and decreases gradually to its lowest at the edge.
- Single mode fiber is made of much smaller diameter and with low density which results in critical angle close to 90^0.

- A typical silica glass fiber exhibits different path losses at different wavelengths.
- Path loss is minimum in three regions of light ‘color’ with wavelengths of 1.2, 1.3 and 1.5 μm with losses of less than 1 dB/km.



Optical Power Splitters

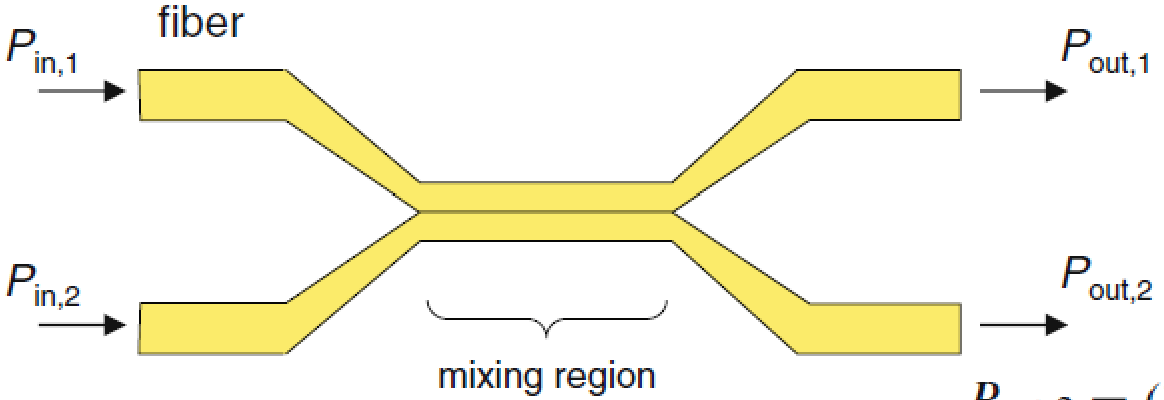
- Optical power splitting devices enable the distribution of light from its input port to multiple output ports (i.e. Splits an incoming light source into two separate paths)
- The light is replicated and has no affect on bandwidth
- If the splitter is designed to divide the incident optical power evenly into N separate paths and if P is the optical power entering the splitter, then the power level going to each subscriber is P/N.
- Designs of power dividers with other splitting ratios are also possible depending on the application. The number of splitting paths can vary from 2 to 64, but in a PON they typically are 8, 16, or 32.
- optical point-to-multipoint access networks.
- Types of splitters
  - Fused Biconical Taper (FBT) – low split count
  - Planar Lightwave Circuits (PLC) – high split count



Optical Power Splitter

- Basic optical power splitter is a 2 × 2 fused fiber coupler, schematically shown in Fig

$$P_{\mathrm{out},1} = x \cdot \varepsilon P_{\mathrm{in},1} + (1-x) \cdot \varepsilon P_{\mathrm{in},2}$$

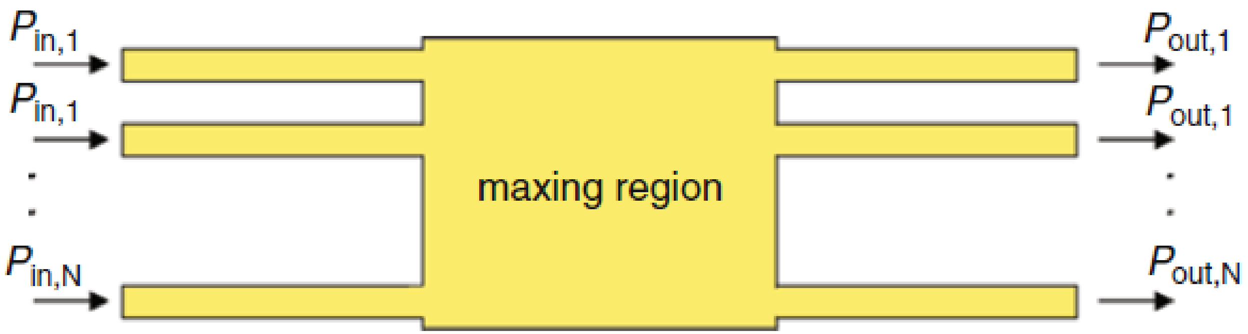


$$P_{\mathrm{out},2} = (1-x) \cdot \varepsilon P_{\mathrm{in},1} + x \cdot \varepsilon P_{\mathrm{in},2}$$

where the excess loss factor

$\varepsilon = (P_{\mathrm{out},1} + P_{\mathrm{out},2})/(P_{\mathrm{in},1} + P_{\mathrm{in},2})$ with $\varepsilon \leq 1$

the slitting ration is $x/(1-x)$

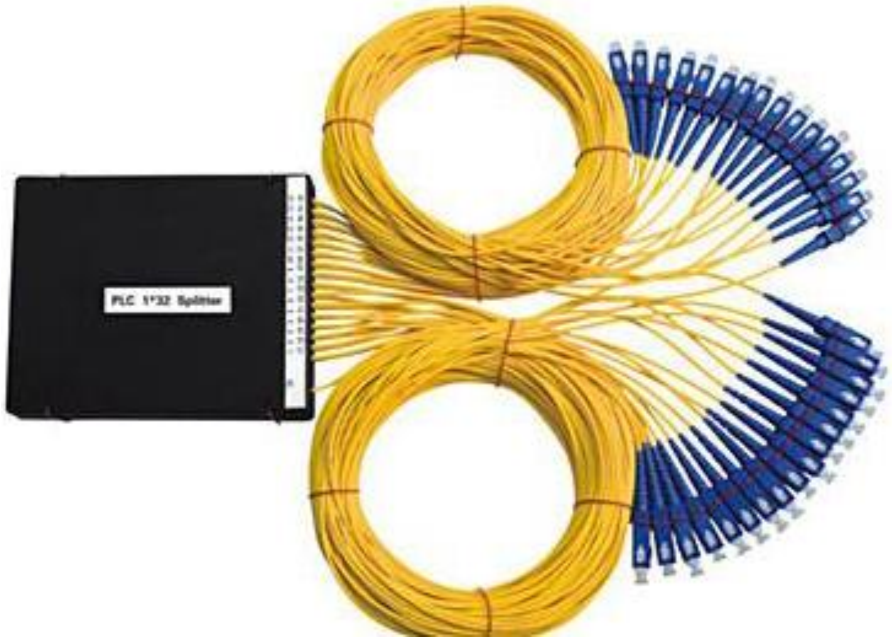


$N \times N$ power splitter

The relation between the input and output powers is

$$P_{\text{out},\,j} = \varepsilon \sum_{i=1}^{N} x_{ij}\, P_{\text{in},i}$$

$$\varepsilon = \sum_{j=1}^{N} P_{\text{out},\,j} \Big/ \sum_{i=1}^{N} P_{\text{in},i} \text{ with } \varepsilon \le 1.$$

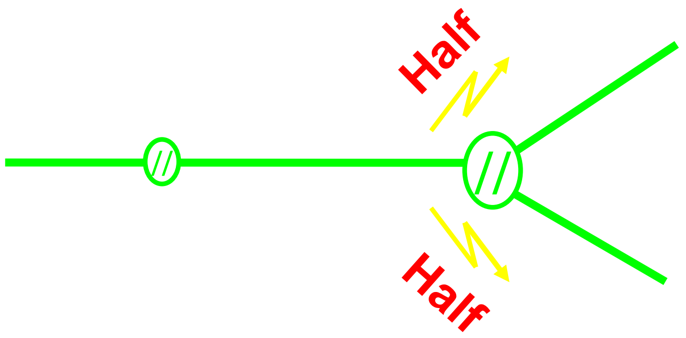


Fiber Loss in PON

- In PONs, the channel loss consists of fiber and splitter losses (neglecting connector and splice losses), given by
- where α_f is the fiber loss in dB/km, L the fiber length, and C_{splitter} the splitter loss.

$$C_L = \alpha_f L + C_{splitter}$$

- Typical fiber loss per km: 0.25 dB for1550 nm and 0.4 dB 1260 - 1360 nm
- When the signal is split two ways, half the power goes one way and half goes the other.
- So each direction gets half the power, or the signal is reduced by 10log(0.5)=3 dB.



PON LINK BUDGETS

- In optical communication system design, a certain power budget is required to ensure that enough power will reach the receiver to maintain reliable performance
- The minimum average power required by the optical receiver is specified by the receiver sensitivity P_s , and the average launch power of a transmitter P_t . Then the power budget is expressed in the equation

$$P_t - P_s > C_L + M_s$$

$$P_{budget}(dB) > \alpha L + 10 \log_{10}(N) + M_s(dB)$$

- The maximum transmission distance in PONs is given by

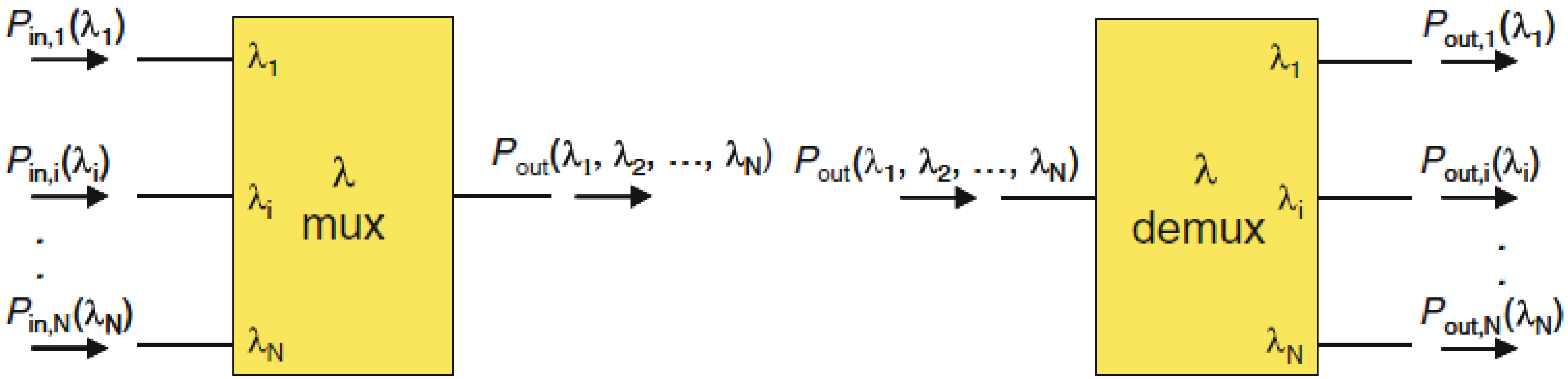
$$L \leq \frac{P_{budget}(dB) - C_{splitter} - M_s}{\alpha}$$

Example

- Link budget (Maximum loss planned) is 21 dB
- Typically, at 1550 nm, fiber exhibits loss of about 0.25 dB/km & at 1310 nm loss is 0.4 db/km.
- The Maximum distance without amplification is about 80 km
- Each two-way split results in a loss of nominally ~3.5 dB of level, assume 4 dB worst case.
  - Thus, each two-way split costs about 16 km distance for 1550 nm & 10 km for 1310 nm

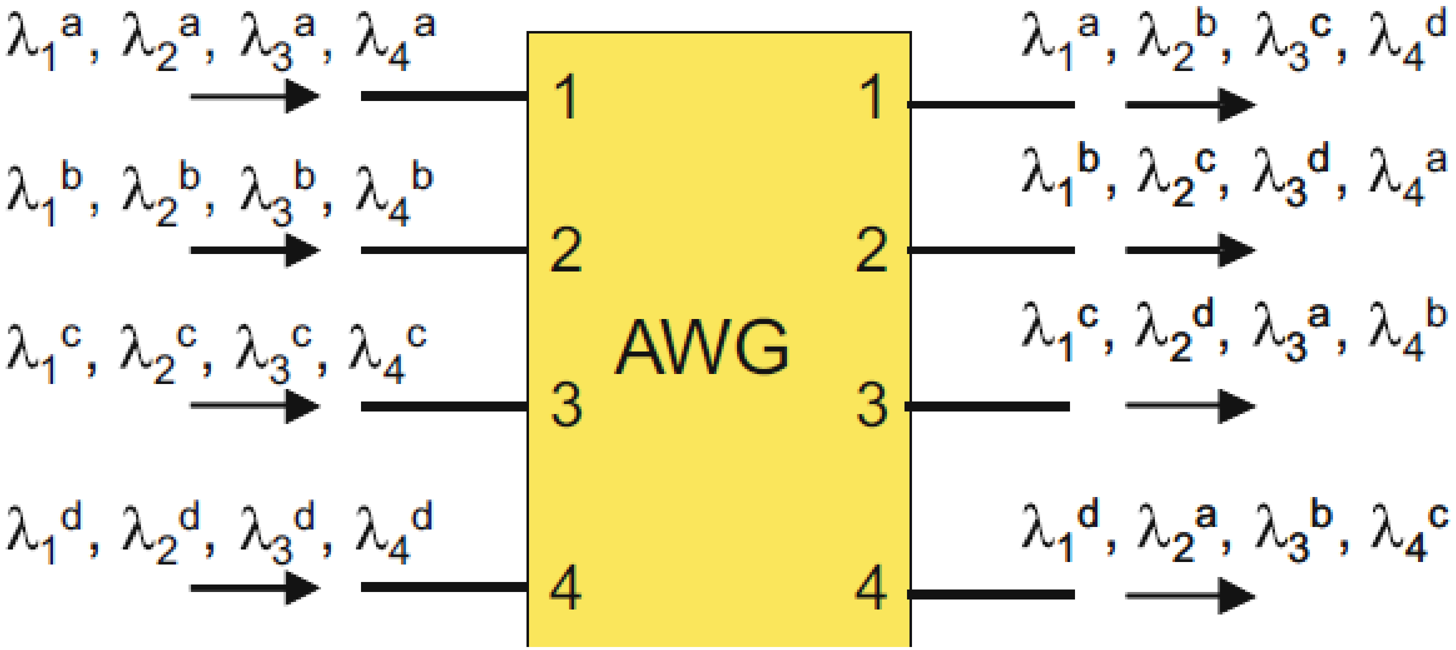
Wavelength Routing Devices

- A wavelength multiplexer accepts optical signals inserted at its input ports and routes these signals to its output port
- At each input port, it accepts only a signal which is positioned in a specific wavelength band
- As the routing of each signal is dependent on its wavelength, there are no power splitting losses
- The wavelength-dependent routing can be accomplished by means of wavelength dependent refraction, such as in a **prism, or by means of multiple beam interference processe**s such as in **grating structures or multilayer interference filters**.



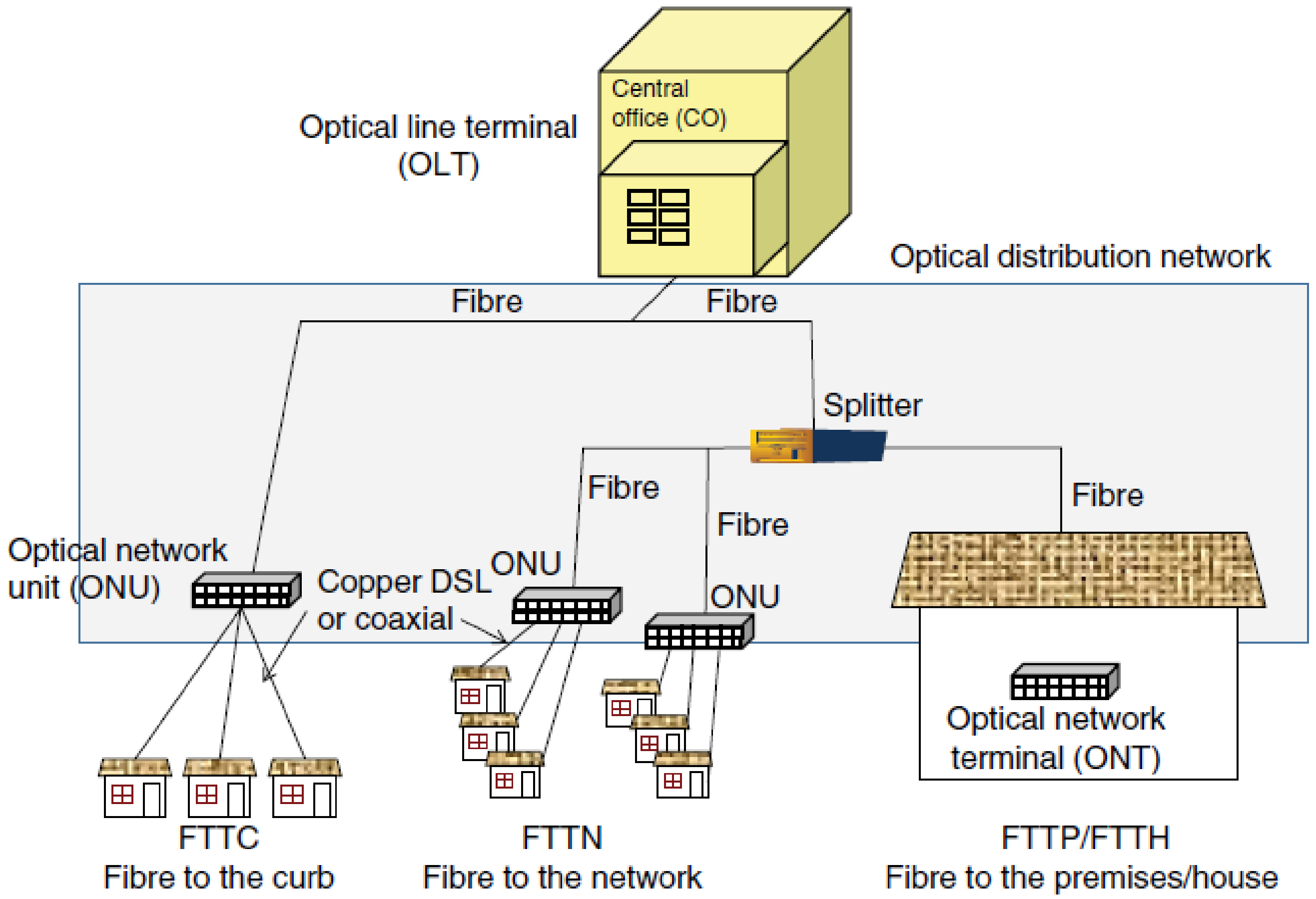
(a) Wavelength multiplexer (b) Wavelength demultiplexer

A wavelength router with multiple input ports and output ports can perform more comprehensive wavelength routing actions. The so-called **arrayed waveguide grating router (AWG) performs** a cyclic routing of the wavelengths injected at its input ports toward its output ports.



PON ARCHITECTURE

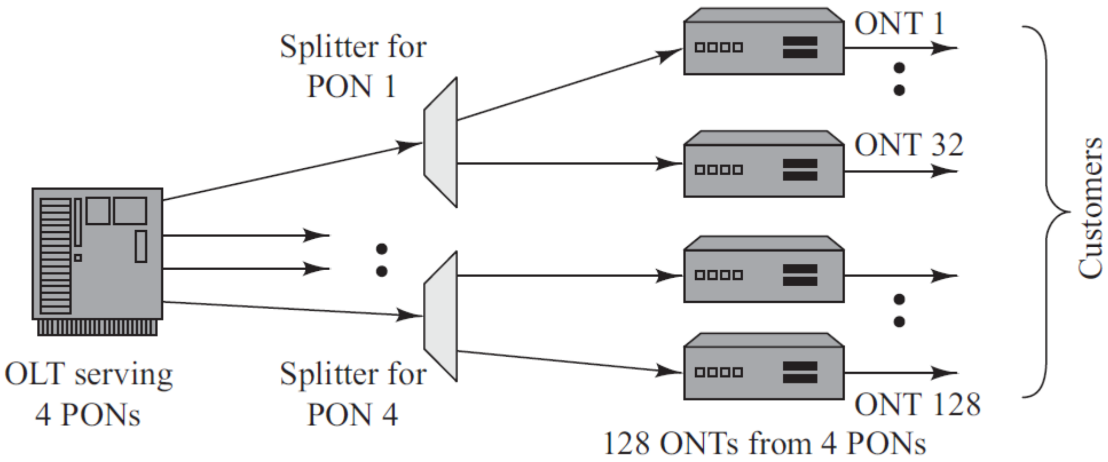
- A PON implements point – to – multipoint architecture, where a single optical line is divided into many optical splitters to serve multiple customers.
- PON systems are limited in range and bandwidth.
- Current PONs typically support up to 32 to 64 splits and up to 20 km.
- The dimension of a PON system is restricted in part by the power budget.
- In realistic deployment, this dimension is further restricted by the fiber dispersion and dynamic range of the upstream receiver
- The active devices exist only in the central office and at the user end.
  - optical line terminal (OLT)
  - optical network units (ONUs)



A passive optical network architecture

OPTICAL LINE TERMINAL (OLT)

- The OLT is located in a central office and controls the bidirectional flow of information across the network.
- It must be able to support transmission distances of up to 20 km and transmits signals to all optical network units (ONUs), which forward the downstream packets to all subscribers within their networks.
- A typical OLT is designed to control more than one PON. In this case, if there are 32 connections to each PON, then the OLT can distribute information to 128 users.
- Downstream traffic is sent from OLTs using a 1490-nm wavelength, and upstream traffic (voice and data) from ONUs is carried on a 1310 nm wavelength and a 1550-nm wavelength for video distribution.



OPTICAL NETWORK UNIT (ONU)

- At the user end, an optical network unit (ONU), also called an optical network terminal (ONT), transmits upstream data at 1310-nmwavelength and has interfaces to user devices like PC, TV set, telephone set, etc.
- The link from the ONU to the customer premises can be a twisted-pair copper wire, a coaxial cable, an independent optical fiber link, or a wireless connection.

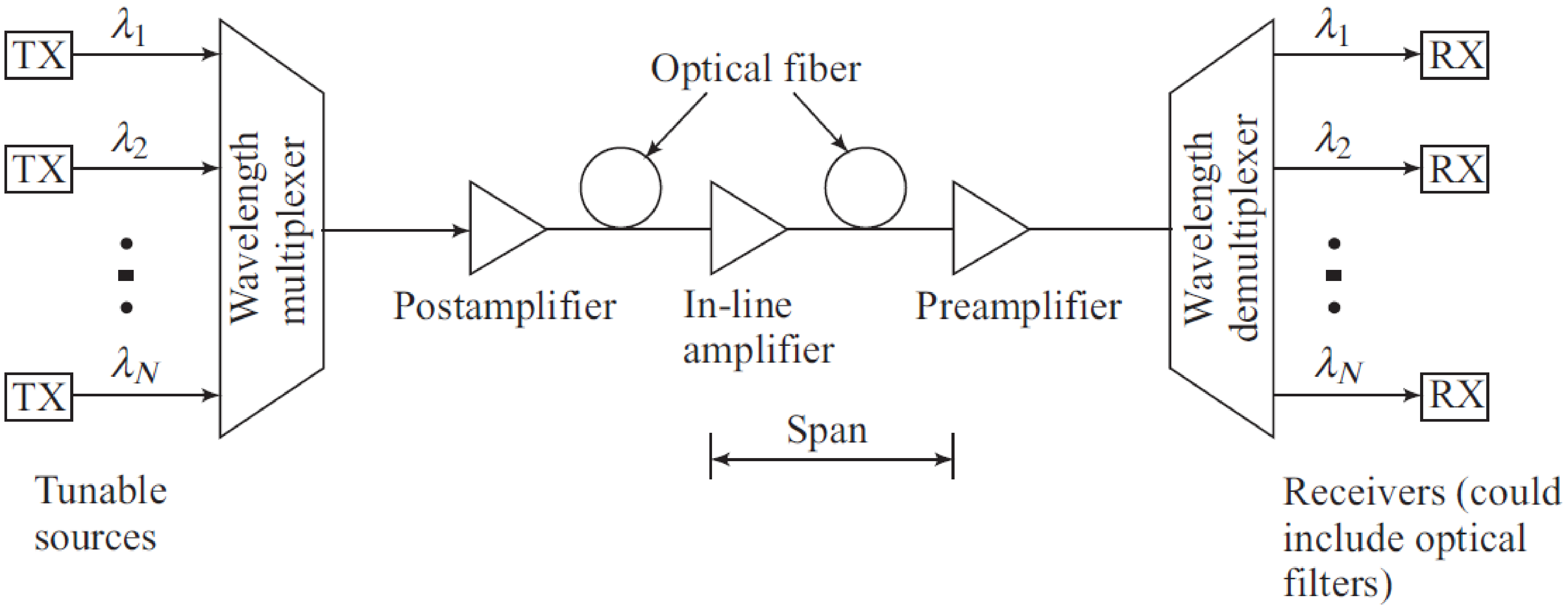
Types of PONs

- **Asynchronous Transfer Mode PONs (APON)**
  - the first standardized PON solution, supports the legacy of ATM protocols at 622 Mb/s (OC-12) of downstream bandwidth and 155 Mb/s (OC-3) of upstream bandwidth
- **Broadband PONs (BPONs)**
  - improved solution for ITU-T G.983.1
  - relatively high cost compared to Ethernet
- **Gigabit- PONs (GPONs)**
  - combines the features of both ATM and Ethernet to provide a more efficient and flexible network usage.
  - GPON provides downstream speeds of 2.5 Gb/s and upstream speeds of 1.25 Gb/s. It is based on the G.984.1 to G.984.6 series of ITU-T Recommendations
- **Ethernet PONs (EPONs)/ gigabit Ethernet PON (GE-PON)**
  - the Ethernet in the first-mile (EFM) 802.3ah study group has standardized Ethernet PON (EPON) to leverage the commercial success of Ethernet as a local area network (LAN) technology
- **WDM PON** uses a different wavelength for each user to greatly enhance network capacity. In this architecture a wavelength multiplexer (usually an AWG) is used in place of the power splitter

WAVELENGTH DIVISION MULTIPLEXING (WDM)

- The basic principle of WDM is that the discrete wavelengths form an orthogonal set of carriers that can be separated, routed, and switched without interfering with each other.
- The implementation of sophisticated WDM networks requires a variety of **passive and active devices to combine, distribute, isolate, and amplify optical power** at different wavelengths.
- Passive devices require **no external control for their operation**, so they are somewhat limited in their application flexibility. These components are mainly used to **split and combine or tap off optical signals**.
- The wavelength-dependent performance of active devices can be **controlled electronically or optically**, thereby providing a **large degree of network flexibility**. Active WDM components include **tunable optical filters, tunable sources, and optical amplifiers**.

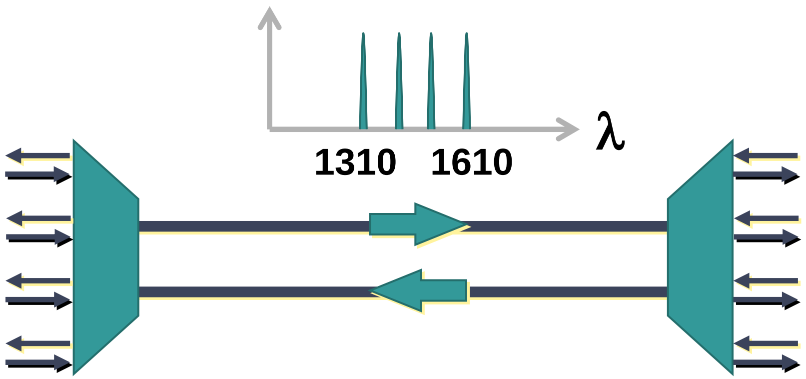
WDM

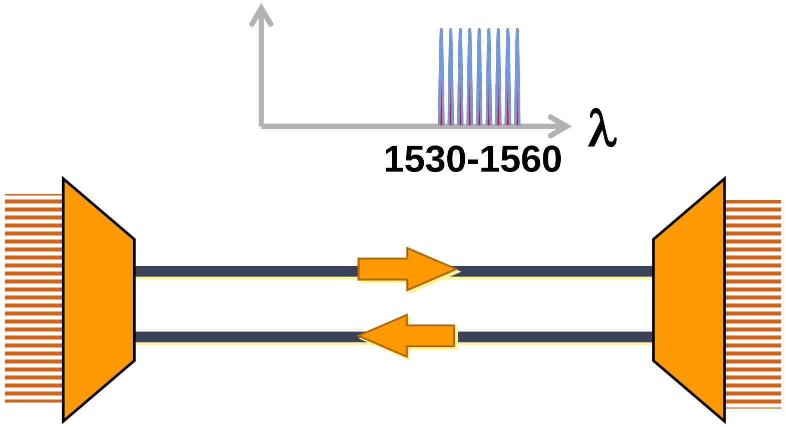


- At the transmitting end there are several independently modulated light sources, each emitting signals at a unique wavelength. Here a multiplexer is needed to combine these optical outputs into a continuous spectrum of signals and couple them onto a single fiber.
- At the receiving end a demultiplexer is required to separate the optical signals into appropriate detection channels for signal processing.

Variations in WDM

- **CWDM—Coarse Wavelength Division Multiplexing**
  - Typically 4–16 wavelengths per fiber
  - Wavelengths spread farther apart
  - Difficult to amplify
  - Low cost
- **DWDM—Dense Wavelength Division Multiplexing**
  - Typically 16+ wavelengths per fiber
  - Wavelengths close together: less than 200 GHz
  - Increased density and capacity

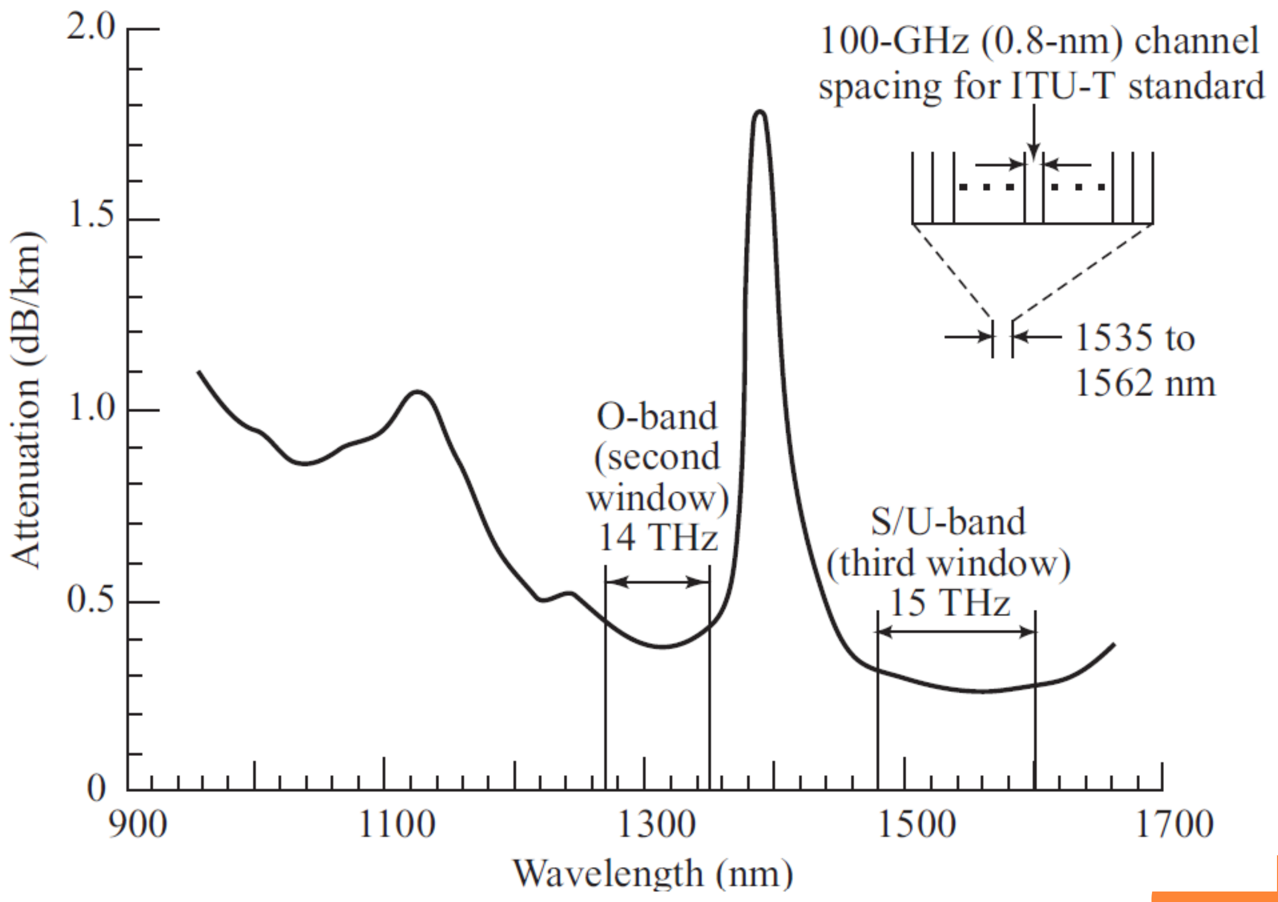




Spectrum Partitioning

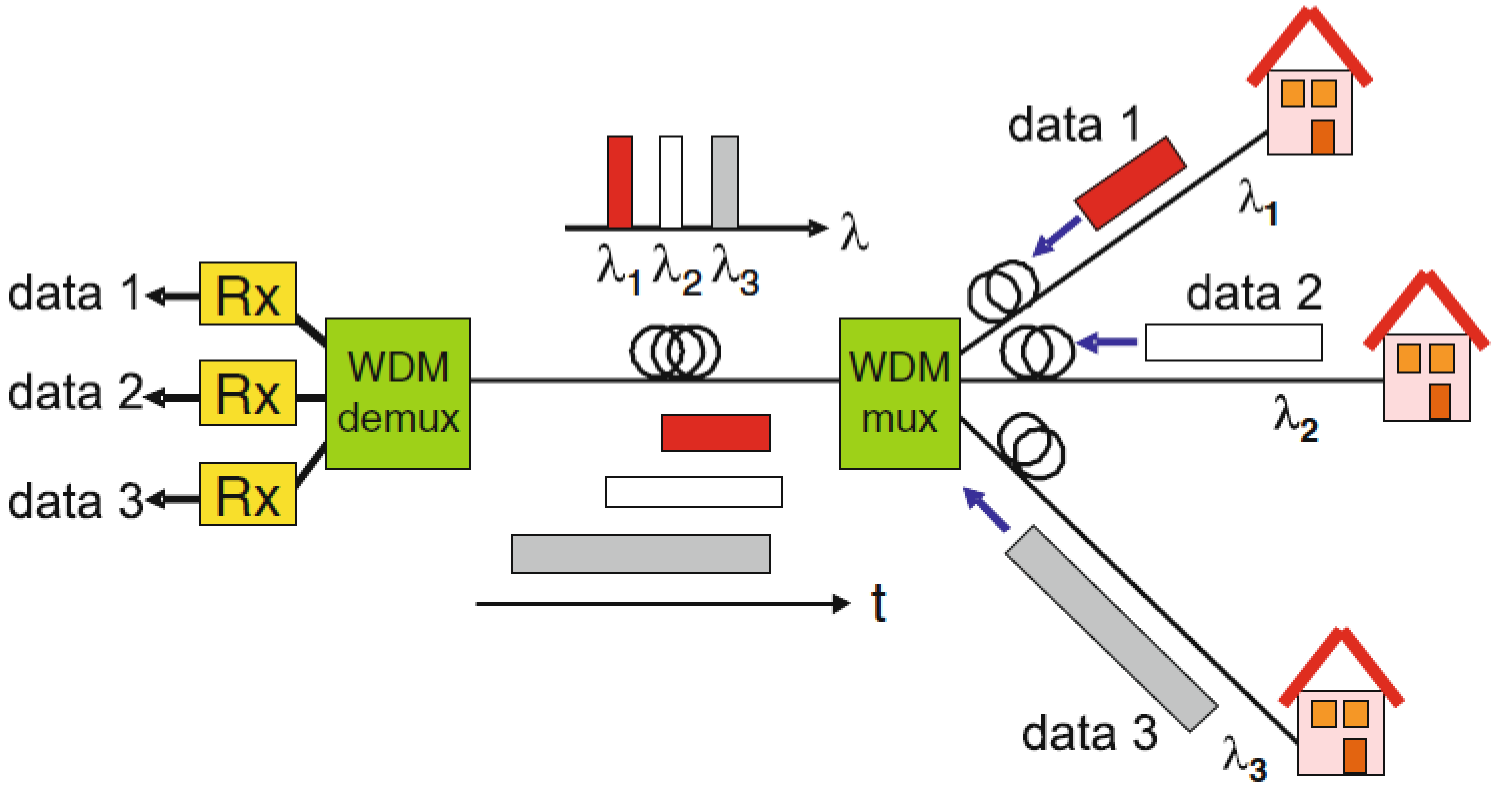
- there are many independent operating regions across the spectrum ranging from the O-band through the L-band in which narrow-linewidth optical sources can be used
- To find the optical bandwidth corresponding to a particular spectral width in these regions, we use the fundamental relationship f = c/λ.

$$\Delta f = \frac{c}{\lambda^2}\Delta\lambda$$



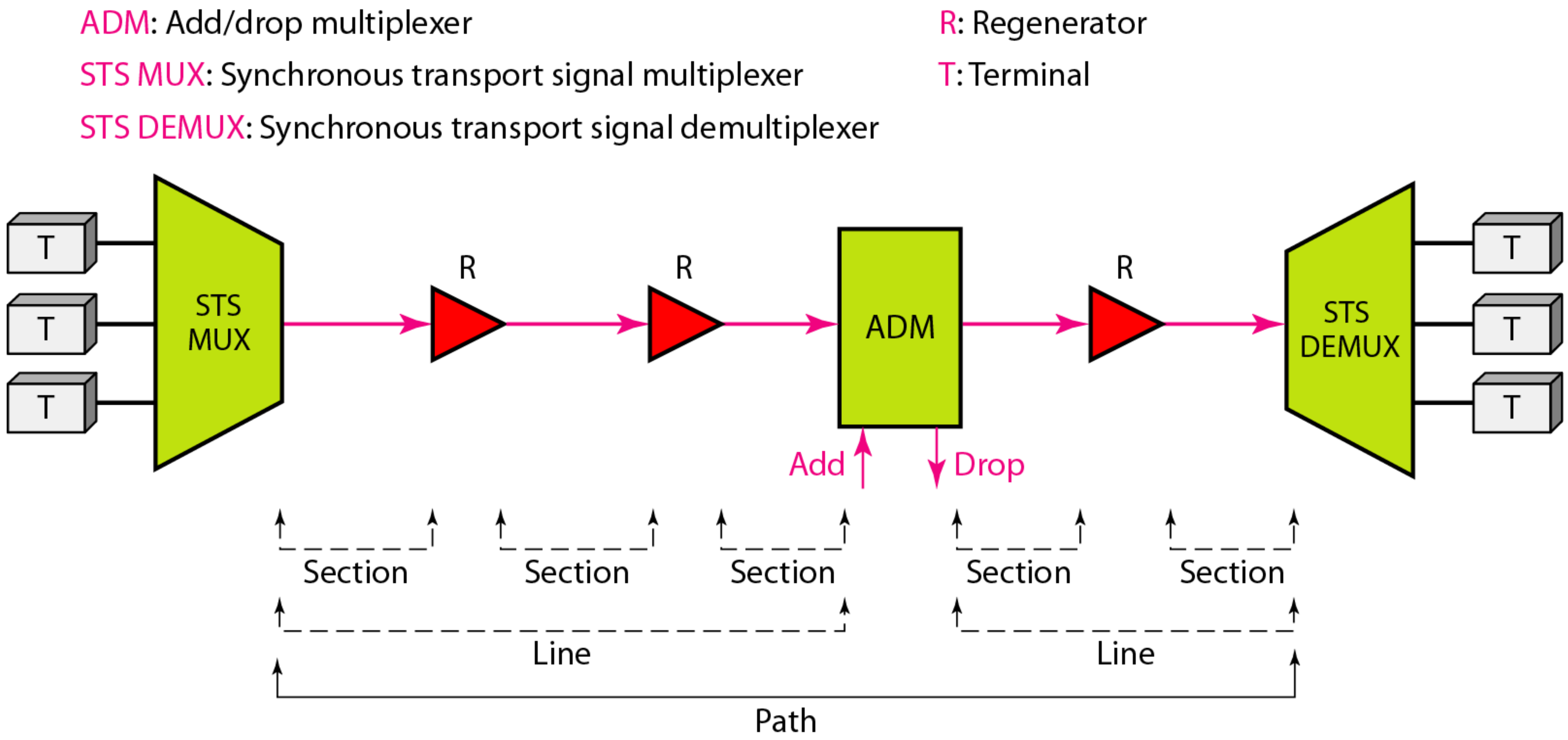
WAVELENGTH DIVISION MULTIPLE ACCESS (WDMA)

- Each channel uses a specific wavelength, and in the splitter point of the PON a wavelength multiplexer/de-multiplexer is used to combine/ separate these wavelength channels into/from the feeder fiber



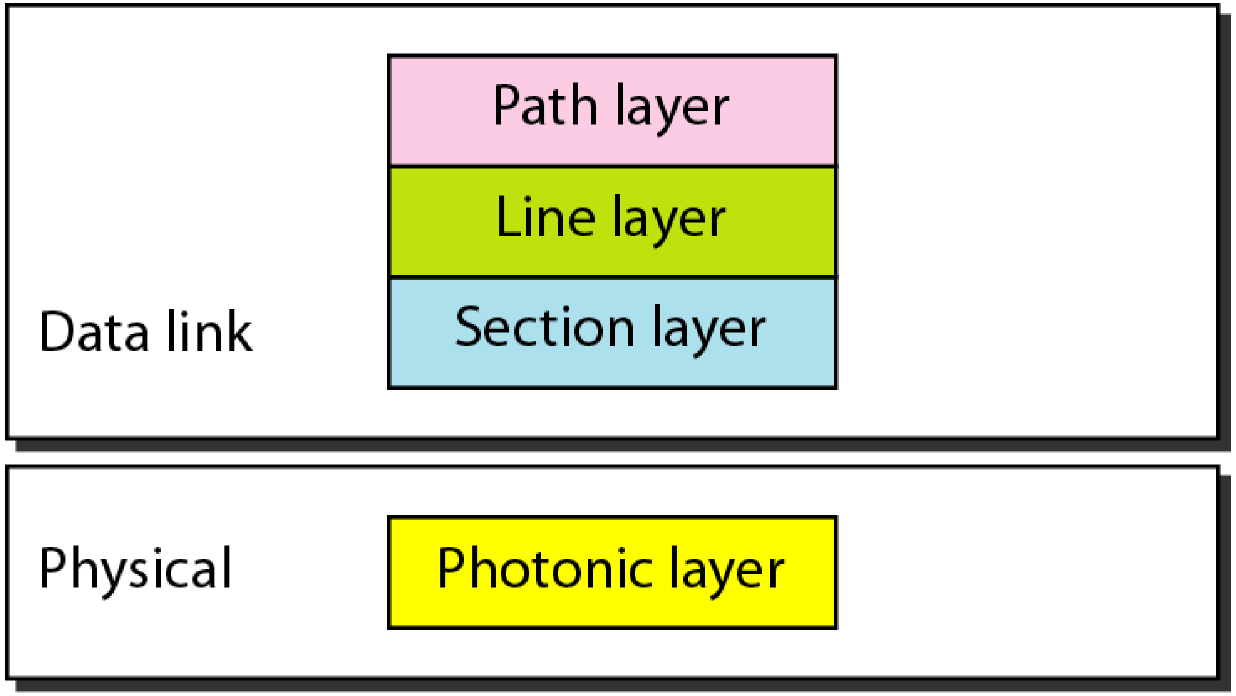
SONET & SDH Standards

- **SONET** (Synchronous Optical NETwork) is the network standard used in north America & **SDH** (Synchronous Digital Hierarchy) is used in other parts of the world.

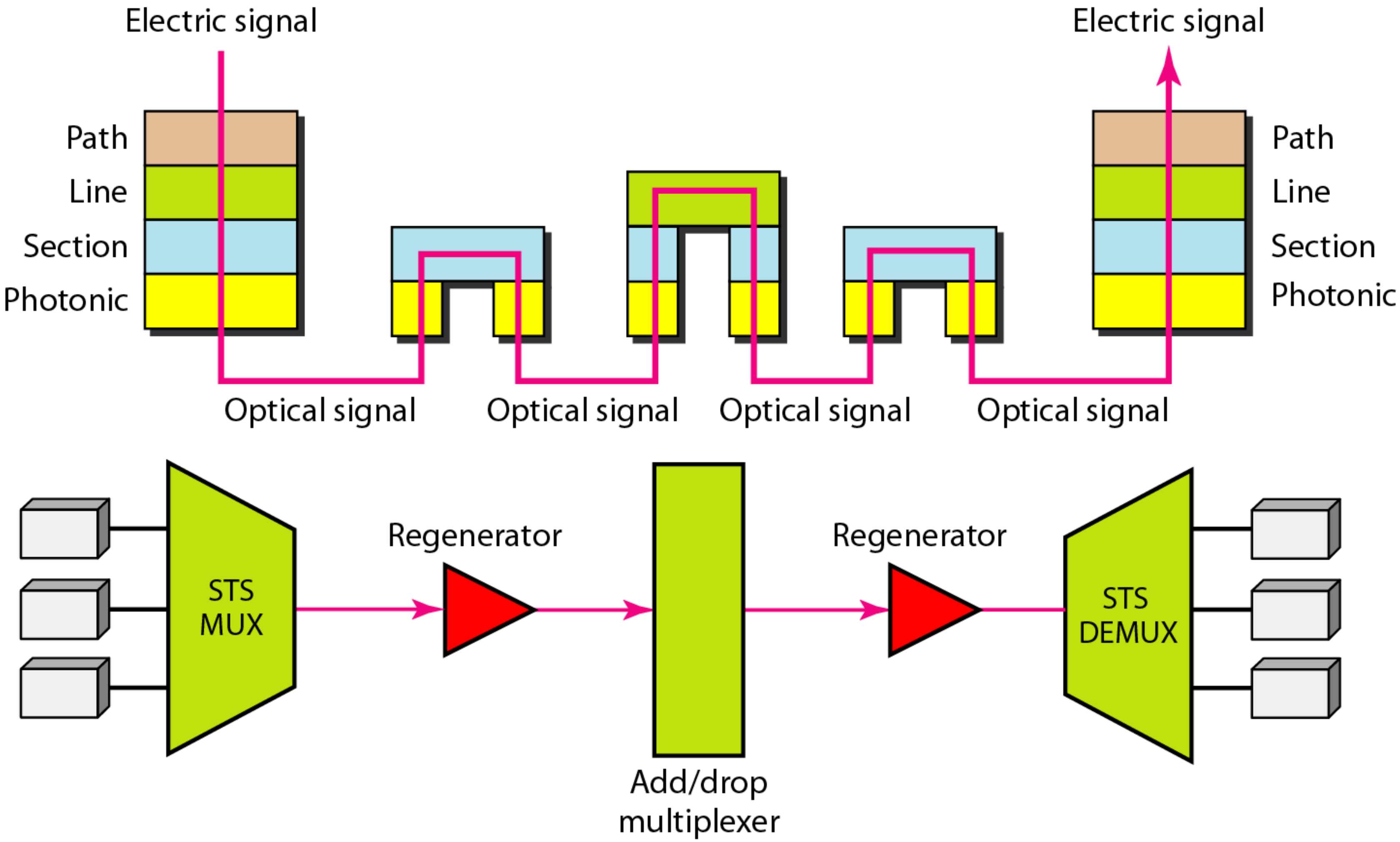


SONET layers

The SONET standard includes four functional layers: the **photonic(/Physical)**, the **section**, the **line**, and the **path layer**. They correspond to both the physical and the data link layers.



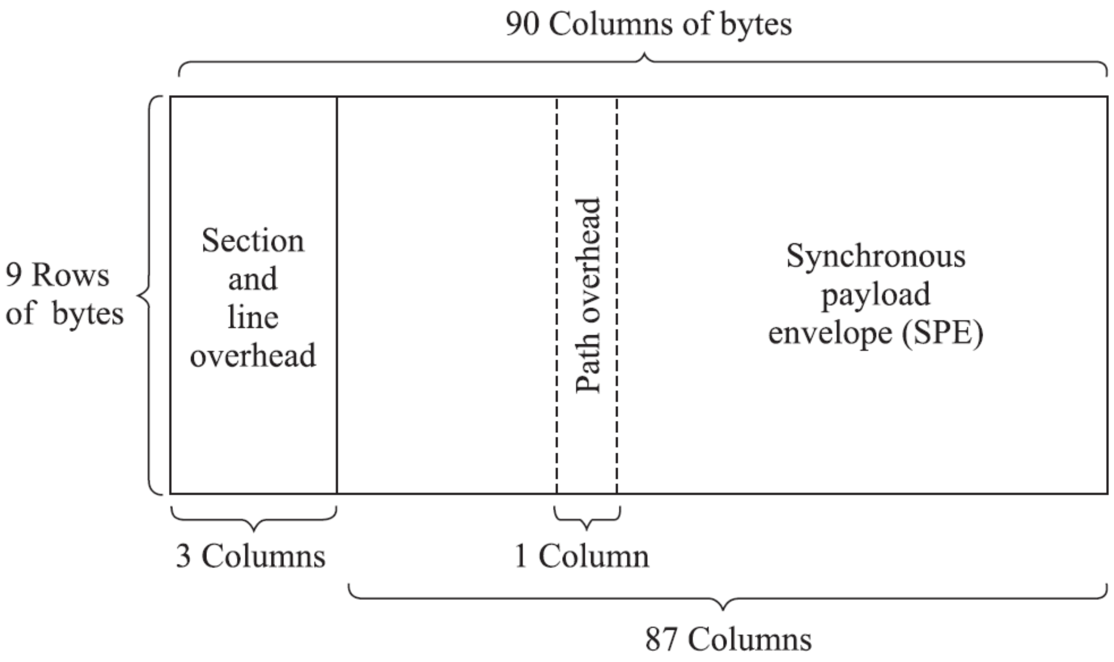
Device layer relationship in SONET



BASIC STRUCTURE OF AN STS-1 SONET FRAME

- It 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)

- This is a two-dimensional structure consisting of **90 columns by 9 rows of bytes**, where one byte is eight bits.
- The first three columns comprise transport overhead bytes that carry network management information.
- The remaining field of 87 columns is called the synchronous payload envelope (SPE) and carries user data plus nine bytes of path overhead (POH).
- The POH supports performance monitoring by the end equipment, status, signal labeling, a tracing function, and a user channel.
- The nine path-overhead bytes are always in a column and can be located anywhere in the SPE.



SONET Frame structure

- The fundamental SONET frame has a 125-μs duration. Thus, the transmission bit rate of the basic SONET signal is $\frac{9 \times 90 \times 8}{125\ \mu s/frame} = 51.84\ Mbps$
- All other SONET signals are integer multiples of this rate, so that an STS-N signal has a bit rate equal to N times 51.84 Mb/s.
- Higher-rate SONET signals are obtained by byte-interleaving *N* STS-1 frames
- After undergoing electrical-to-optical conversion, the resultant physical-layer optical signal is called **OC-N**, where OC stands for **optical carrier.**
- 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.
- SDH does not distinguish between a logical electrical signal (e.g., STS-N in SONET) and an optical signal (e.g., OC-N), so that both signal types are designated by STM-M.

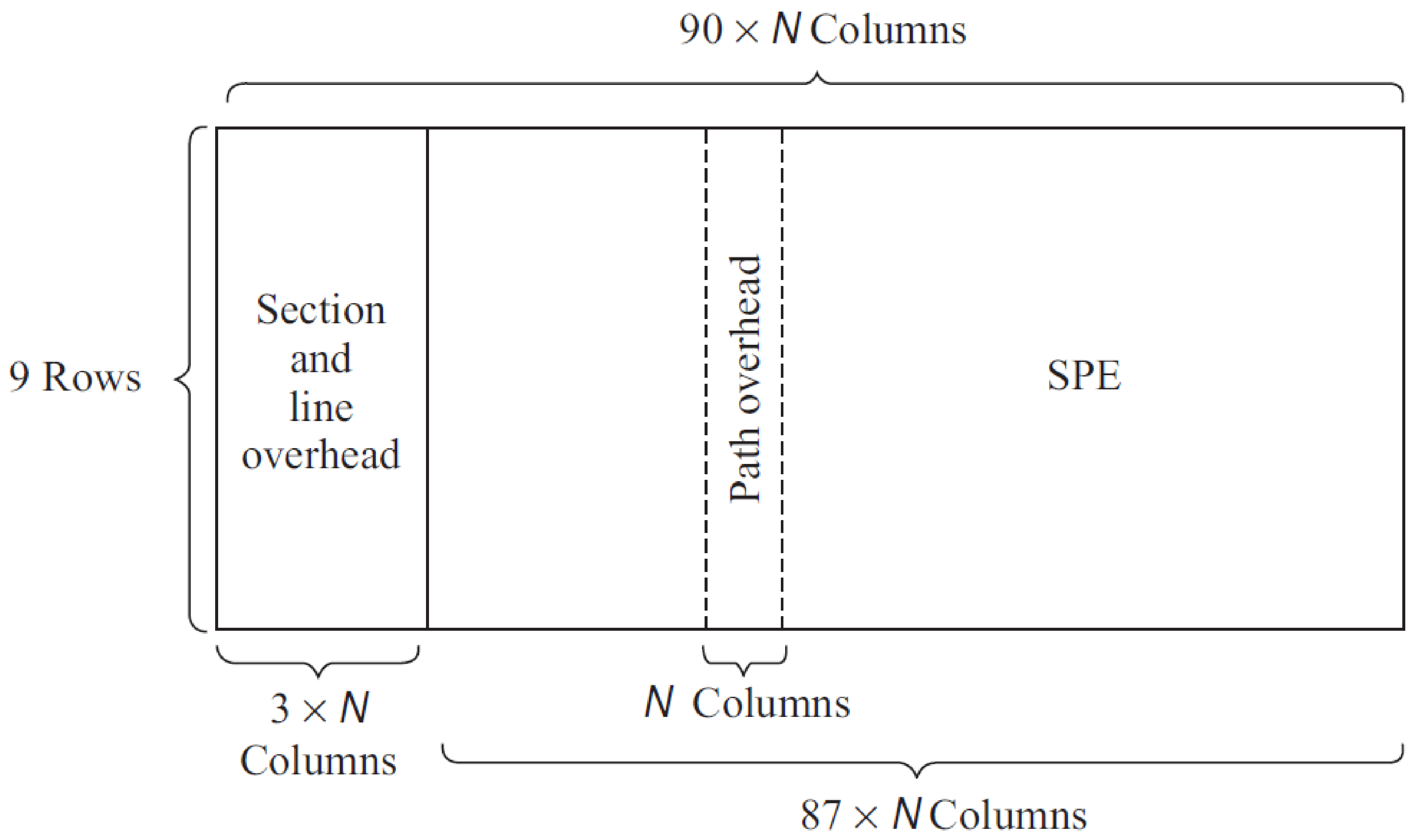


Fig: Basic formats of an STS-N SONET frame

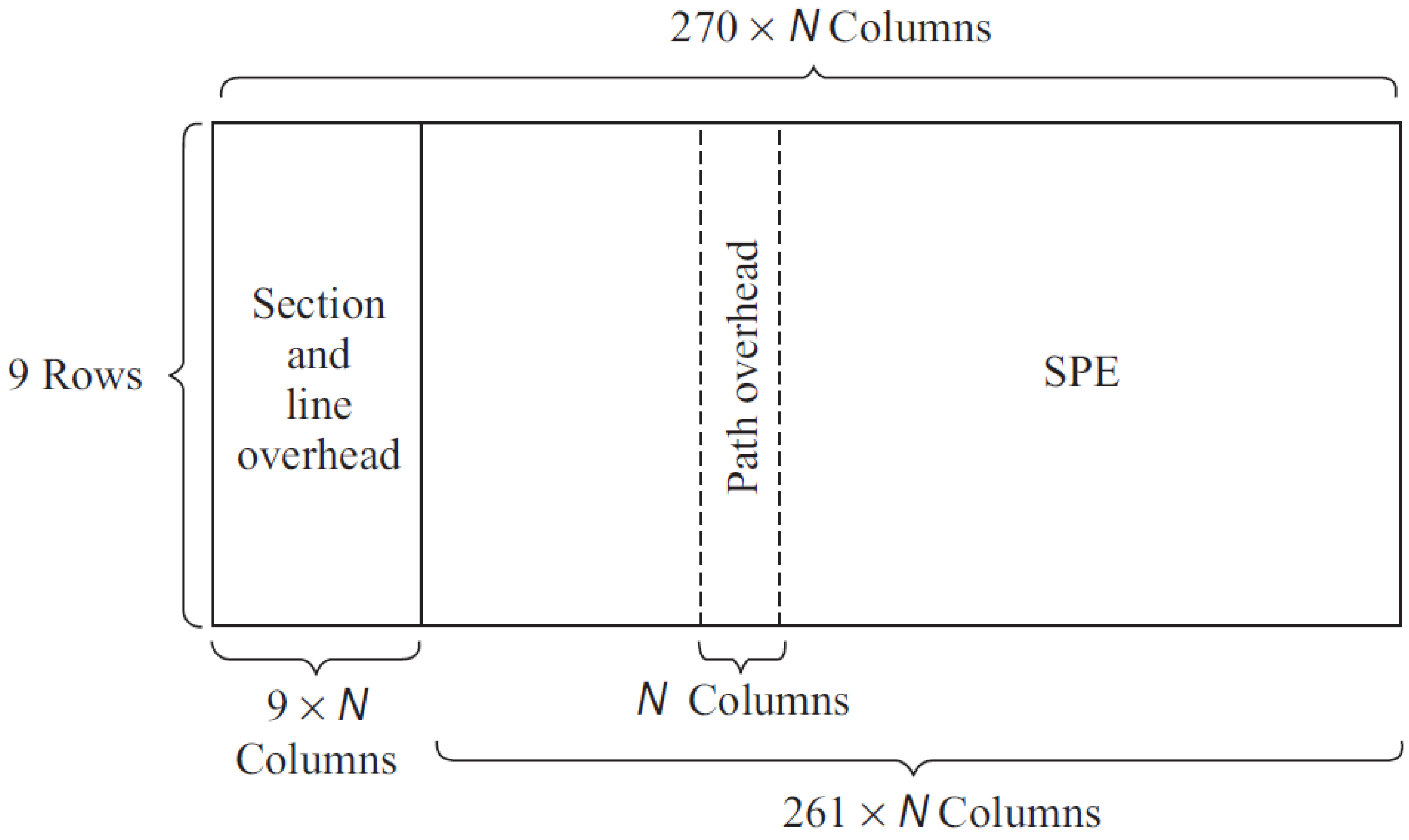


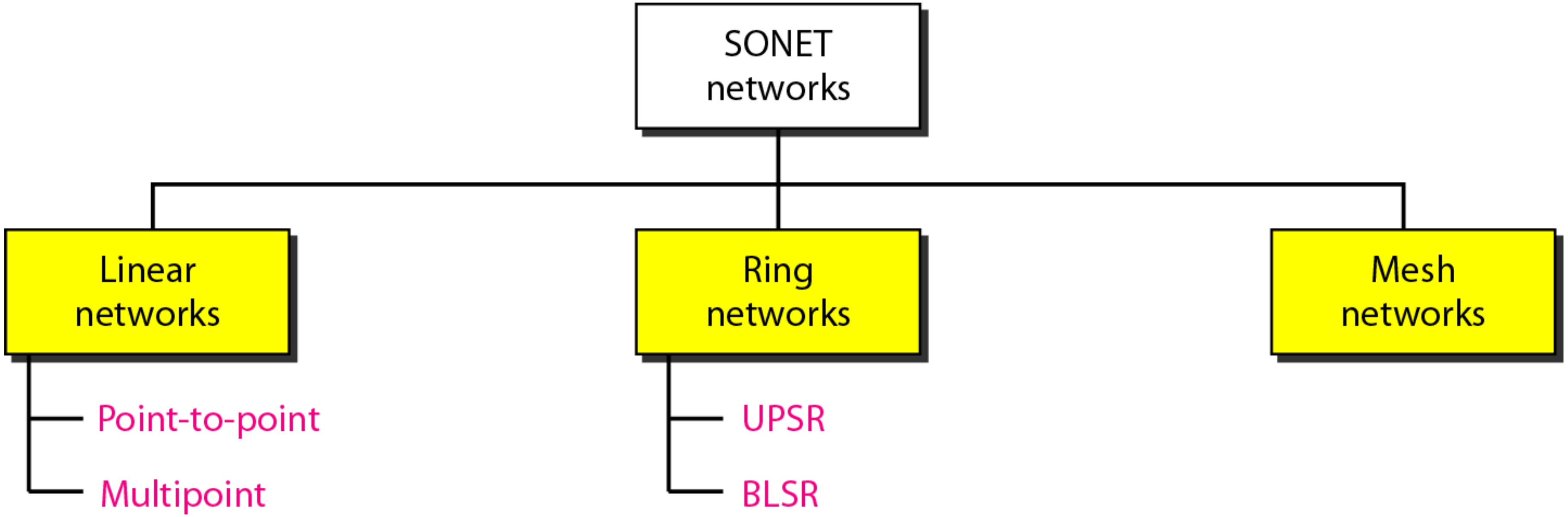
Fig: Basic formats of an STM-N SDH frame

SONET/SDH Bit Rates

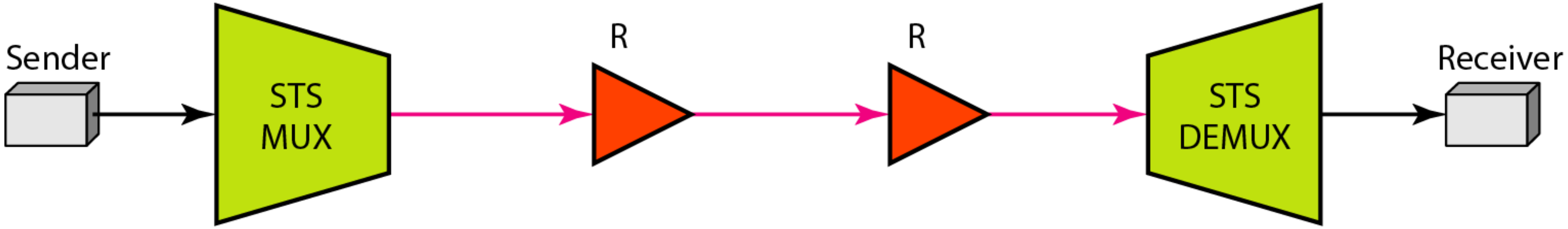
SONET	**Bit Rate (Mbps)**	**SDH**
OC-1	51.84	-
OC-3	155.52	STM-1
OC-12	622.08	STM-4
OC-24	1244.16	STM-8
OC-48	2488.32	STM-16
OC-96	4976.64	STM-32
OC-192	9953.28	STM-64
OC-768	39813 (40 Gbps)	STM-256

SONET networks topologies

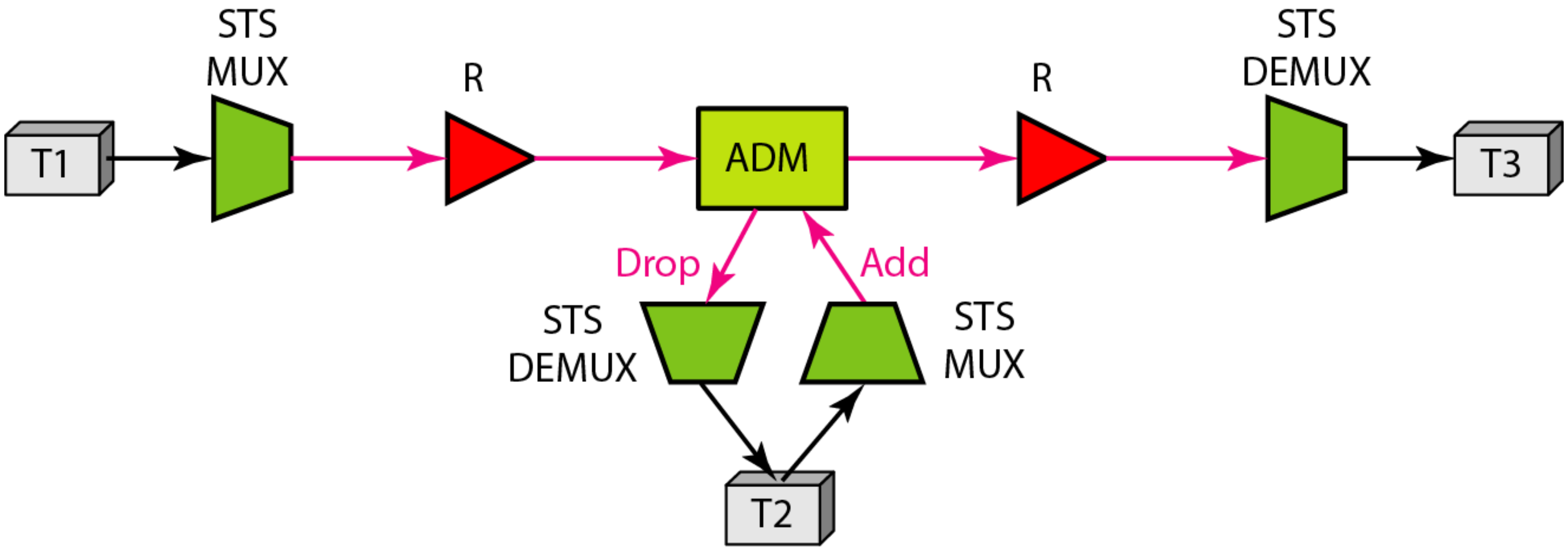
Using SONET equipment, it can roughly divide SONET networks into three categories: linear, ring, and mesh networks.



A point-to-point SONET network



A multipoint SONET network

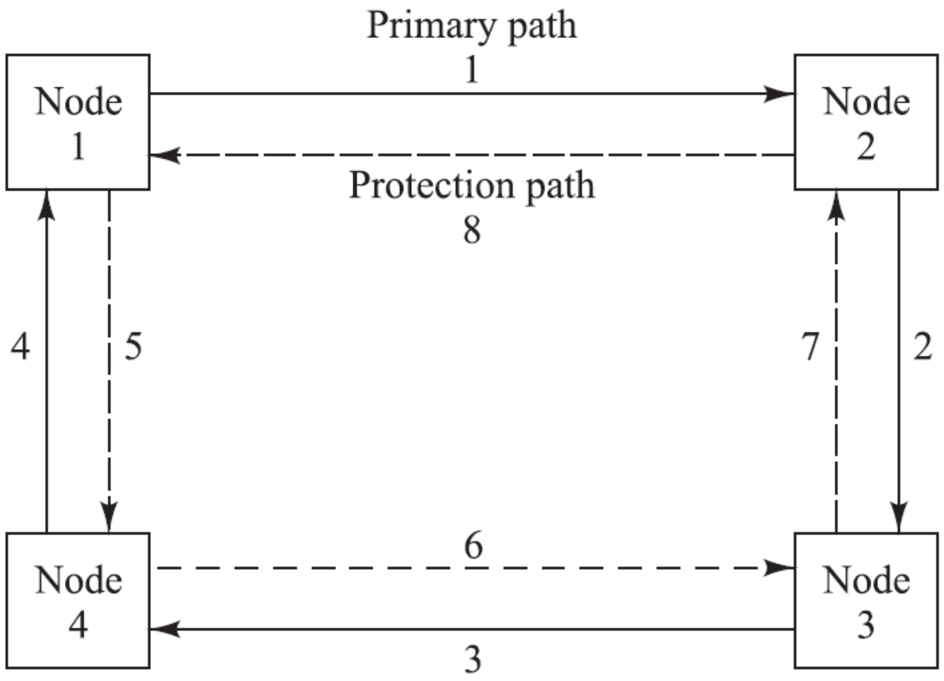


SONET & SDH RINGS

- SONET/SDH are usually configured as a **ring architecture**, which is achieved by creating **loop diversity** for uninterrupted service protection purposes in case of link or equipment failures.
- The SONET/SDH rings are also called as ***self-healing rings*** because the traffic flowing along a certain path can **automatically be switched to an alternate or standby path following failure or degradation of the link segment**.
- Three main features, each with two alternatives, thus yielding eight possible combinations of SONET/SDH ring types.
  - First, there can be **either two or four fibers** running between the nodes on a ring.
  - Second, the operating signals can be **unidirectional** or **bidirectional** .
  - Third, protection switching can be performed **either via a line-switching** or a **path-switching scheme**
- Upon link failure or degradation, **line switching** moves all signal channels of an entire OC-N channel to a protection fiber. Conversely, **path switching** can move individual payload channels within an OC-N channel (e.g., an STS-1 subchannel in an OC-12 channel) to another path.

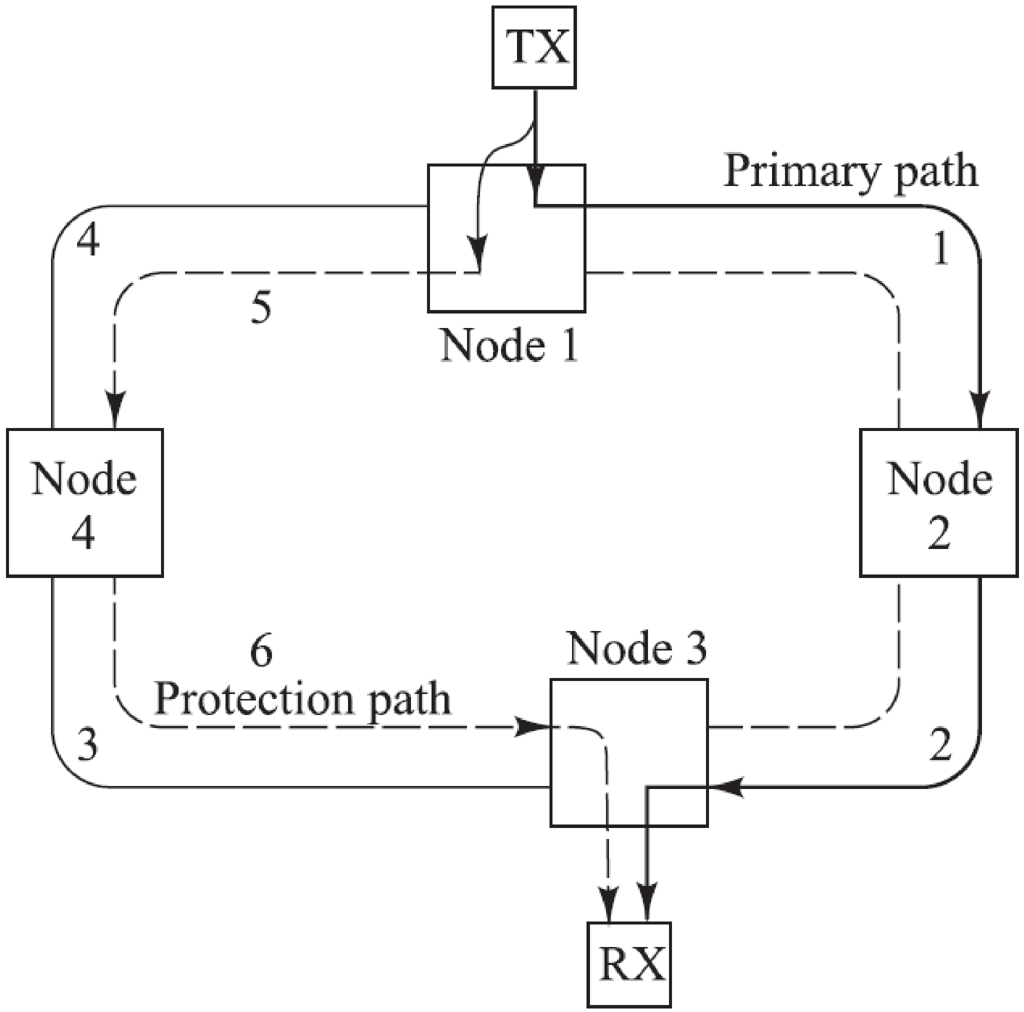
TWO FIBER UNIDIRECTIONAL PATH SWITCHED RING (UPSR)- USHR

- In a unidirectional ring the normal working traffic travels clockwise around the ring, on the primary path.
- The counter clockwise path is used as an alternate route for protection against link or node failures. This protection path is indicated by dashed lines.
- To achieve protection, the signal from a transmitting node is dual-fed into both the primary and protection fibers.
- The receiver selects the signal from the primary path, but it compares the fidelity of each signal and chooses alternate signal in case of severe degradation or loss of the primary signal.



- For example, the connection from node 1 to node 3 uses links 1 and 2, whereas the traffic from node 3 to node 1 traverses links 3 and 4. Thus, two communicating nodes use a specific bandwidth capacity around the entire perimeter of the ring.

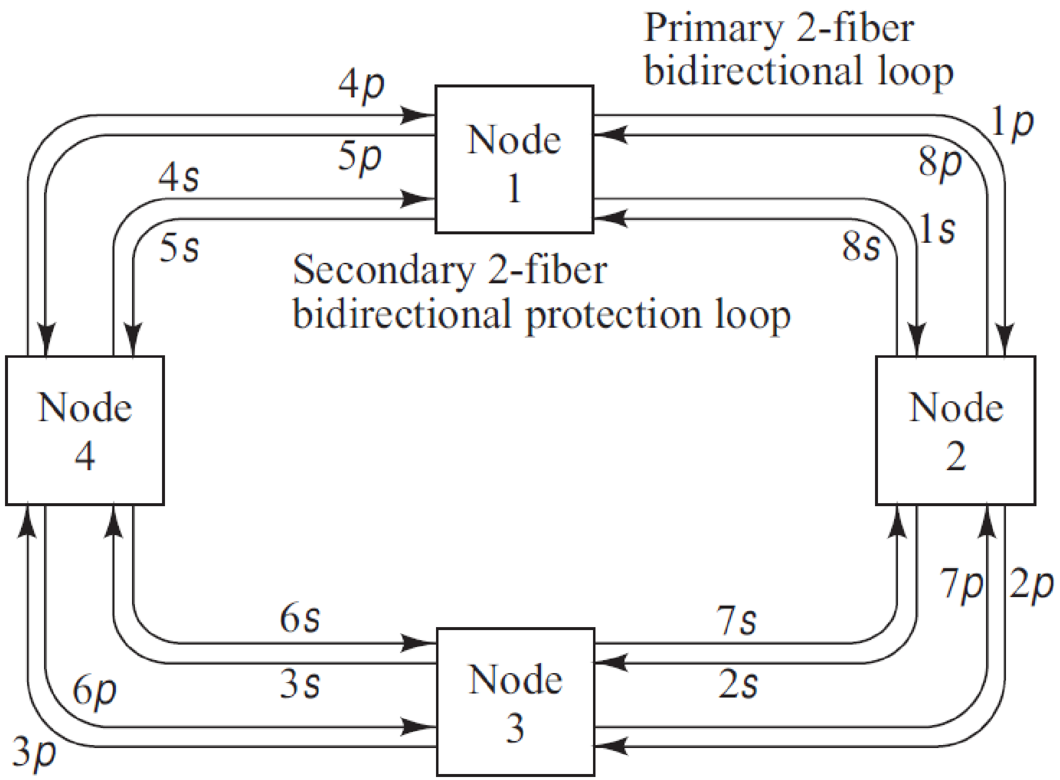
Two fiber unidirectional path switched ring (UPSR)- USHR



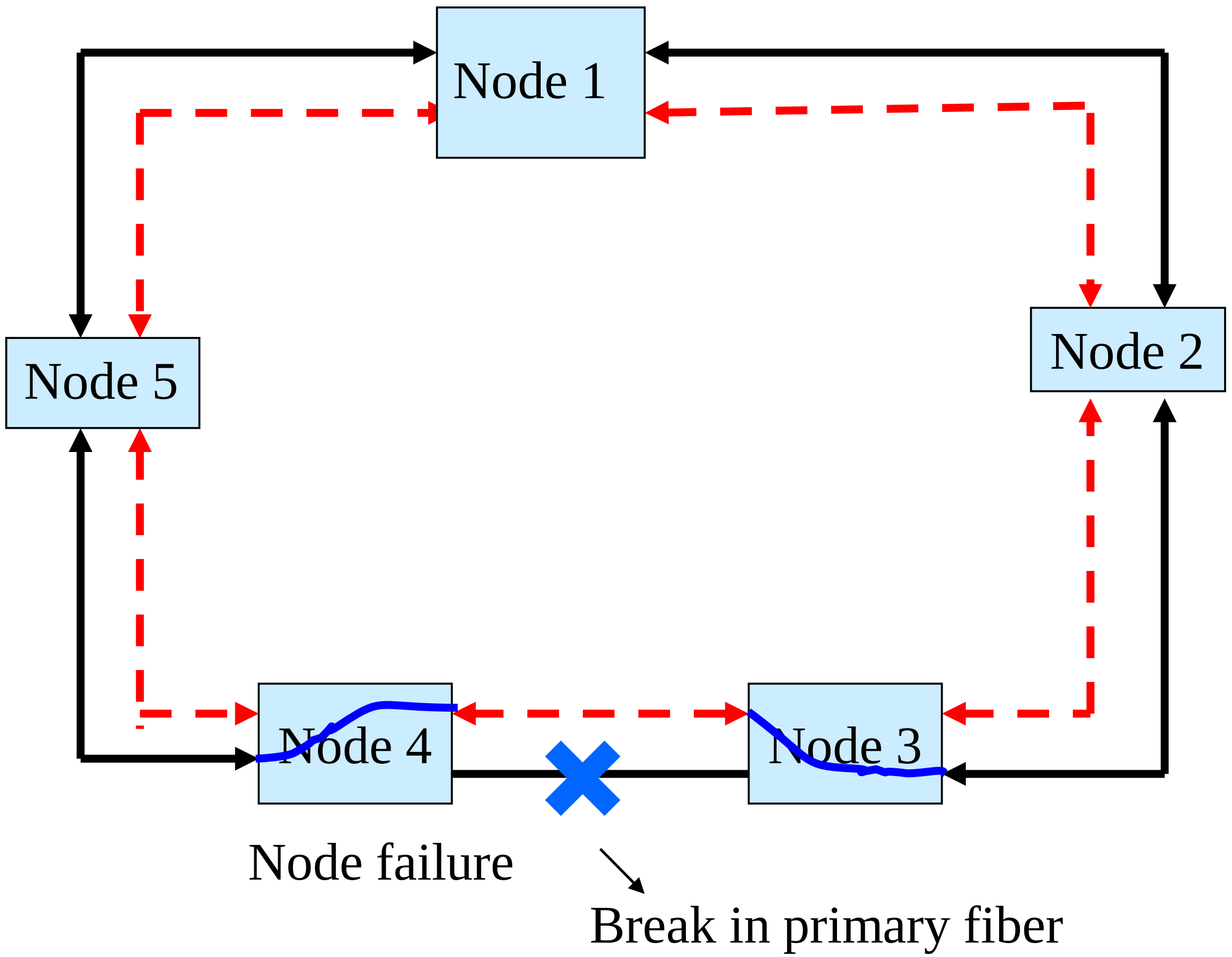
- Two identical signals from a particular node arrive at their destination from opposite directions, usually with different delays
- The receiver normally selects the signal from the primary path.
- However, it continuously compares the fidelity of each signal and chooses the alternate signal in case of severe degradation or loss of the primary signal.
- For example, if path 2 breaks or equipment in node 2 fails, then node 3 will switch to the protection channel to receive signals from node 1.

A bidirectional line switched ring (BLSR) (Two-fiber or four-fiber BLSR)

- Two primary fiber loops (with fiber segments labeled 1p through 8p) are used for normal bidirectional communication, and the other two secondary fiber loops are standby links for protection purposes (with fiber segments labelled 1s through 8s)

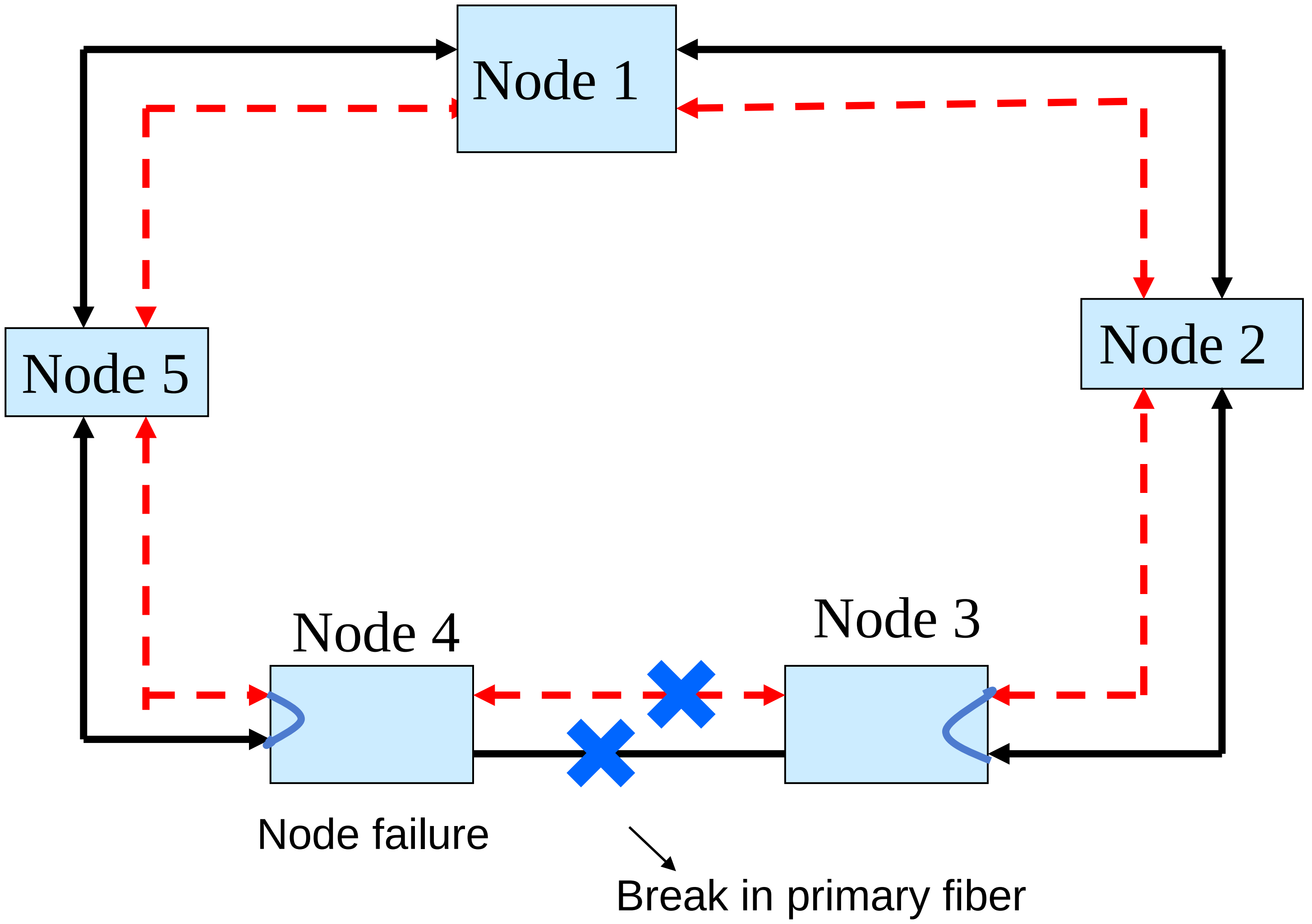


Case1: What happens when both primary fibers in a given span are failed?

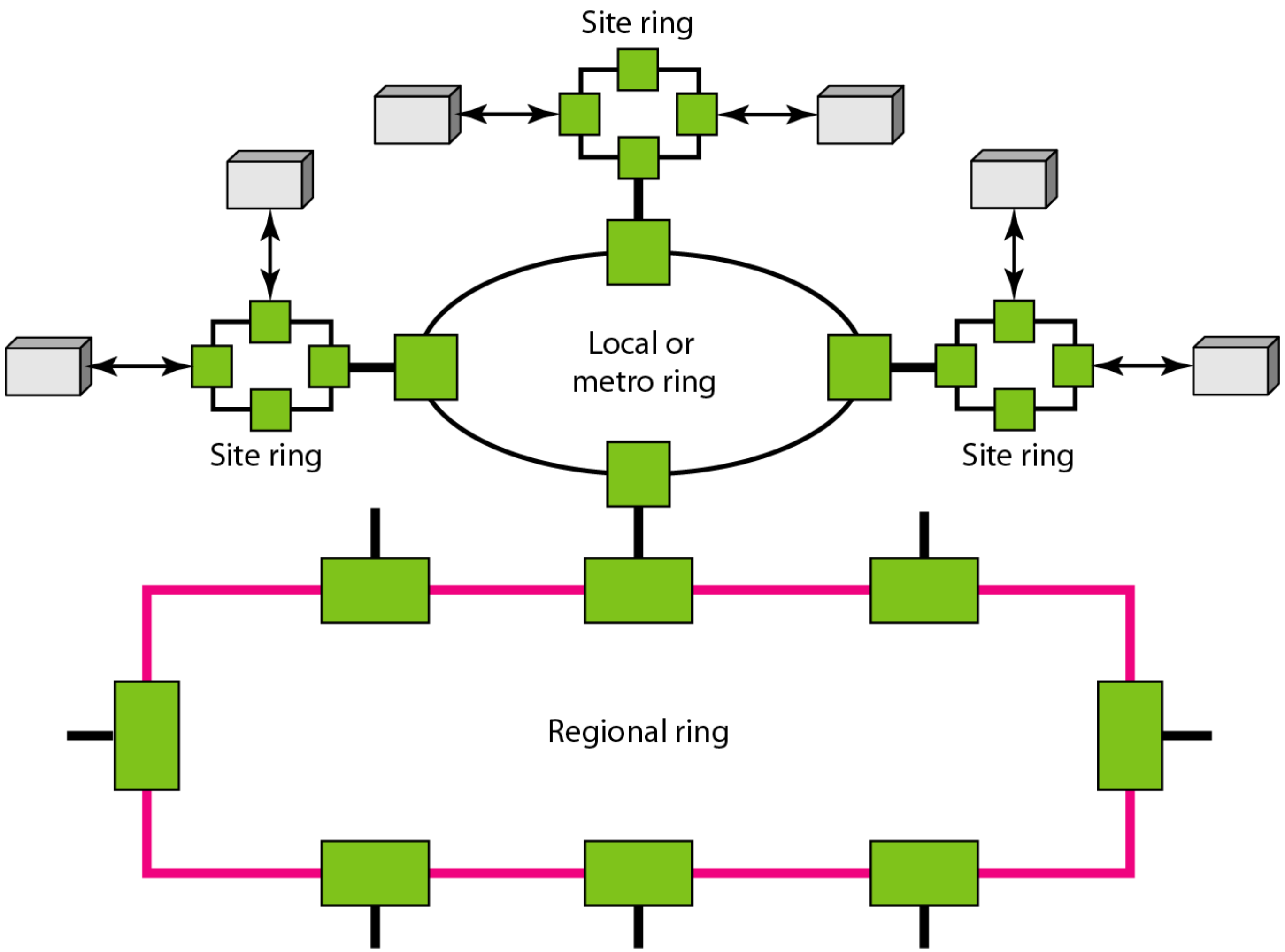


- In this situation, the affected nodes detect a loss-of-signal condition and switch both primary fibers connecting these nodes to the secondary protection pair
- The protection segment between nodes 3 and 4 now becomes part of the primary bidirectional loop. The exact same reconfiguration scenario will occur when the primary fiber connecting nodes 3 and 4 breaks.

Case 2: What happens when both primary and protection fibers in a given span are failed?



A combination of rings in a SONET network



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- Senior John M., Optical Fiber Communications, Pearson Education India, Third Edition, 2009.