OPTICAL COMMUNICATION

Course code:AEC018

IV. B.Tech II semester

Regulation: IARE R-16)

BY

U SOMANAIDU

Asst.Professor

DEPARTMENT OF ELECTRONICS AND COMMUNICATIONENGINEERING

INSTITUTE OF AERONAUTICAL ENGINEERING

(Autonomous)

DUNDIGAL, HYDERABAD - 500 043

CO's	Course outcomes
CO1	Overview Of Optical Fiber Communication, Vector Nature Of light, types of optical fibers, modal analysis.
CO2	Understand Signal Degradation And Optical Sources, Attenuation- Absorption, Material Dispersion, Optical sources, Principles of operation.
CO3	Understand Optical Detectors, Optical Erectors, Sensitivity And Quantum Efficiency, WDM Concepts And Components

COs	Course Outcome
CO4	Understand Optical Amplifiers, Basic concepts, semiconductor amplifier, principles of operation, intermediation effects
CO5	Understand Optical Networks And Dispersion Compensation, Optical networks, soliton based communication system design.

UNIT-I
OVERVIEW OF OPTICAL FIBRE COMMUNICATION

CLOs	Course Learning Outcome
CLO1	Understand Basic principles of optical fiber Communications.
CLO2	Define light, propagation of light, modes, propagation of light different levels.
CLO3	Given the propagation of light in a cylindrical dielectric rod; rays and modes types of optical fibers.
CLO4	Given the Photonic components in optical communication systems.

Introduction to Light

- Light is basic to almost all life on Earth.
- Light is a form of electromagnetic radiation.
- Light represents energy transfer from the source to the observer.
- Many phenomena depend on the properties of light.
  - Seeing a TV or computer monitor
  - Blue sky, colors at sunset and sunrise
  - Images in mirrors
  - Eyeglasses and contacts
  - Rainbows
  - Many others

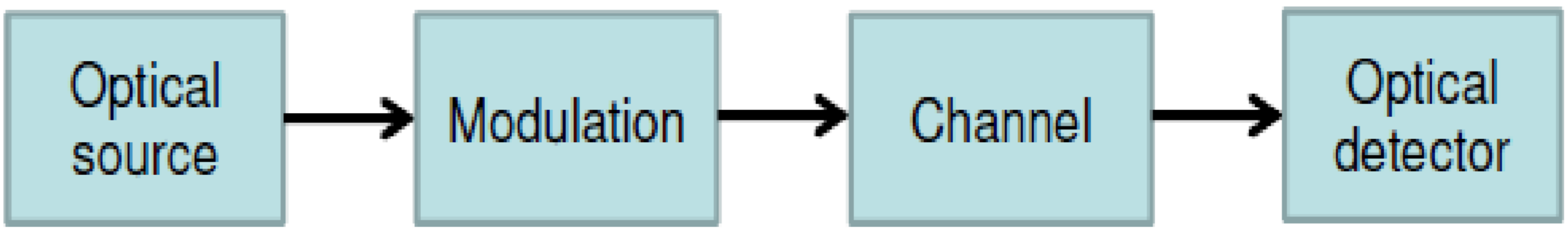
The Nature of Light

- Before the beginning of the nineteenth century, light was considered to be a stream of particles.
- The particles were either emitted by the object being viewed or emanated from the eyes of the viewer.

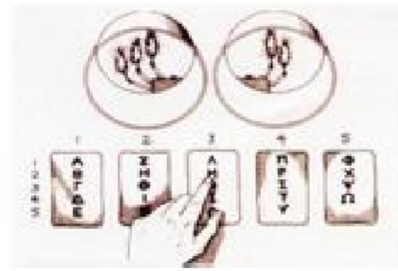
Newton was the chief architect of the particle theory of light.

- He believed the particles left the object and stimulated the sense of sight upon entering the eyes.

The most basic optical communication link:

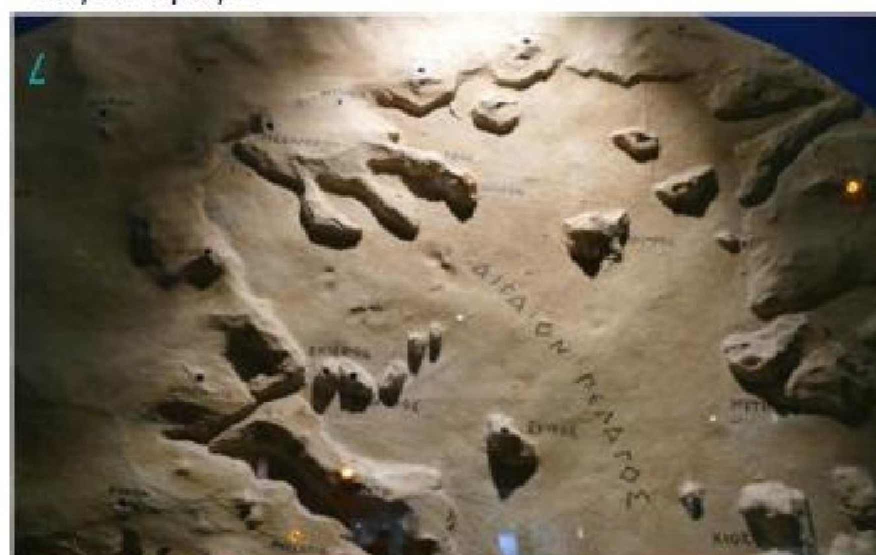


Optical communications has a long history, having been used by many civilizations. One example is the friktories of ancient Greece:

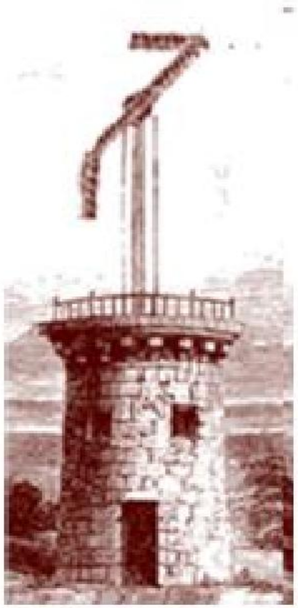


This was a very early example of digital optical communications.

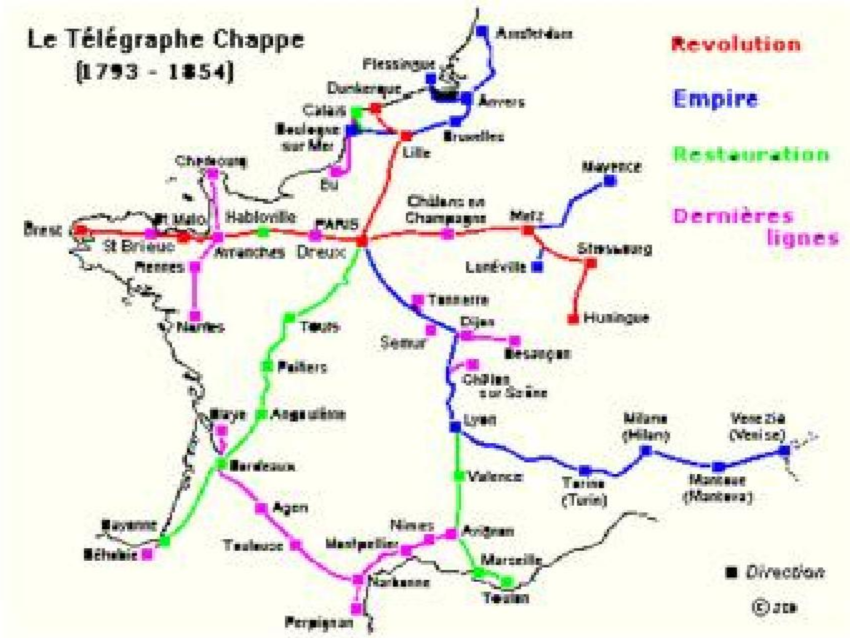
Το σύστημα με τις Φρυκτωρίες παρουσιάζεται στον ειδικό χάρτη όπου εμφανίζει με φωτεινές ενδείξεις τους πυρσούς να ανάβουν και να μεταδίδουν το μήνυμα από την Τροία στις Μυκήνες....



Digital optics, 1793-1852:

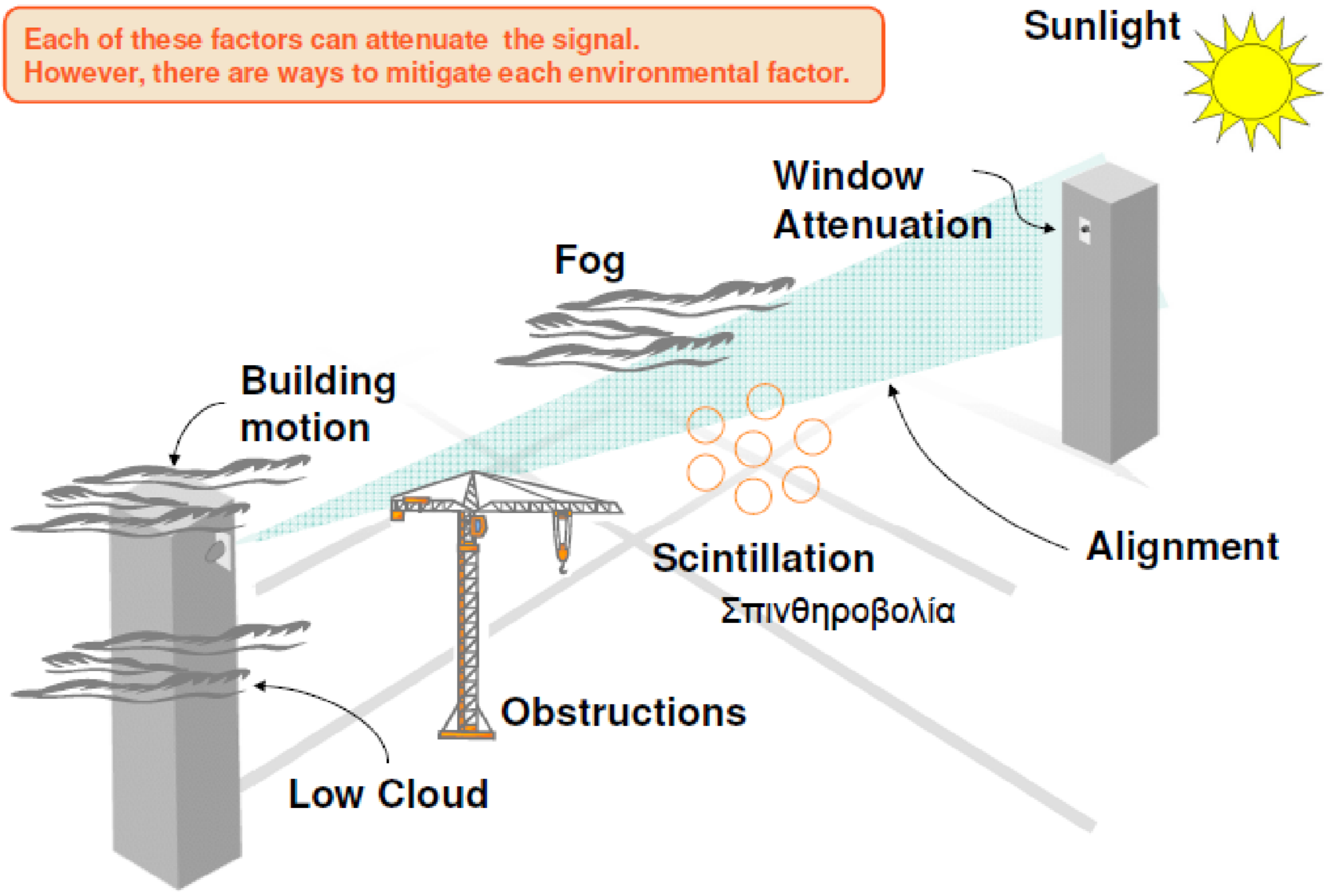


http://www.ec-lyon.fr/tourisme/Chappe/



- Claude Chappe's Optical Telegraph (France)
- Based on a semaphore system
- Repeater spacing ≈ 6 miles
- Message could cover 100 miles in 30 minutes
- Bit rate < 1 bit/s

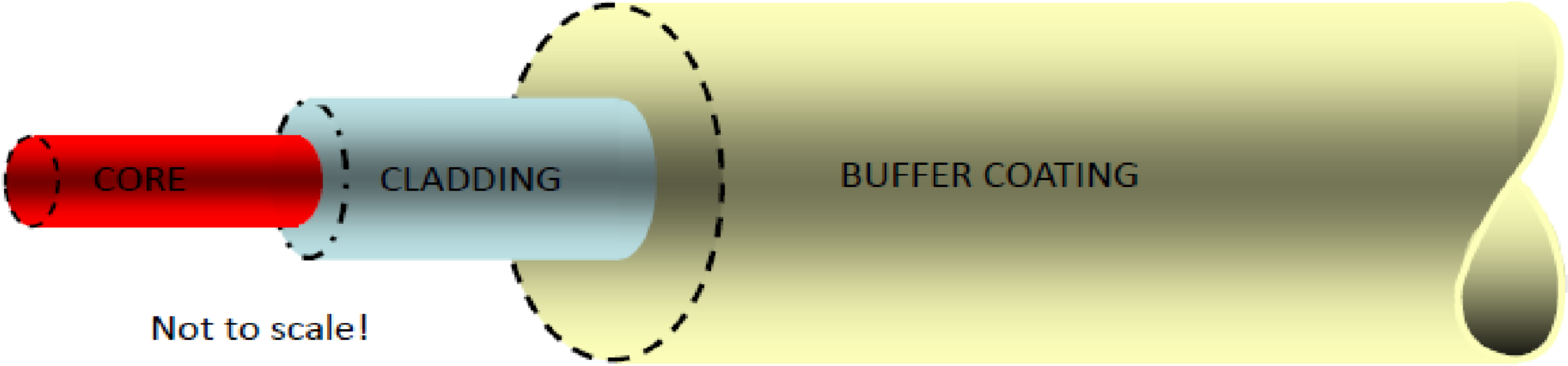
Each of these factors can attenuate the signal.
However, there are ways to mitigate each environmental factor.



Optical Fibres: Basic Structure

- dielectric waveguides that operate at optical wavelengths; mostly made from silica glass, but plastic versions (for multimode) also available

- confine electromagnetic energy in the form of light within core and guide the light parallel to the longitudinal axis:



Not to scale!

•A circular core of refractive index n_1 is surrounded by cladding with a slightly lower value of refractive index ($n_2 < n_1$). The fibre is encapsulated by the buffer and additional layers as appropriate.

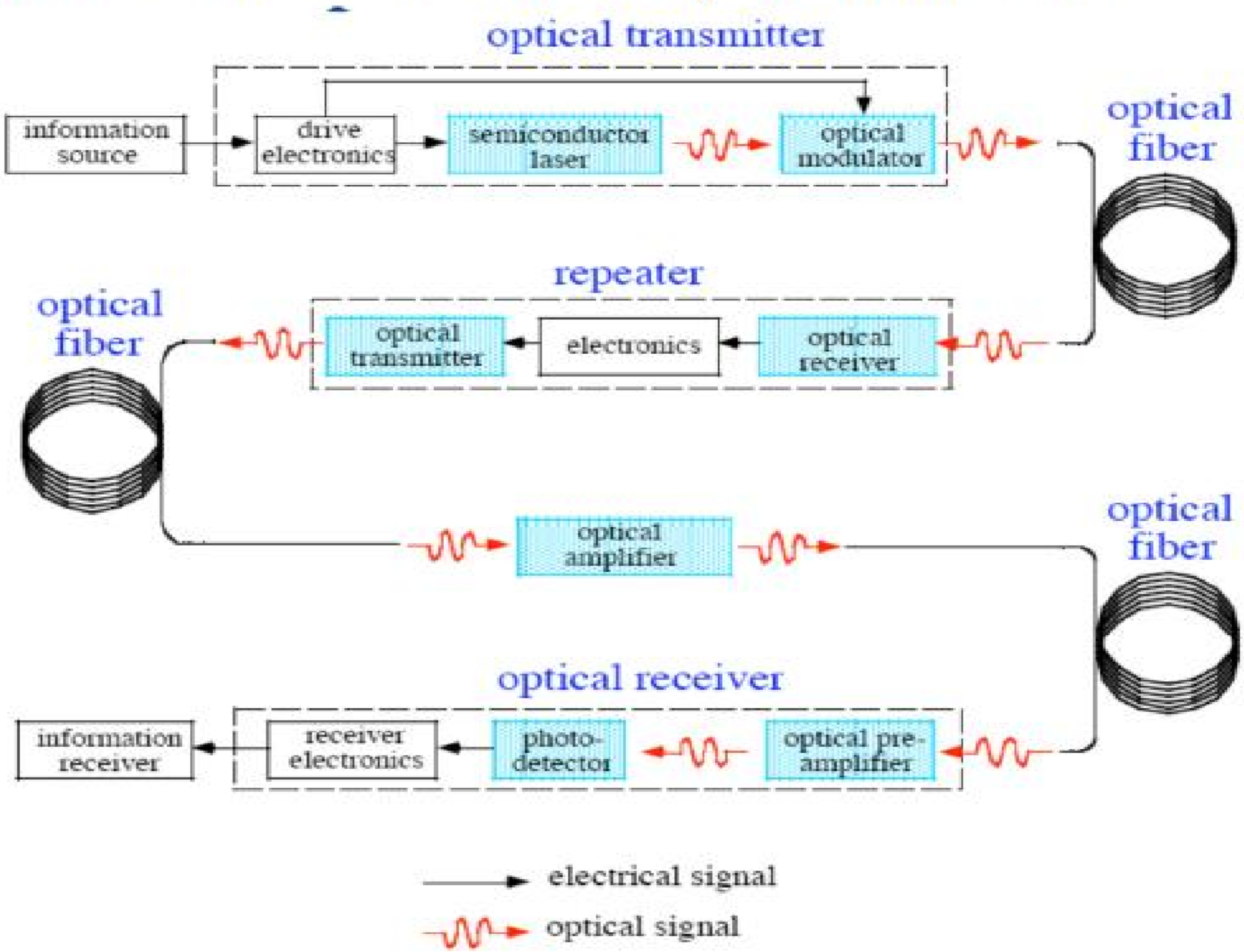
• Light is confined to the core of the fibre by total internal reflection – TIR at the core-cladding interface.

Advantages of optical fibre

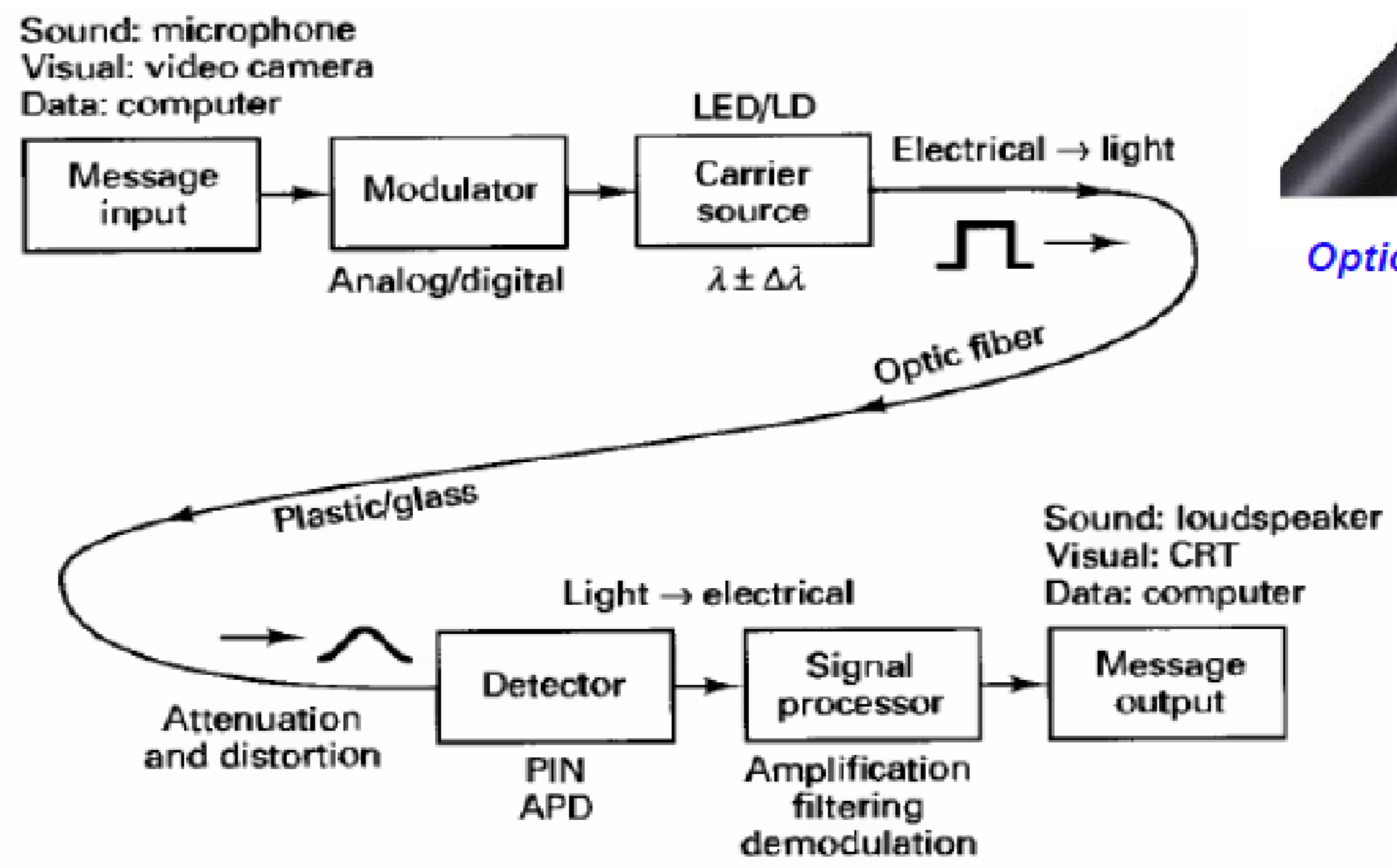
- Very wide bandwidth compared to metallic transmission lines, *i.e. potentially thousands of GHz*
- Very low loss (as low as 0.2 dB/km)
- Can achieve low dispersion (depends on wavelength of source and fibre type)
- Small size and weight
- Electrical isolation (glass and plastic)

A fiber-optic cable (right) containing 144 tiny glass fibers is compared with a cross section of a conventional copper cable.

Basic architecture of an optical fibre link

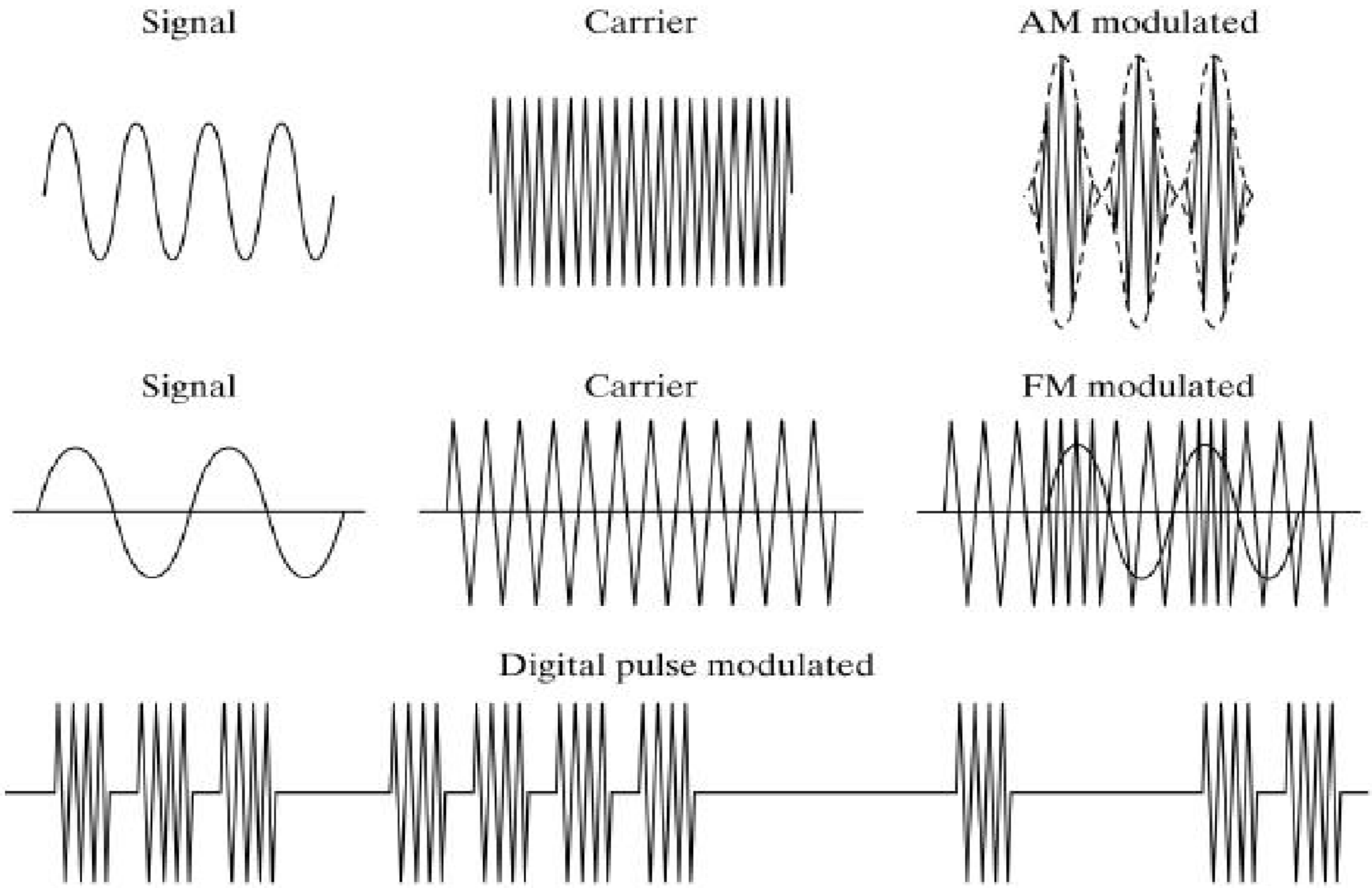


Optical communication systems



Optical-fiber cable

AM, FM, and Digital



Light guides

(a)
(b)
(c)

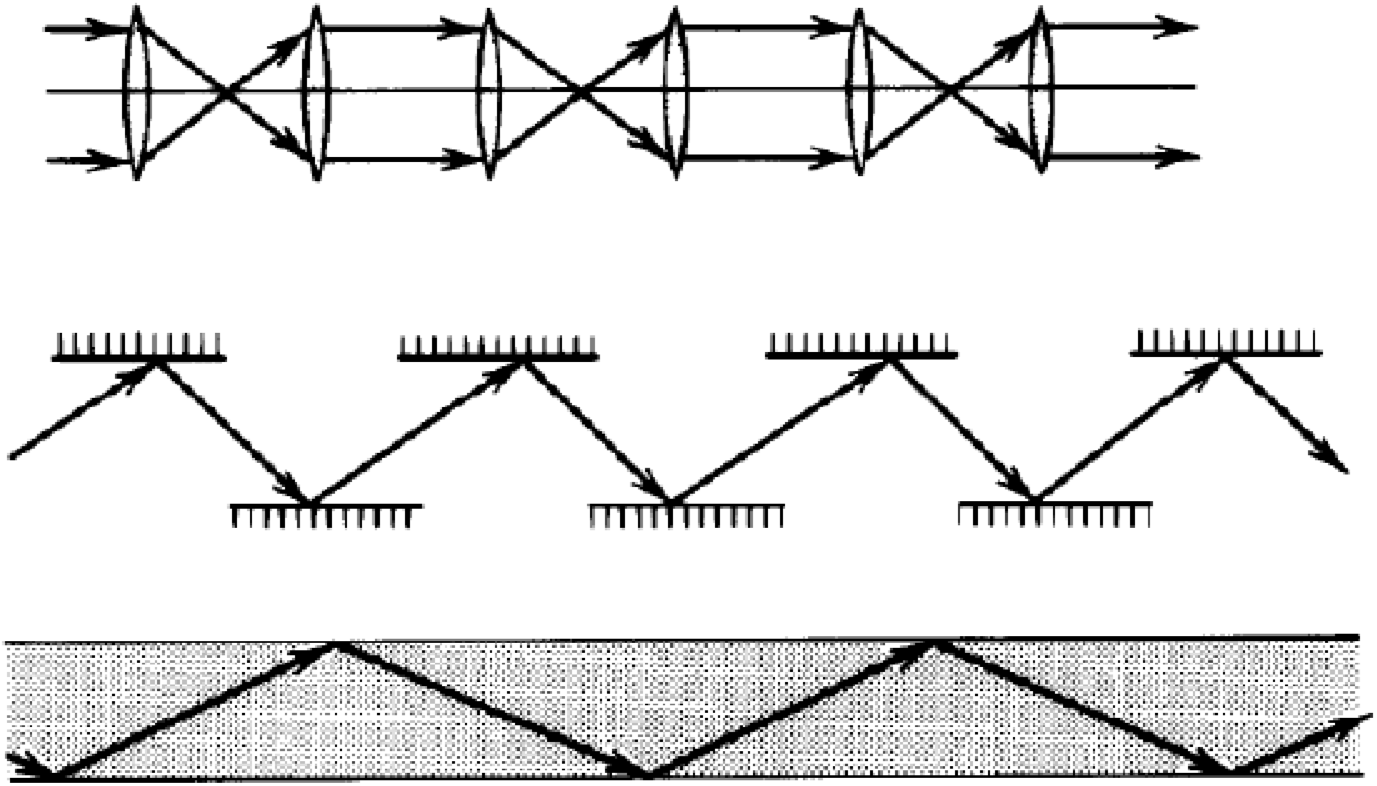


Figure 1.2-16 Guiding light: (*a*) lenses; (*b*) mirrors; (*c*) total internal reflection.

Optical fibers

Fiber-Optic Communications Systems, Third Edition. Govind P. Agrawal

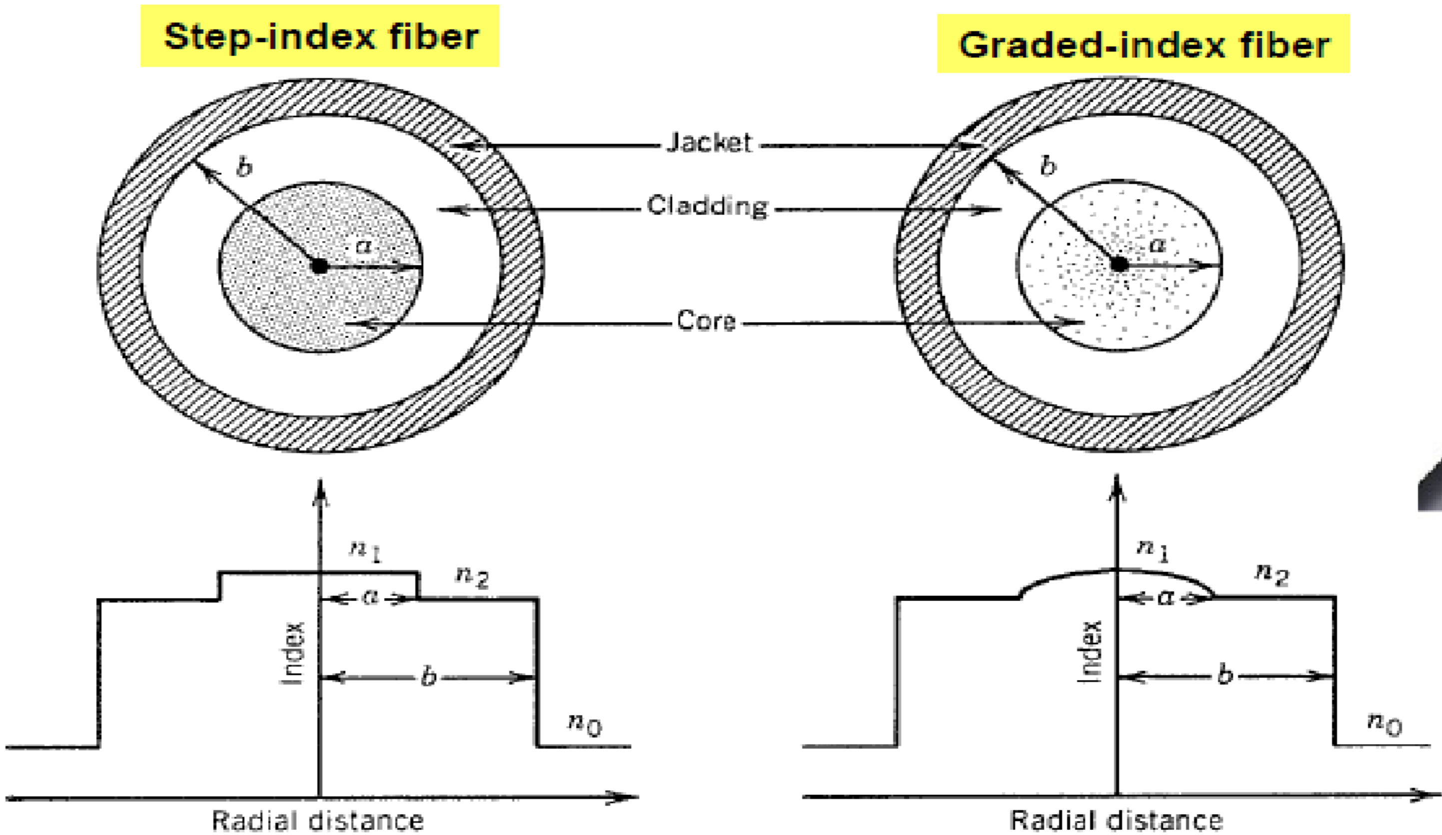


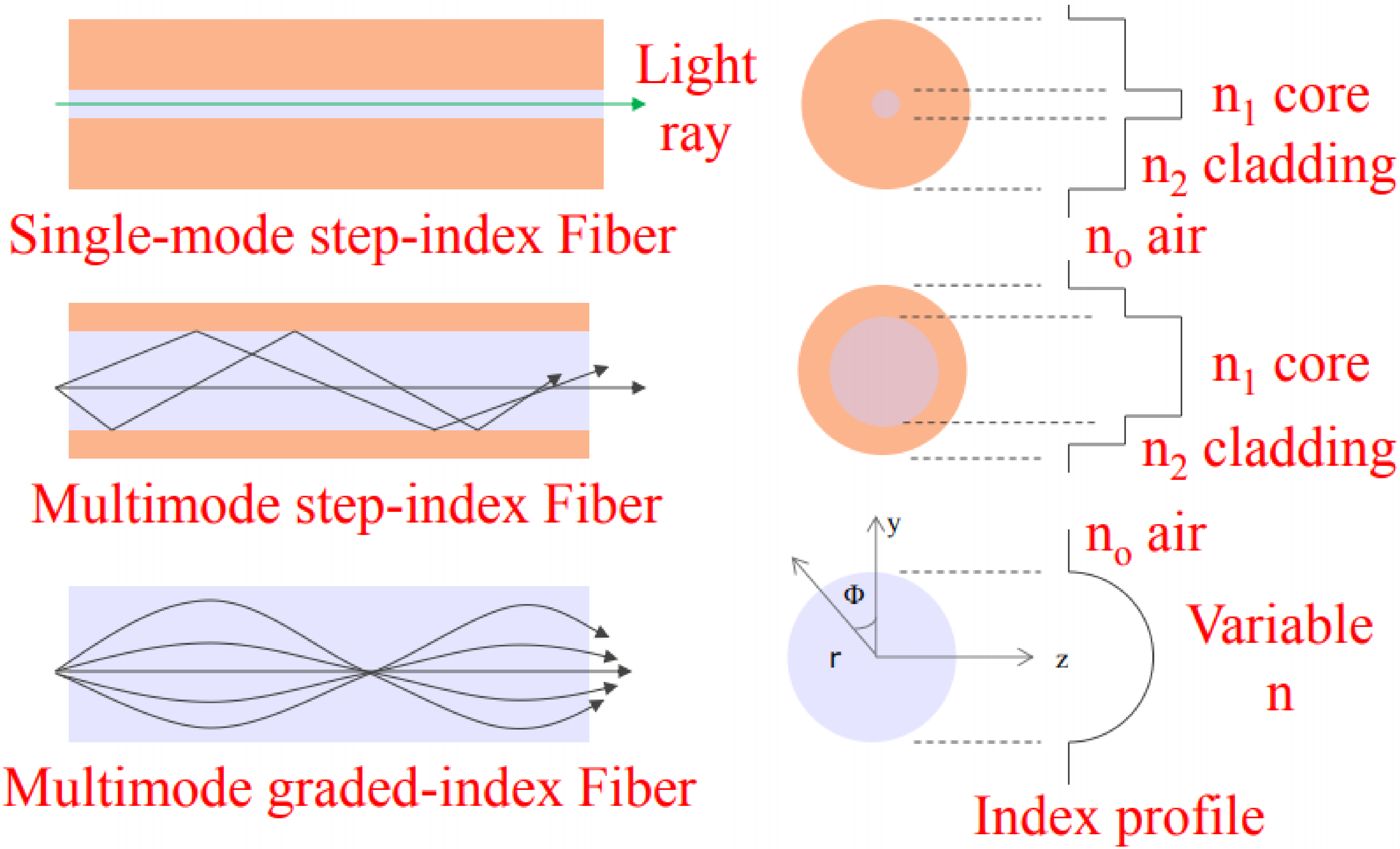
Figure 2.1: Cross section and refractive-index profile for step-index and graded-index fibers.

Optical Fiber Fabrication Methods

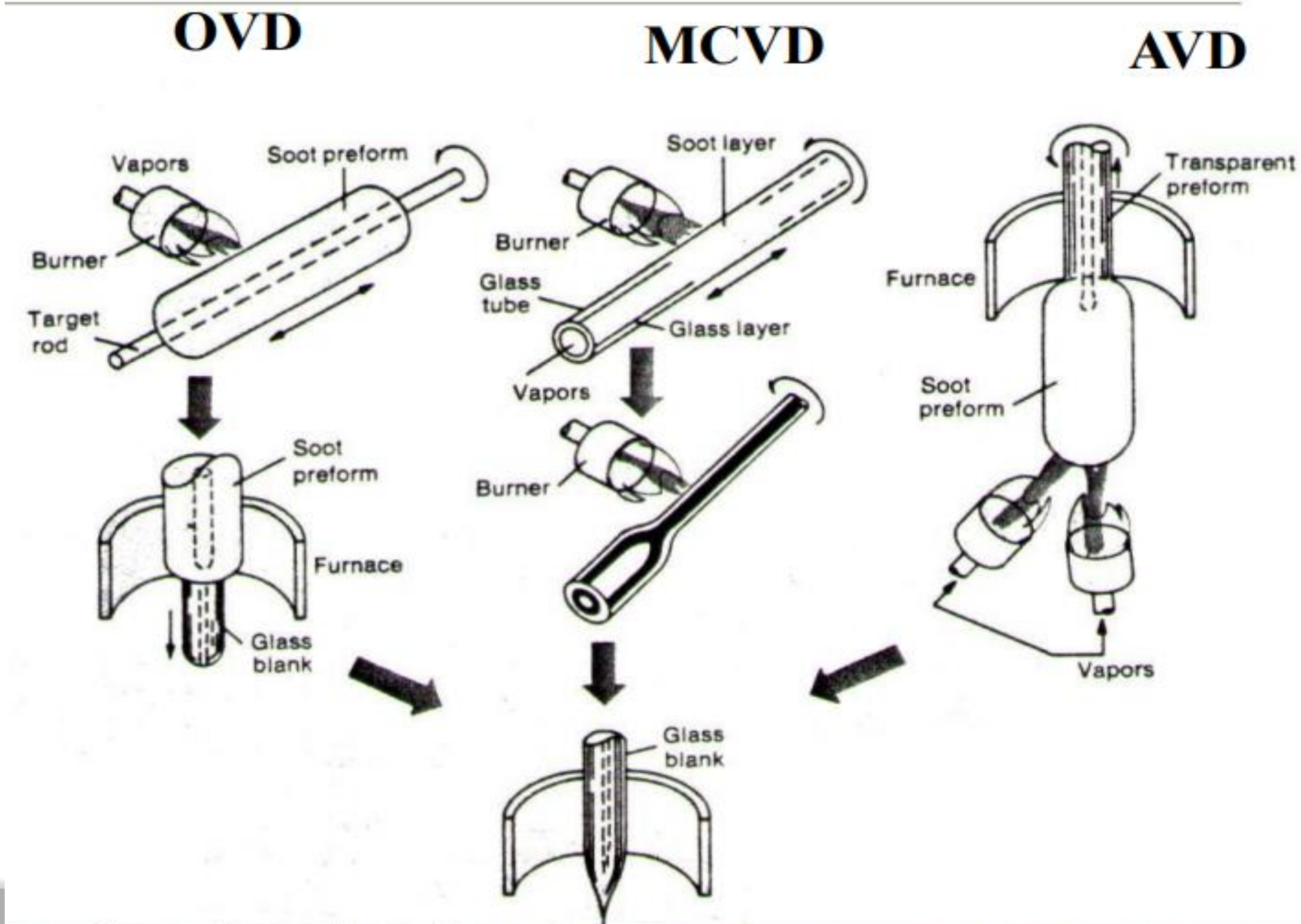
- **Glass**
  - CVD preform→ fiber drawing
  - Rod-in-tube prefrom → fiber drawing
  - Cast preform → fiber drawing
  - Double crucible → direct draw
  - Sol gel preform → fiber drawing
  - Stack and draw → PCFs
- **Polycrystalline**
  - Extrusion
  - Hot rolling
- **Monocrystalline**
  - Seed crystal growth from melt
  - Zone melting
- **Polymer**
  - Extrusion
  - Cast prefrom → fiber drawing

MCVD—Modified Chemical Vapor Depos
PMCVD—RF Plasma Enhanced MCVD
PCVD—Microwave Plasma CVD
OVD—Outside Vapor Deposition
VAD—Axial Vapor Deposition

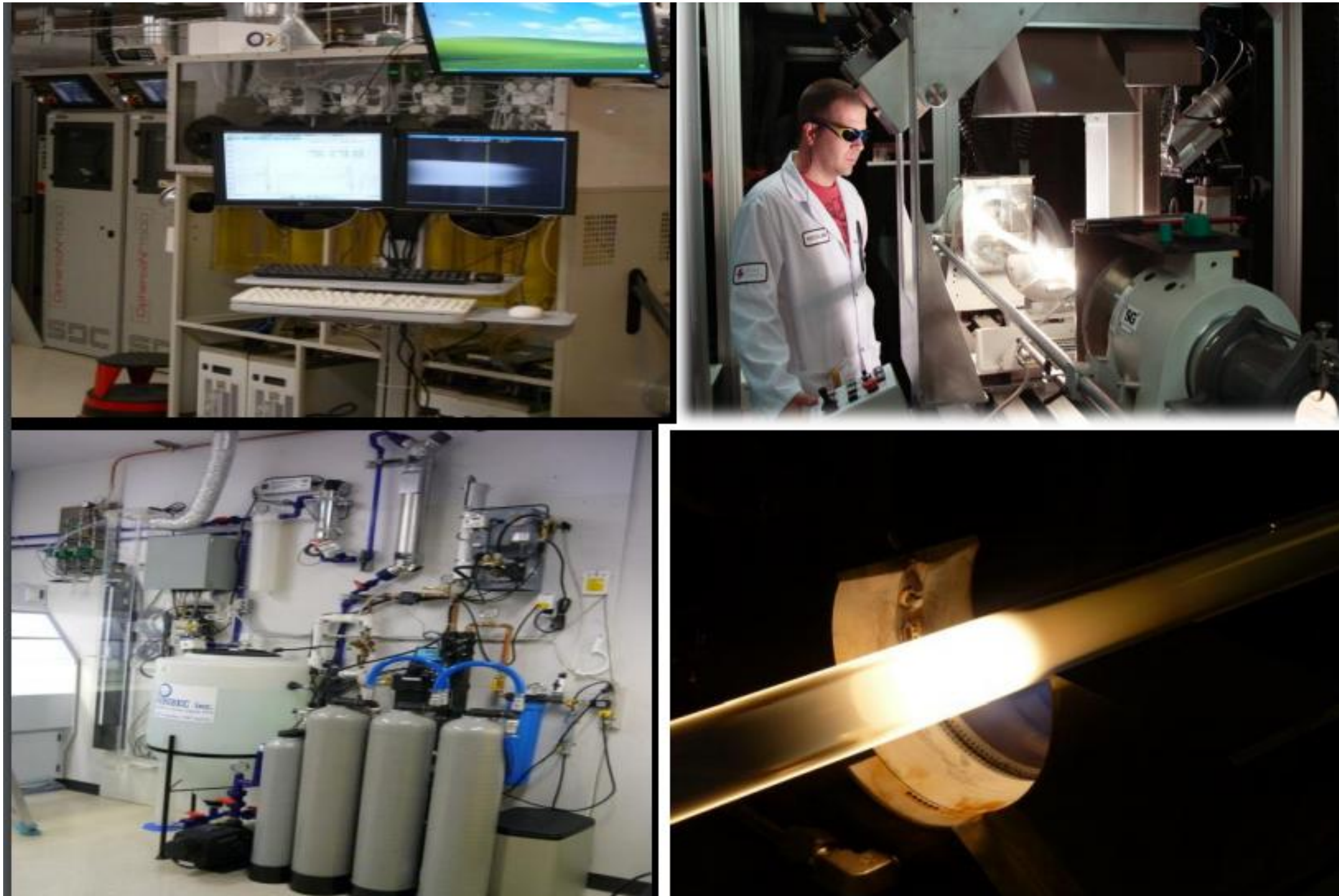
Types Of Optical Fiber



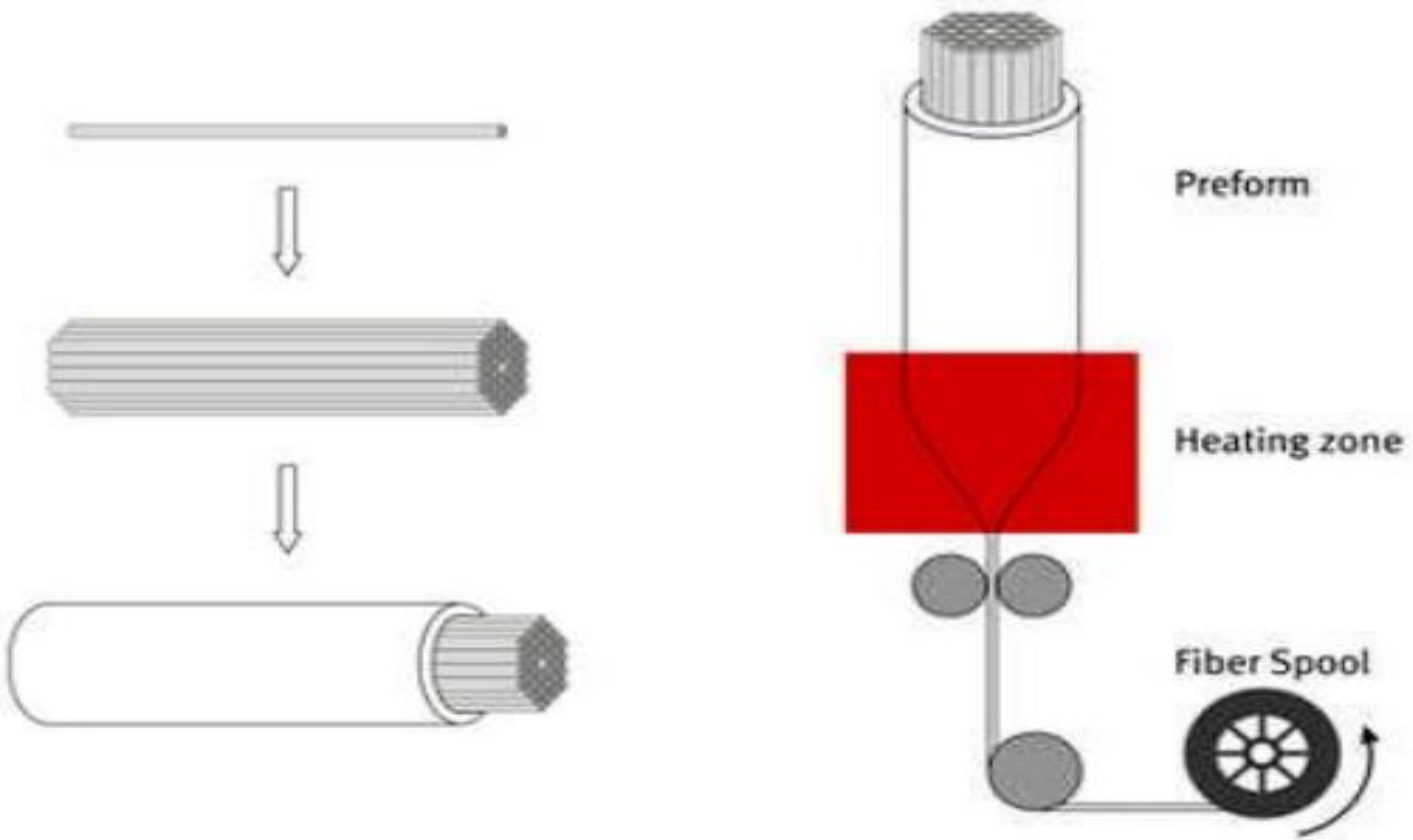
Optical Fiber Fabrication Methods



MCVD system



PCF Fabrication:
Stack-and-Draw Process



Special Fibers

- **Telecommunications**
  - Dispersion compensation
  - Transmission fibers
  - Broadband SM fibers

- **Lasers**
  - Double Clad fibers (laser cavity)
  - Large Area fibers (high power transmission)
  - White Light Sources

- **Sensing**
- **Metrology**
- **Medical**
  - Optical Coherence Tomography

What are optical fibers

- Thin strands of pure glass
- Carry data over long distances
- At very high speeds
- Fiber can be bent or twisted

Fiber optic technology

- Sources
- Transmission medium
- Detectors

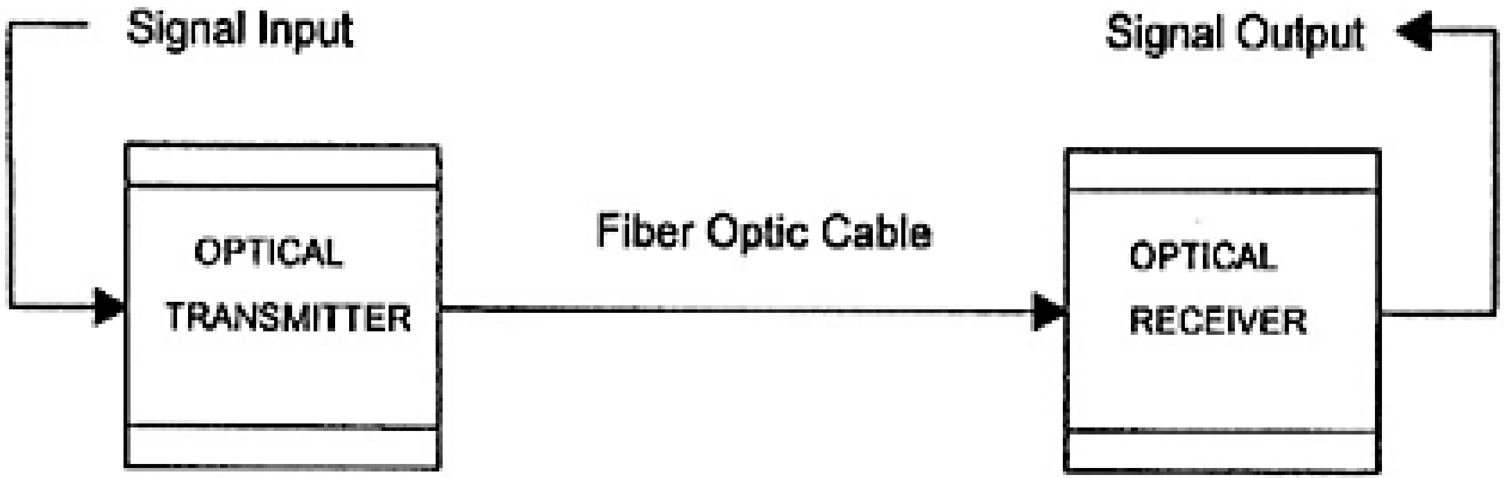
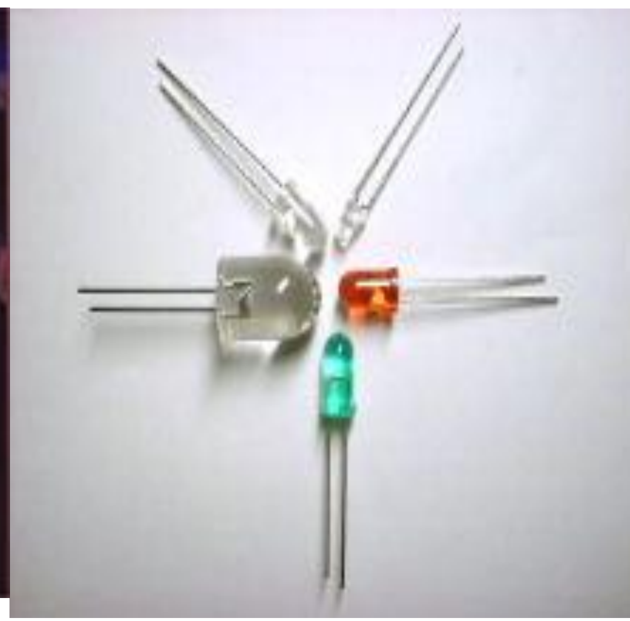
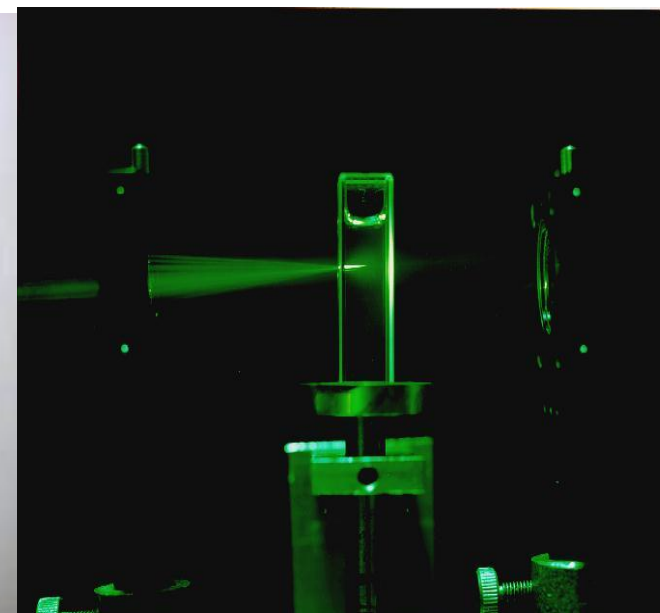


Fig: The fiber optic communication system

Sources of light

- Light emitting diodes
- Lasers

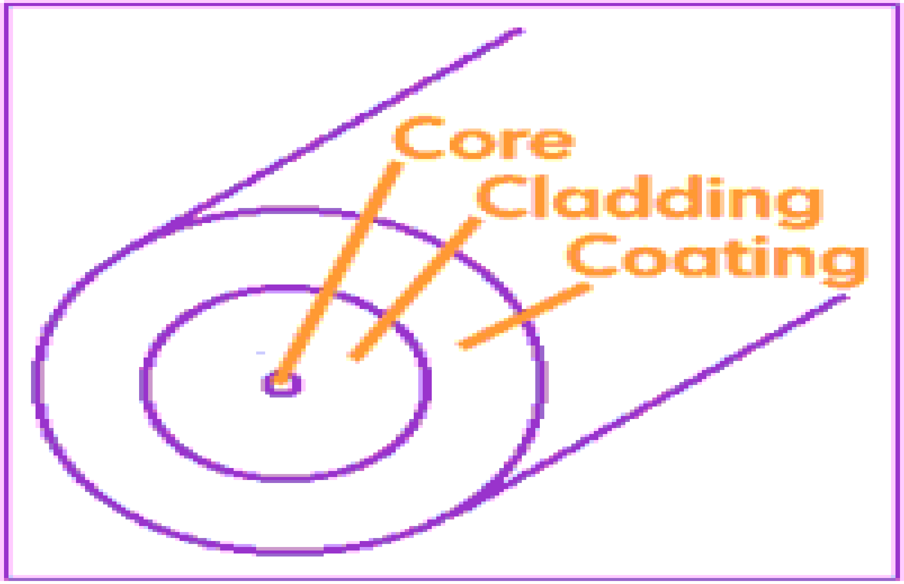




Sources

- Modulate electrical signals into optical signals
- Mostly modulate at 850nm, 1300nm and 1550 nm
- Lasers give high intensity, high frequency light
- LEDs are economical

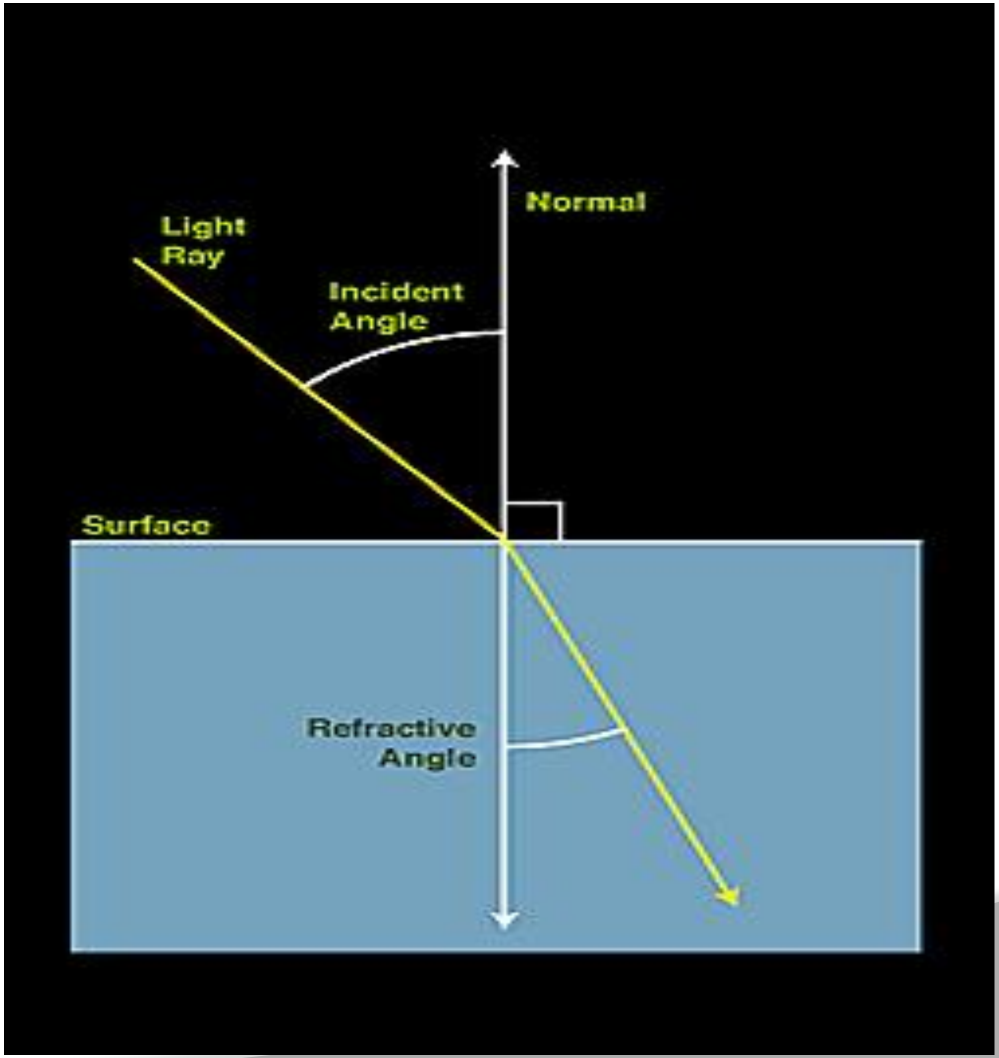
- Optical fiber is replacing copper
- Light is used as the carrier of information
- Much higher data rate



The optical fiber

Refraction of light

- Speed of light changes as it across the boundary of two media
- Angles w.r.t normal



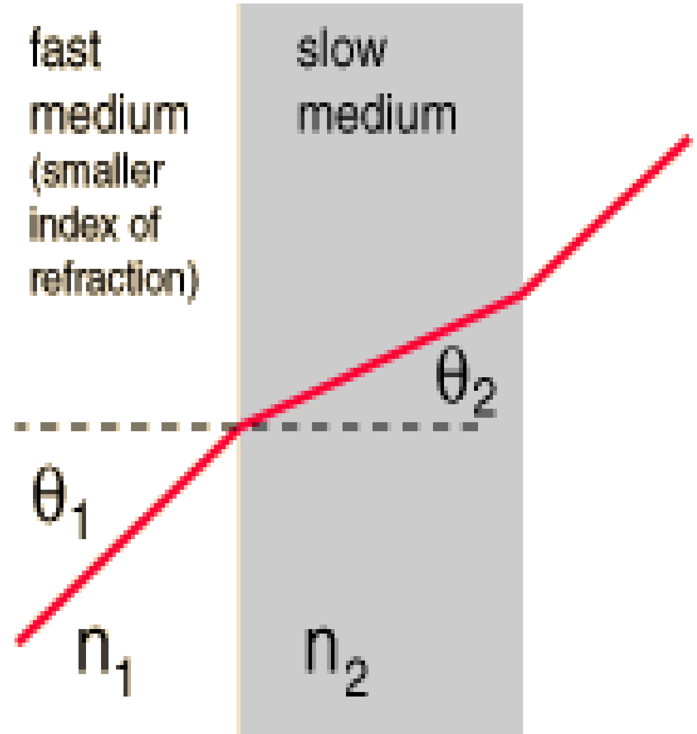
Refraction Indices

- Vacuum…….1.00000 (exactly)
- Air ……1.00029
- Alcohol 1.329
- Diamond 2.417
- Glass 1.5
- Ice 1.309
- Sodium Chloride (Salt) 1.544
- Sugar Solution (80%) 1.49
- Water (20 C) 1.333

Snell's Law

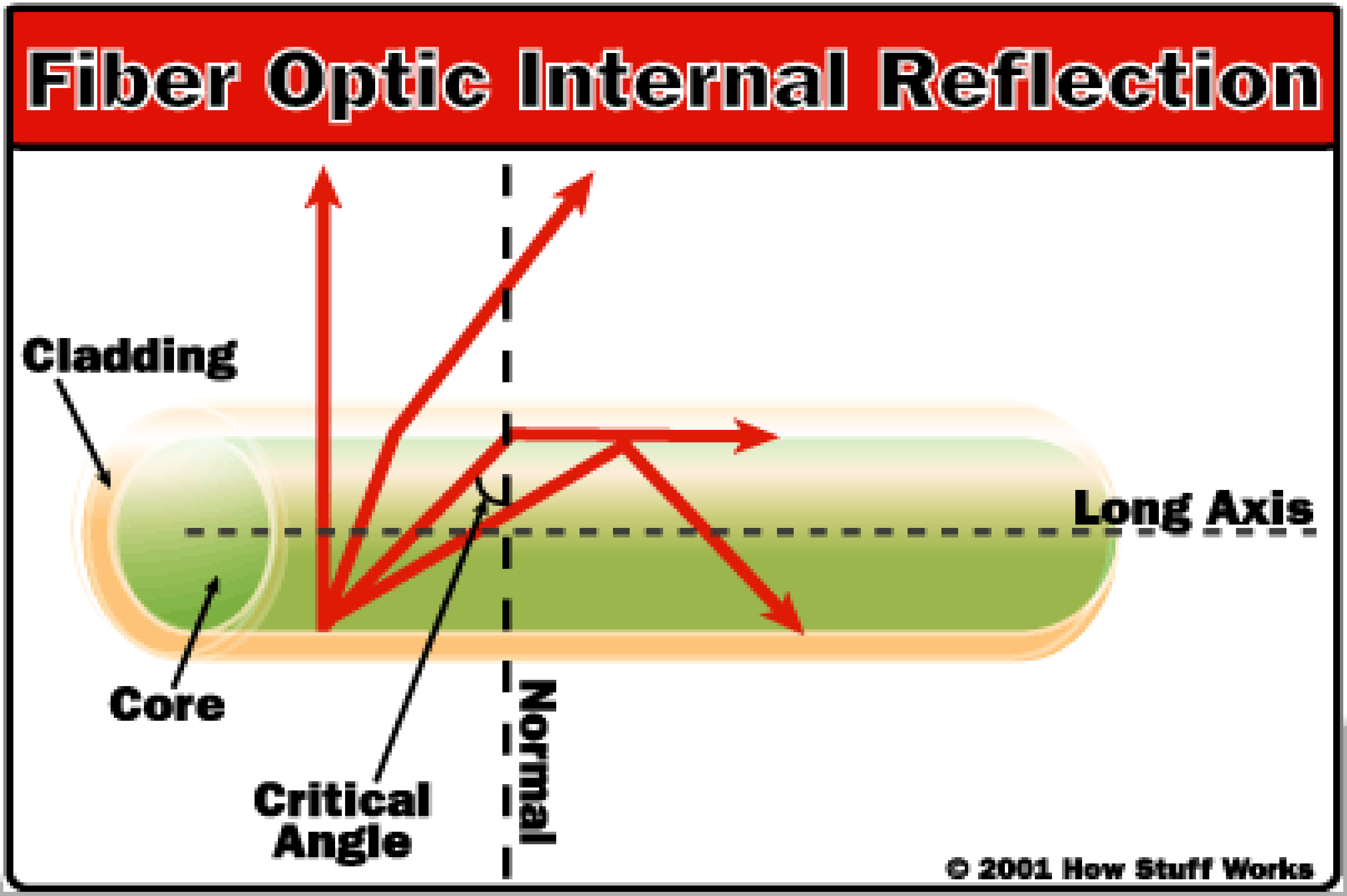
Snell's Law

$$\frac{n_1}{n_2} = \frac{\sin\theta_2}{\sin\theta_1}$$



- ➢Critical angle: Angle of incidence at which angle of refraction = 90^0

- Trapping light in the fiber



Fibers can be bent!!

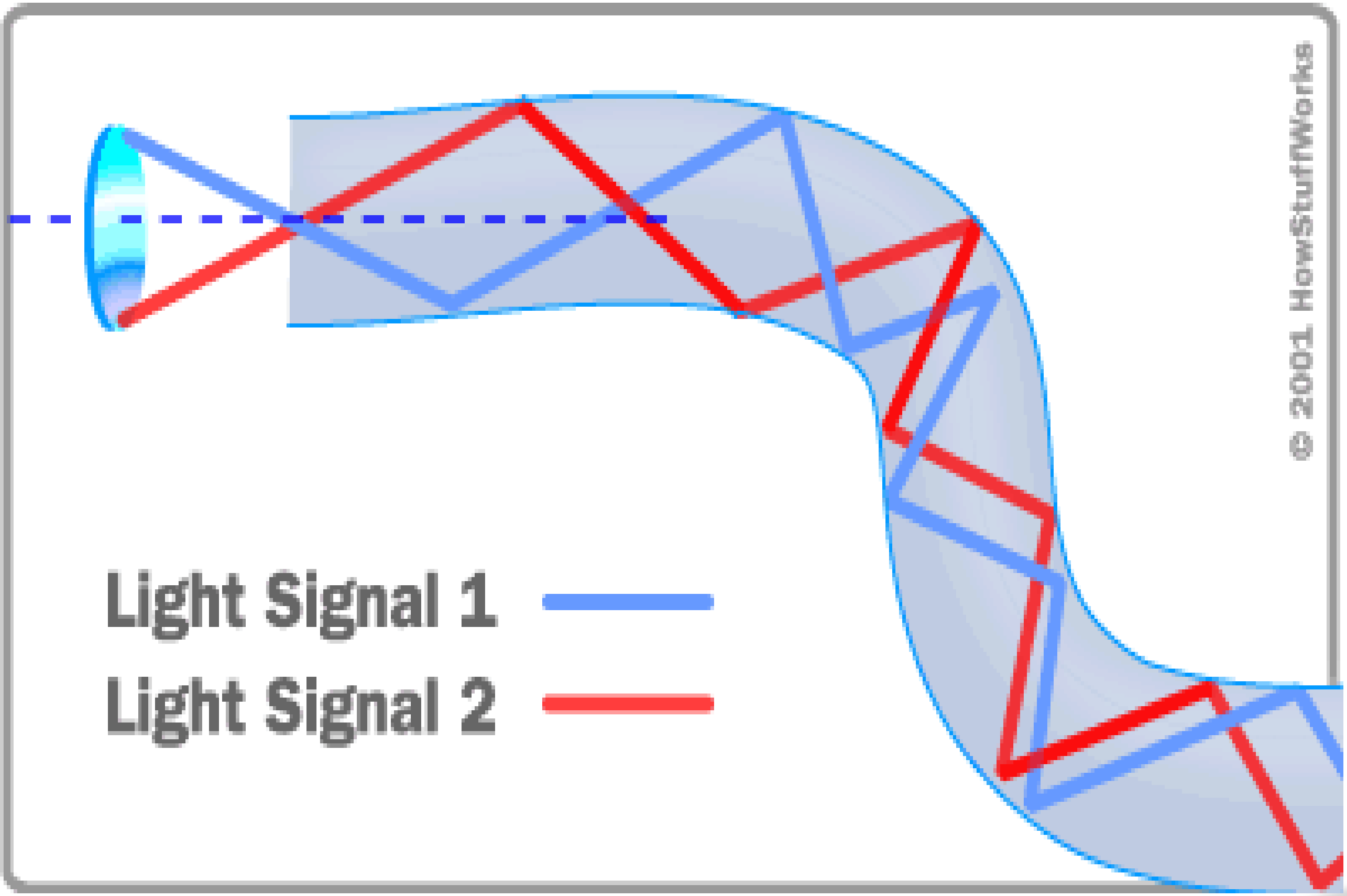


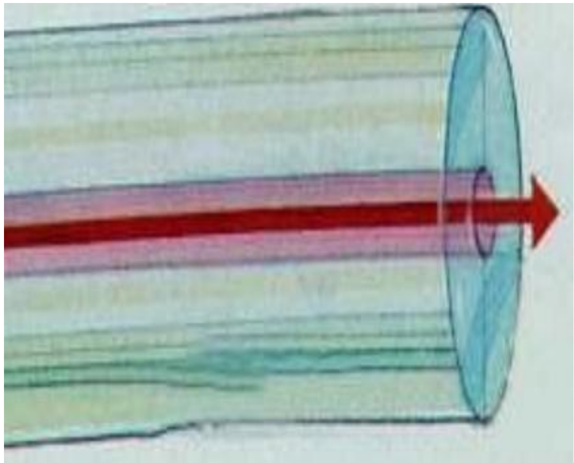
Fig: Illustration of total internal reflection

Types of optical fibers

Single mode

only one signal can be transmitted

use of single frequency



Multi mode

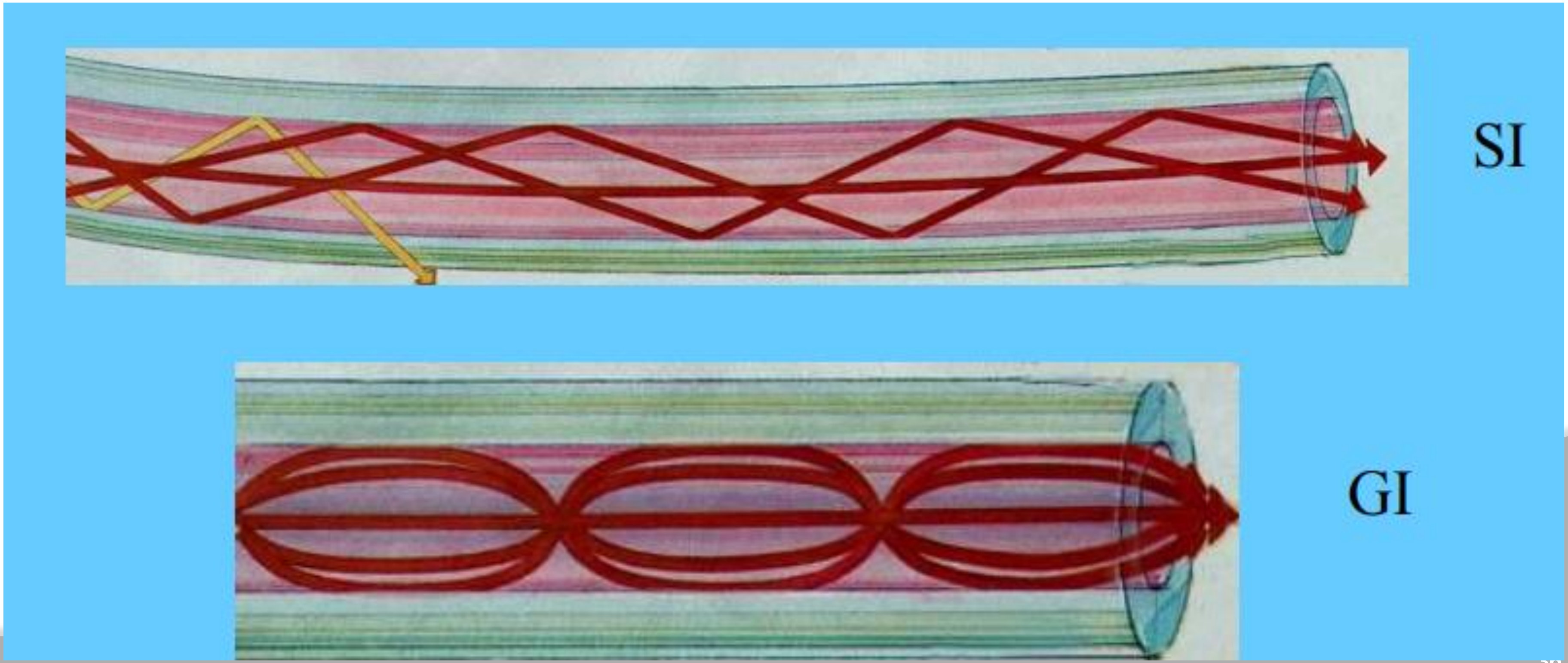
Several signals can be transmitted

Several frequencies used to modulate the signal

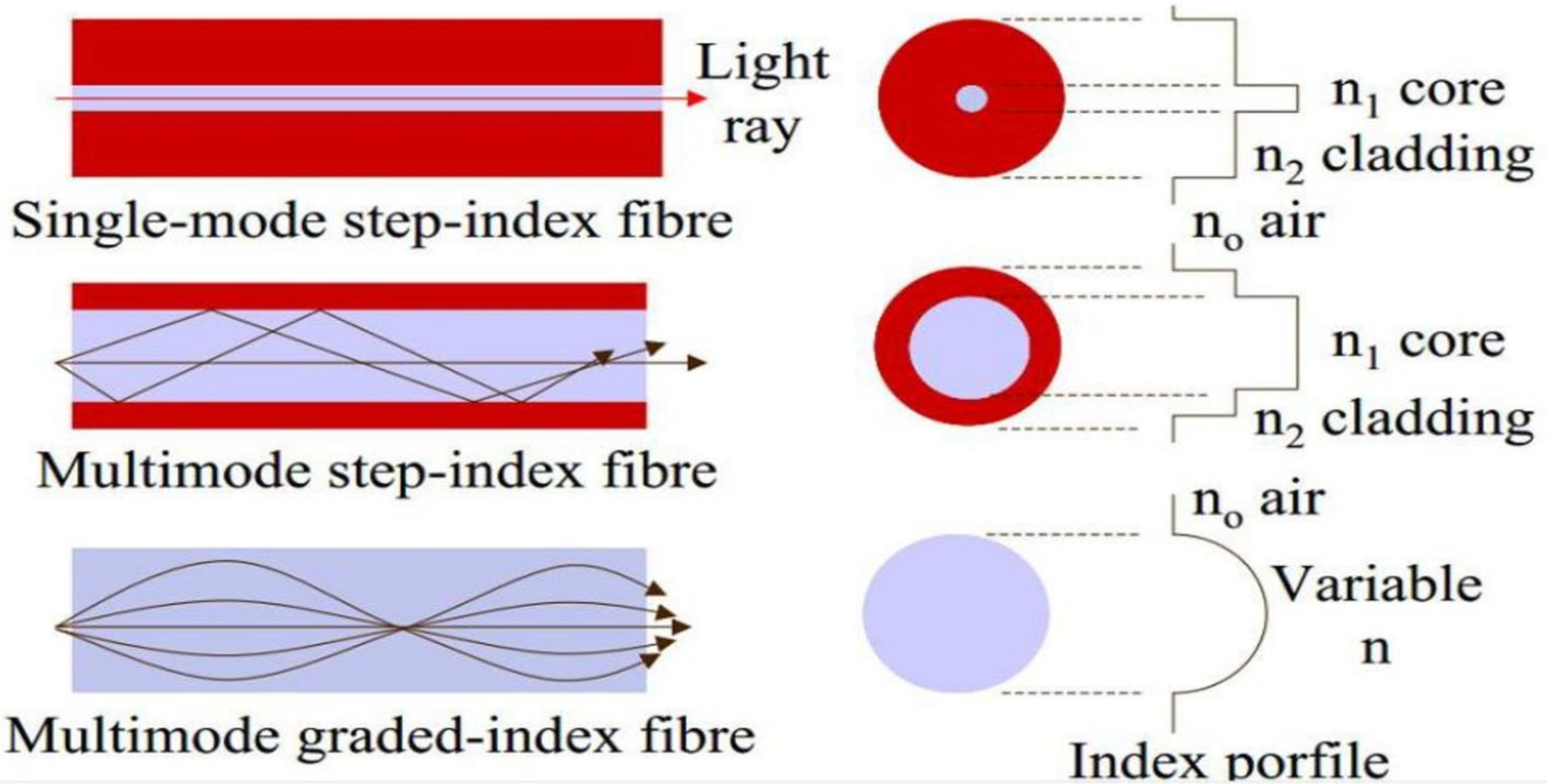
Types of optical fibers

Multimode Fibers

- Relatively large diameter core (50 to 100 microns)
- Step-index multimode cable has an abrupt change between core and cladding. It is limited to about 50 Mbits/sec
- Graded-index multimode cables has a gradual change between core and cladding. It is limited to 1 Gbit/sec.



Types of optical fibers



Multimode Step Index Fiber

- **Intrinsic Fiber Core Attenuation**

  Internal reasons of fiber optic loss caused by the fiber optic itself, which is also usually called intrinsic attenuation

- **Light absorption** is a major cause of losses in optical fiber during optical transmission. The light is absorbed in the fiber by the materials of fiber optic.

- **Scattering** is another major cause for losses in optical fiber. It refers to the scattering of light caused by molecular level irregularities in the glass structure.

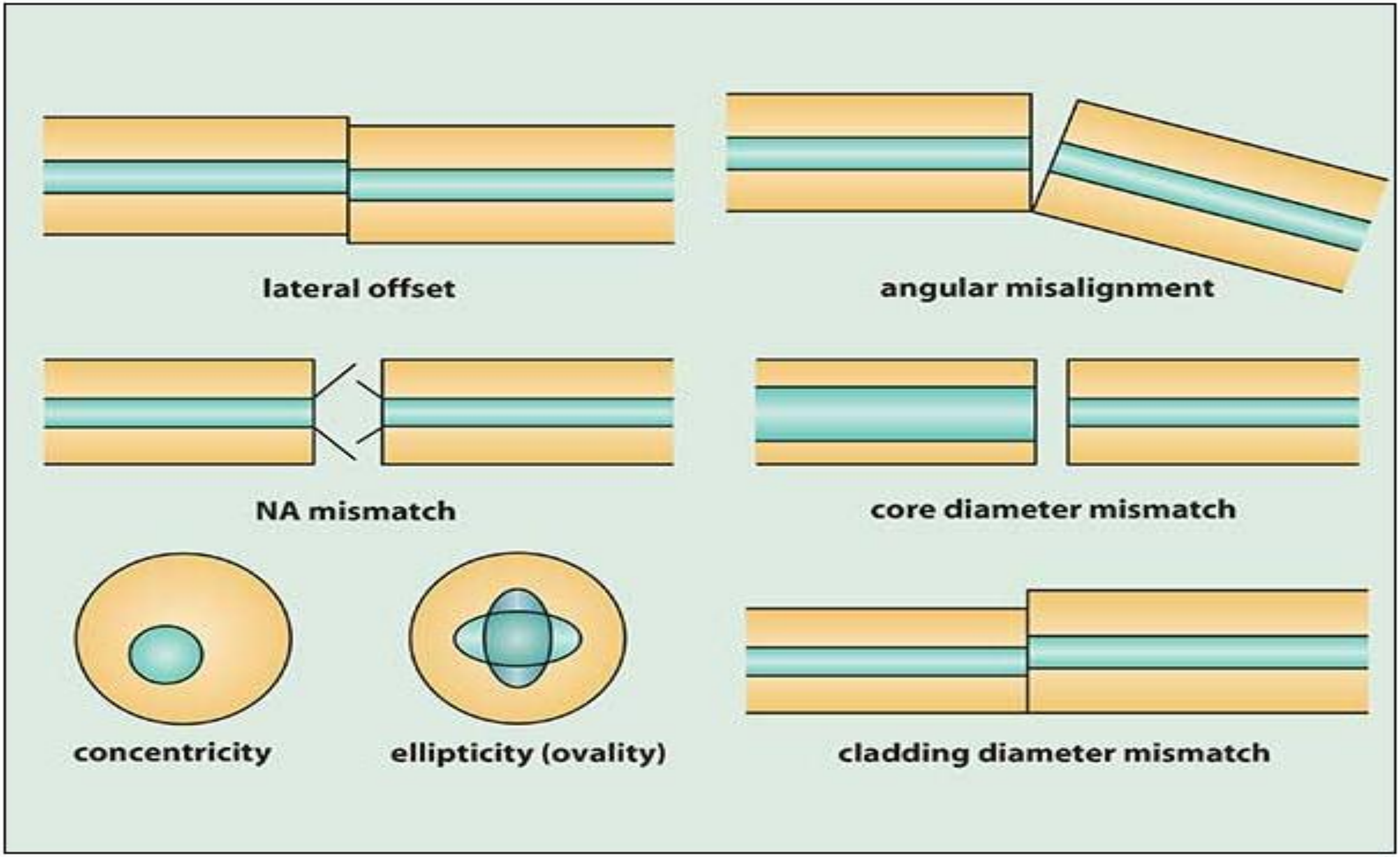
Losses in optical fibers

- **Extrinsic Fiber Attenuation:**

  Intrinsic fiber core attenuation including light absorption and scattering is just one aspect of the cause in fiber optic loss. Extrinsic fiber attenuation is also very important, which are usually caused by improper handling of fiber optic.
- **Bend loss** :is the common problems that can cause fiber optic loss generated by improper fiber optic handling. Literally, i
  - Fiber core deviate from the axis;
  - Defects of manufacturing;
  - Mechanical constraints during the fiber laying process;
  - Environmental variations like the change of temperature, humidity or pressure.

Losses in optical fibers

i.Attenuation loss ii. Dispersion loss iii. Waveguide loss



SC Subscriber Connector (NTT)

ST Straight Tip (AT&T Trademark)

Small-Form-Factor, SFF connectors

LC (Lucent Technology, 1.25 mm ferrule)

MT-RJ (AMP, Tyco Electronics)

optical fibers Connectors

E2000/LX-5

MT is a 12 fiber connector for ribbon cable.

MU

Volition

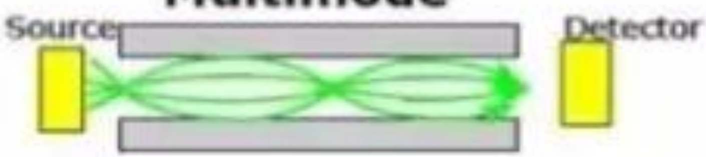
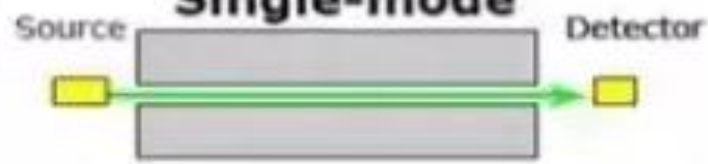
Opti-Jack

Difference between Single Mode and Multi Mode fiber

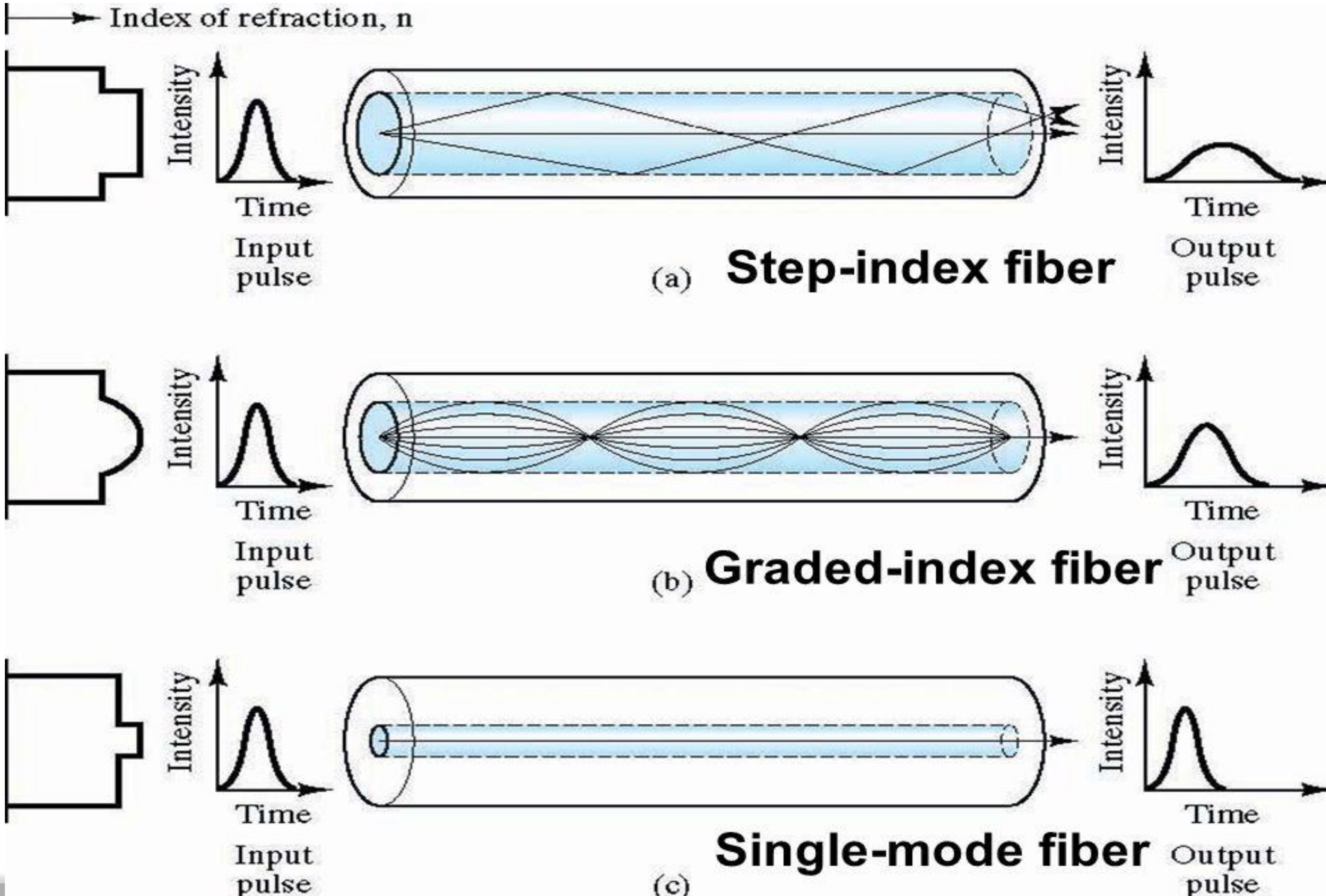
- Single mode fiber is one in which only one mode propagate through the fiber whereas Multi mode fiber is one in which multiple mode propagate through the fiber.
- Single mode fiber contains small core whereas Multi mode fiber contains large core.
- Single mode fiber employ for long distance communication whereas Multi mode fiber employ for short distance communication.
- Single mode fiber has less attenuation whereas Multi mode fiber has more attenuation.
- Single mode fiber has lower bandwidth whereas Multi mode fiber has higher bandwidth.
- Single mode fiber is less costly whereas Multi mode is more costly.

Difference between Single Mode and Multi Mode fiber

Multi-mode v/s Single mode

Multimode	Single-mode
	
+ Low cost sources	- High cost sources
+ 850 nm and 1310 nm LEDs	- 1310+ nm lasers 1 and 10 Gb/s
+ 850 nm lasers at 1 & 10 Gb/s	- 1 Gb/s + w/ DWDM
+ Low precision packaging	- High precision packaging
+ Low cost connectors	- Higher cost connectors
+ Lower installation cost	- Higher installation cost
- Higher fiber cost	+ Lower fiber cost
+ Lower system cost	**- Higher system cost**
- Higher loss, lower bandwidth	+ Lower loss, higher bandwidth
- Distance up to 2 km	+ Distance to 60 km+
Best for:	***Best for:***
• ***LAN, SAN, Data Center, CO***	• ***WAN, MAN, Access, Campus***

Difference between Single Mode and Multi Mode fiber



Fiber modes - single mode and multi-mode fibers

V-number

$$V = \frac{2\pi a}{\lambda}(n_1^2 - n_2^2)^{1/2}, \quad V_{cutoff} = \frac{2\pi a}{\lambda_c}(n_1^2 - n_2^2)^{1/2} = 2.41,$$

Number of modes when V>>2.41

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

Normalized propagation constant

$$b = \frac{n_{eff}^2 - n_2^2}{n_1^2 - n_2^2}, \qquad b \approx (1.1428 - 0.996/V)^2, \quad \text{for V between } 1.5 - 2.5.$$

Mode field diameter (MFD)

$$2w \approx 2a(1 + \frac{1}{V}),$$

Examples --- single mode and multi-mode fibers

1. Calculate the number of allowed modes in a multimode step index fiber, a = 100 μm, core index of 1.468 and a cladding index of 1.447 at the wavelength of 850nm.

Solution:

$$V = \frac{2\pi a}{\lambda}(n_1^2 - n_2^2)^{1/2} = 91.44, \qquad M \approx \frac{V^2}{2} = 4181,$$

2. What should be the core radius of a single mode fiber that has the core index of 1.468 and the cladding index of 1.447 at the wavelength of 1.3μm.

Solution:

$$V = \frac{2\pi a}{\lambda}(n_1^2 - n_2^2)^{1/2} < 2.4, \quad a < 2.1\mu m$$

3. Calculate the mode field diameter of a single mode fiber that has the core index of 1.458 and the cladding index of 1.452 at the wavelength of 1.3μm.

Solution:

$$2w_0 = 2a(1 + 1/V) \approx 10.1\mu m,$$

Fiber modes - single mode and multi-mode fibers

Example: Single mode cut-off wavelength

Calculate the cut-off wavelength for single mode operation for a fiber that has a core with diameter of 8.2 μm, a refractive index of 1.4532, and a cladding of refractive index of 1.4485. What is the V-number and the mode field diameter (MFD) for operation at $\lambda = 1.31$ μm?

Solution

For single mode operation,

$V = (2\pi a/\lambda)(n_1^2 - n_2^2)^{1/2} \leq 2.405$

Substituting for a, n_1 and n_2 and rearranging we get,

$\lambda > [2\pi(4.1 \text{ μm})(1.4532^2 - 1.4485^2)^{1/2}]/2.405 = 1.251$ μm

Wavelengths shorter than 1.251 μm give multimode propagation.

At $\lambda = 1.31$ μm,

$V = 2\pi[(4.1 \text{ μm})/(1.31 \text{ μm})](1.4532^2 - 1.4485^2)^{1/2} = 2.30$

Mode field diameter MFD

Fiber modes - single mode and multi-mode fibers

Solution (continued)

Mode field diameter MFD from the Marcuse Equation is

$$2w = 2a(0.65 + 1.619V^{-3/2} + 2.879V^{-6})$$

$$= 2(4.1)[0.65 + 1.62(2.30)^{-3/2} + 2.88(2.30)^{-6}]$$

$2w = 9.30\ \mu\text{m}$ 86% of total power is within this diameter

$2w = (2a)(2.6/V) = 2(4.1)(2.6/2.30) = 9.28\ \mu\text{m}$

$2w = 2a[(V+1)/V] = 11.8\ \mu\text{m}$ This is for a planar waveguide, and the definition is different than that for an optical fiber

UNIT-II
SIGNAL DEGRADATION AND OPTICAL SOURCES

CLOs	Course Learning Outcome
CLO1	Understand modal analysis of a step index fiber, linearly polarized modes, single mode fibers and graded - index fiber.
CLO2	Understand Signal Degradation And Optical Sources, Attenuation- Absorption, scattering losses, bending losses, core.
CLO3	Explain cladding losses, optical waveguides; Material Dispersion, Waveguide Dispersion; Optical sources.
CLO4	Understand phase noise, switching and modulation characteristics.

Attenuation

- What are the loss or signal attenuation mechanism in a fiber?
- Why & to what degree do optical signals get distorted as they propagate down a fiber?
- Signal attenuation (fiber loss) largely determines the maximum repeater less separation between optical transmitter & receiver.
- Signal distortion cause that optical pulses to broaden as they travel along a fiber, the overlap between neighboring pulses, creating errors in the receiver output, resulting in the limitation of information-carrying capacity of a fiber.

Causes of Attenuation:

The basic attenuation mechanism in a fiber is;

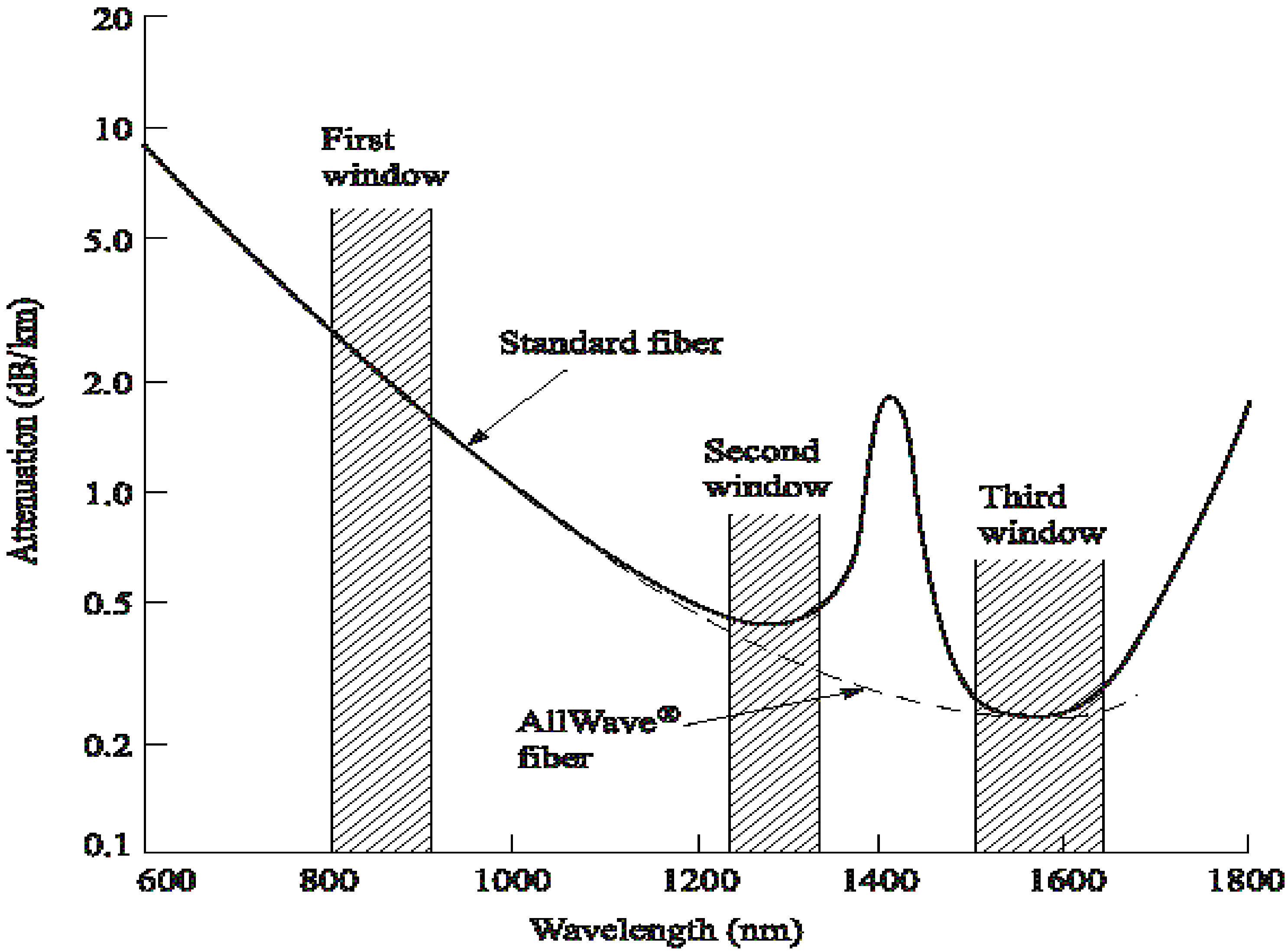
Absorption: This is related to fiber material.

Scattering: It is associated with both the fiber material with structural imperfections in optical waveguide.

Bending (radiative losses): Attenuation owing to radiative effects originates from perturbation in fiber geometry (both micro bending and macro bending)

Dispersion: Due to the modes.

Optical fiber attenuation vs. wavelength

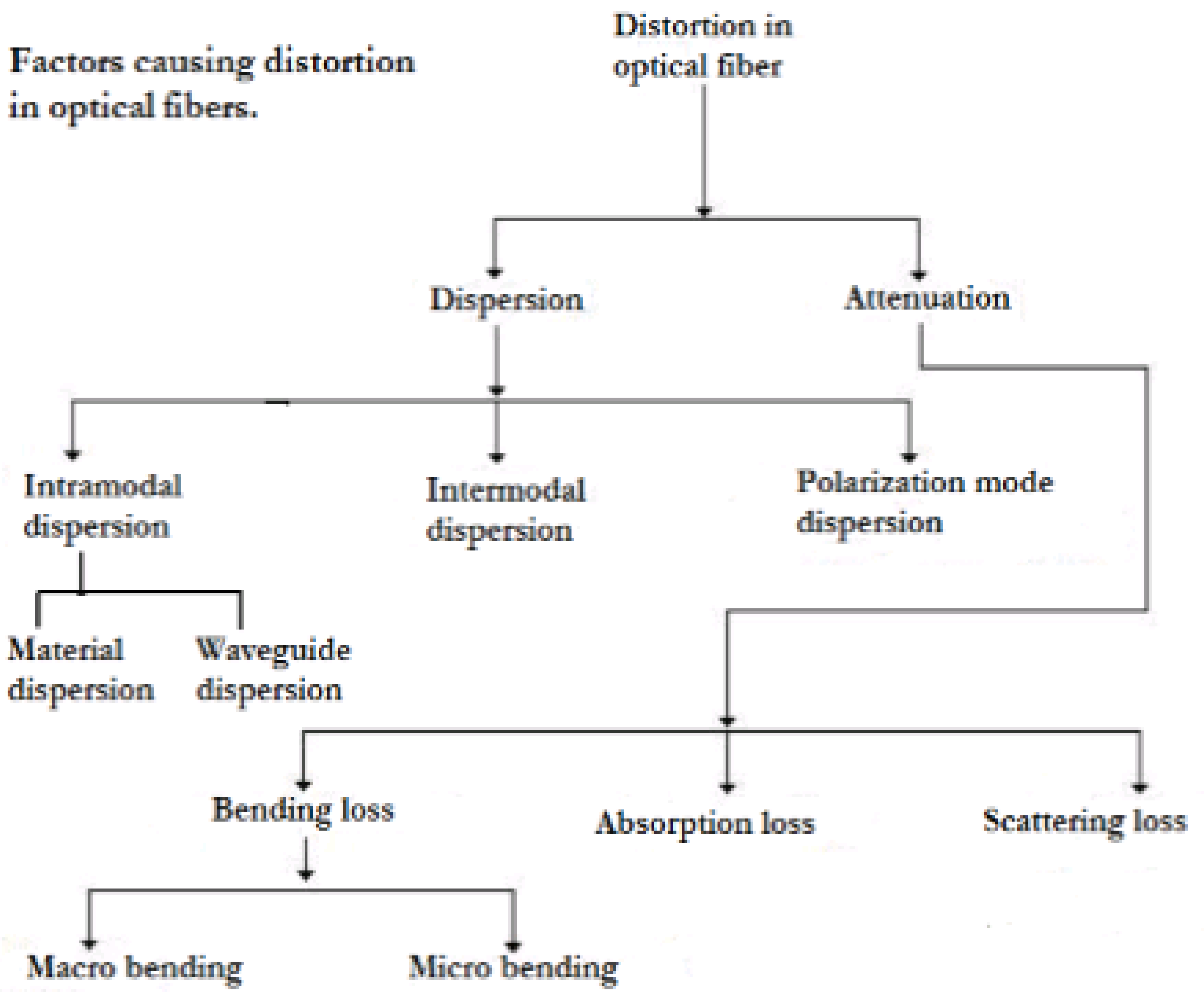


- The attenuation of an optical fiber measures the amount of light lost between input and output. Total attenuation is the sum of all losses.
- Optical losses of a fiber are usually expressed in ***decibels per kilometer (dB/km)***.
- The expression is called the ***fiber's attenuation coefficient α*** and the expression is

$$\alpha = -\frac{10}{z[\mathrm{km}]}\log\left(\frac{P(z)}{P(0)}\right)$$

- where P(z) is the optical power at a position z from the origin, P(0) is the power at the origin.

Factors causing distortion in optical fibers.



Optical Fiber Losses

Attenuation in Optical Fibers

- Attenuation limits the optical power which can reach the receiver, limiting the operating span of a system.
- Once the power of an optical pulse is reduced to a point where the receiver is unable to detect the pulse, an error occurs.
- **Attenuation** is mainly a result of:
- **Light Absorption**
- **Scattering of light**
- **Bending losses**
- **Attenuation** is defined as the ratio of optical input power (P_i) to the optical output power (P_o).
- The following equation defines signal attenuation as a unit of length :

Attenuation $$\alpha(dB/km) = -\frac{10}{L} Log_{10}\left(\frac{P_{out}}{P_{in}}\right)$$

Attenuation

- When the light travels in the optical fiber then due to transmission characteristics it gives signal loss.
- Different factors are responsible for signal attenuation inside the fiber.

Bending loss:

- Once fiber is laid as cables for communication purpose bending losses occur.
- Optical fibers suffer radiation losses at bends or curves on their paths.

The two types of bending losses are as follows:

Macro bending loss:

- Fiber is subjected to gentle bend over a large arc, this bend causes failure of total internal reflection condition of a optical signal at the core-cladding interface which leads to leakage of optical signal from the fiber.
- This causes macro bending loss.

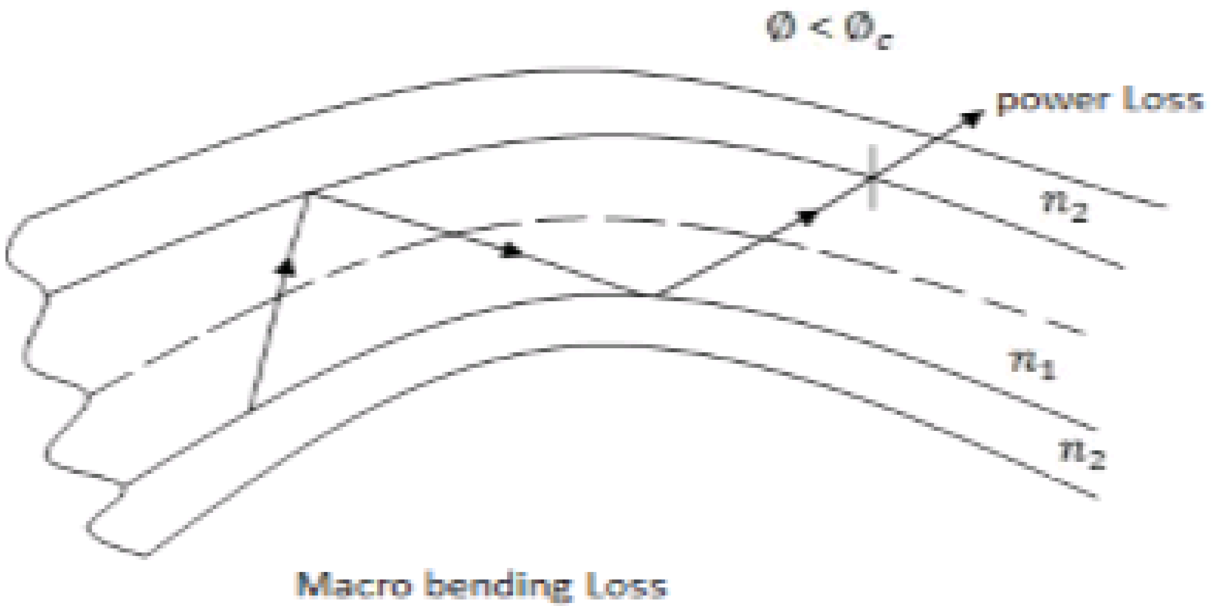


Figure 2.3: Macroscopic bending loss

Microbending losses:

- Micro bends are caused either by non-uniformities in the manufacturing of the fiber or by non-uniform lateral pressures created during the cabling or packaging losses.
- When a light beam strikes these imperfections in the fiber, the condition of total internal reflection is not attained and the beam leaks out of the core causing micro bending losses.

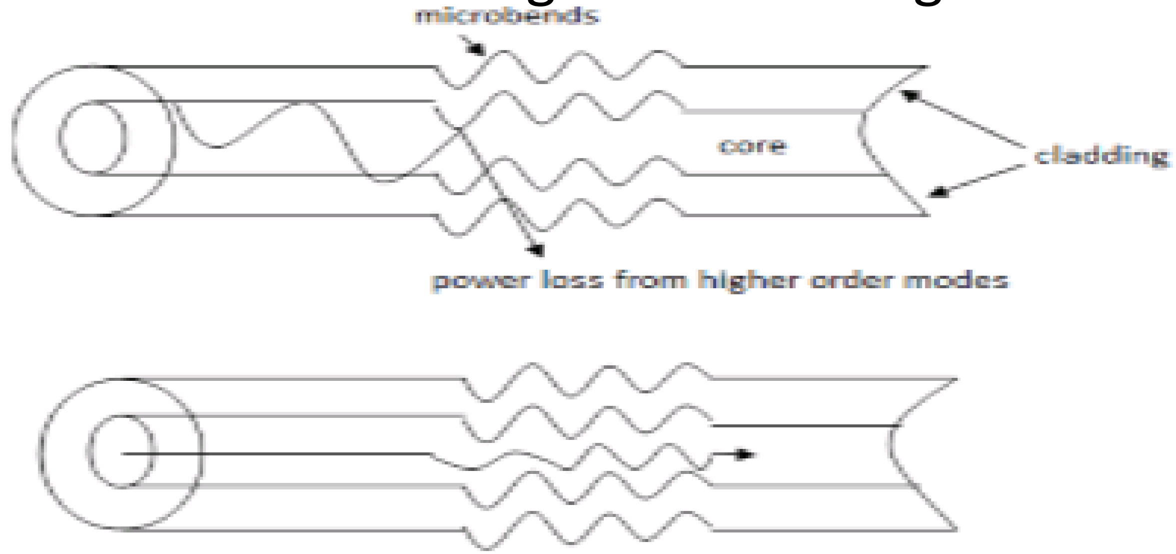


Figure 2.4: Micro bending loss

Absorption loss

Absorption is caused by three different mechanism:

i. Intrinsic absorption by basic constituent atoms of fibre material

ii. Extrinsic absorption by impurity atoms in silica material

iii. Absorption by atomic defects in the composition of glass

Scattering loss

- Scattering losses in glass arise from microscopic variations in the material density, from compositional fluctuations and from structural in homogeneties or defects occurring during fiber manufacture.

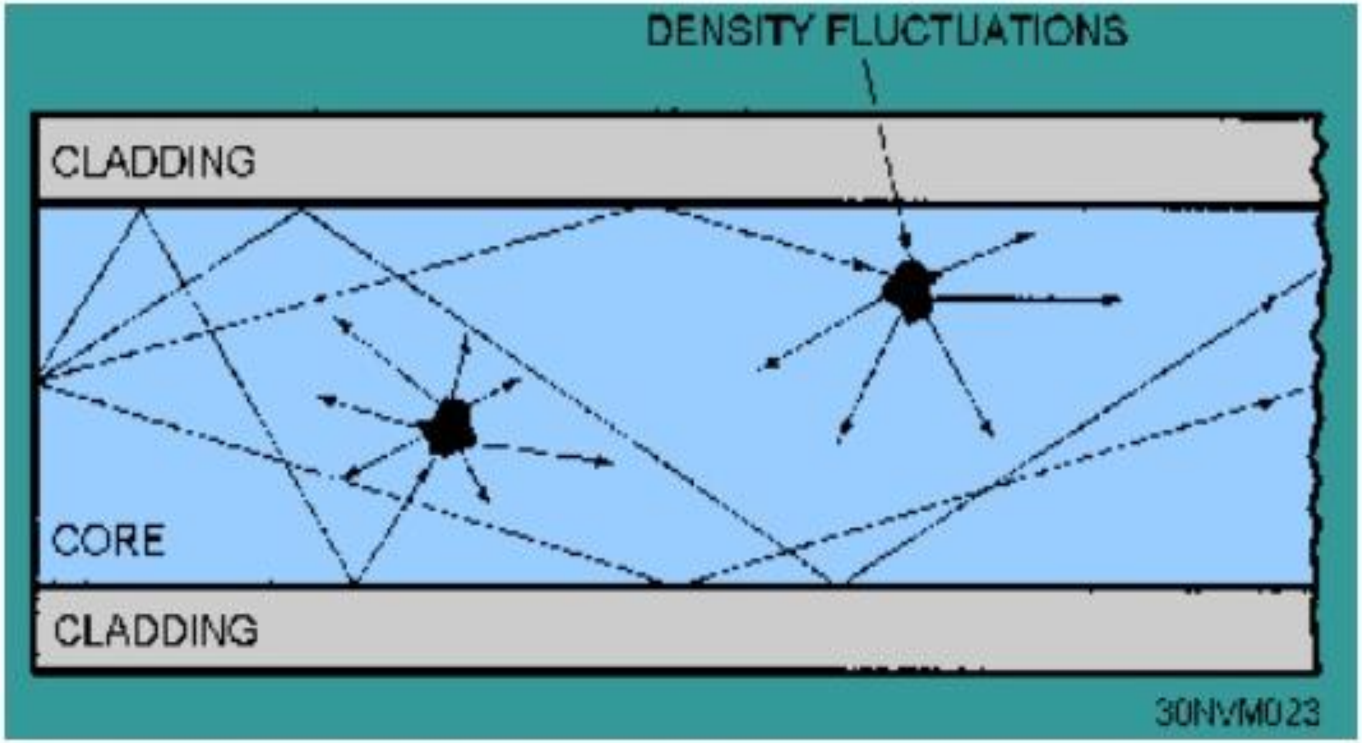


Figure: - 7(Scattering process)

- In commercial fibers operating between 700-nm and 1600-nm wavelength, the main source of loss is called **Rayleigh scattering**.

- As the wavelength increases, the loss caused by Rayleigh scattering decreases.

- If the size of the defect is greater than one-tenth of the wavelength of light, the scattering mechanism is called **Mie scattering**.

- **Linear scattering losses**
- **Nonlinear scattering losses**

- **Rayleigh scattering**

- It occurs because the molecules of silicon dioxide have some freedom when adjacent to one another.
- Thus, setup at irregular positions and distances with respect to one another when the glass is rapidly cooled during the final stage of the fabrication process.
- Those structural variations are seen by light as variations in the refractive index,

Causes of Rayleigh Scattering:

- It results from non-ideal physical properties of the manufactured fiber.
- It results from in homogeneities in the core and cladding.

Because of these in homogeneities problems occur like –

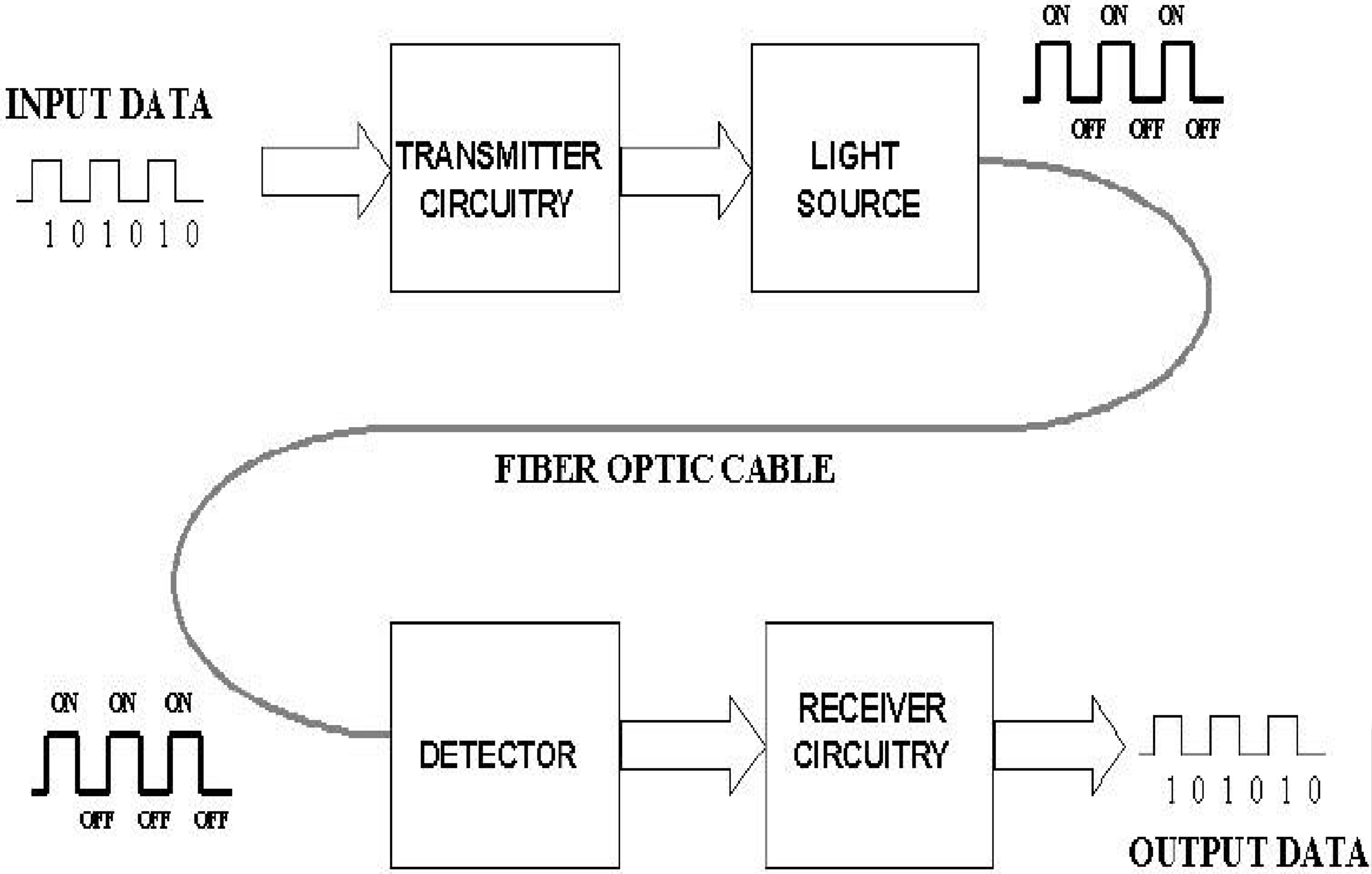
a) Fluctuation in refractive index
b) density and compositional variations.

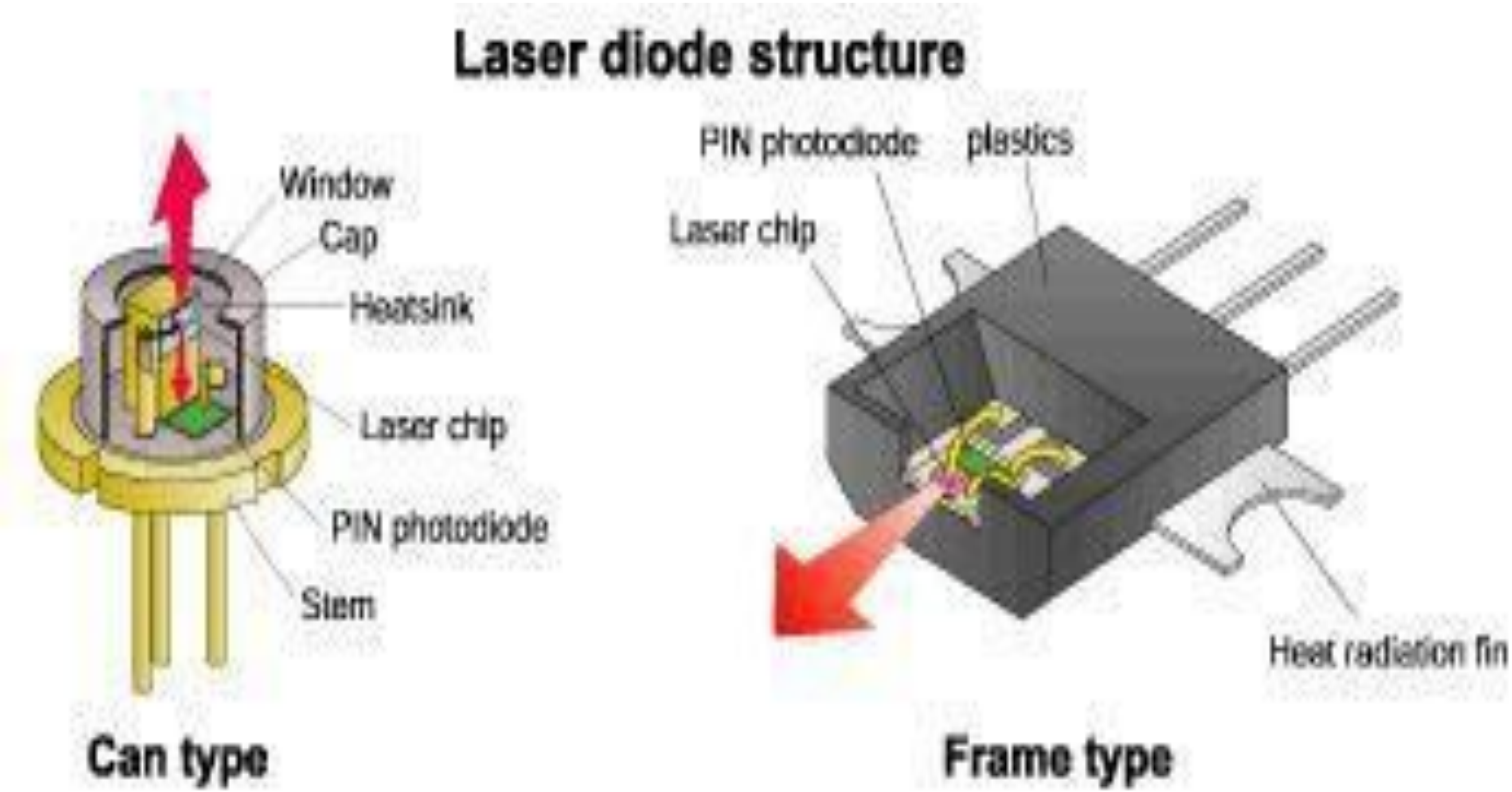
Nonlinear scattering losses

- Specially at high optical power levels scattering causes disproportionate attenuation, due to non linearbehavior.
- Because of this non linear scattering the optical power from one mode is transferred in either the forward or backward direction to the same, or other modes, at different frequencies.

- The two dominant types of non linear scattering are :

a) Stimulated Brillouin Scattering.
b) Stimulated Raman Scattering.


INPUT DATA
1 0 1 0 1 0
TRANSMITTER CIRCUITRY
LIGHT SOURCE
ON ON ON
OFF OFF OFF
FIBER OPTIC CABLE
ON ON ON
OFF OFF OFF
DETECTOR
RECEIVER CIRCUITRY
1 0 1 0 1 0
OUTPUT DATA


Laser diode structure
Window
Cap
Heatsink
Laser chip
PIN photodiode
Stem
Can type
PIN photodiode
plastics
Laser chip
Heat radiation fin
Frame type

Laser Diodes

Depending on the applications like local area

networks and the long haul communication sy•st,ems, the light source requirements vary.

The requirements of the sources include power, speed, spectral line width, noise, ruggedness, cost, temperature, and so on.

Two components are used as light sources: light emitting diodes (LED's) and laser diodes.

- Fibers are used instead of metal wires because signals travel along them with less loss and are also immune to electromagnetic interference.
- Fibers are also used for illumination, and are wrapped in bundles so that they may be used to carry images, thus allowing viewing in confined spaces.
- Specially designed fibers are used for a variety of other applications,

including sensors and fiber lasers.

- Optical fibers typically include a transparent core surrounded by a transparent cladding material with a lower index of refraction.
- Light is kept in the core by total internal reflection. This causes the fiber to act as a waveguide.
- Fibers that support many propagation paths or transverse modes arecalled multi-mode fibers (MMF), while those that only support a single

- mode are called single-mode fibers (SMF).
- Multi-mode fibers generally have a wider core diameter, and are used for short-distance communication links and for applications where high
- power must be transmitted. Single-mode fibers are used for most communication links longer than 1,000 meters (3,300 ft).

- The light emitting diodes are used for short distances and low data rate applications due to their low bandwidth and power capabilities.
- Two such LEDs structures include Surface and Edge Emitting Systems.
- The surface emitting diodes are simple in design and are reliable, but due to its broader line width and modulation frequency limitation edge emitting diode are mostly used.
- Edge emitting diodes have high power and narrower line width capabilities.
- For longer distances and high data rate transmission, Laser Diodes are preferred due to its high power, high speed and narrower spectral line width characteristics.
- But these are inherently nonlinear and more sensitive to temperature variations.

LED Versus Laser

Characteristic	LED	Laser
Output power	Lower	Higher
Spectral width	Wider	Narrower
Numerical aperture	Larger	Smaller
Speed	Slower	Faster
Cost	Less	More
Ease of operation	Easier	More difficult

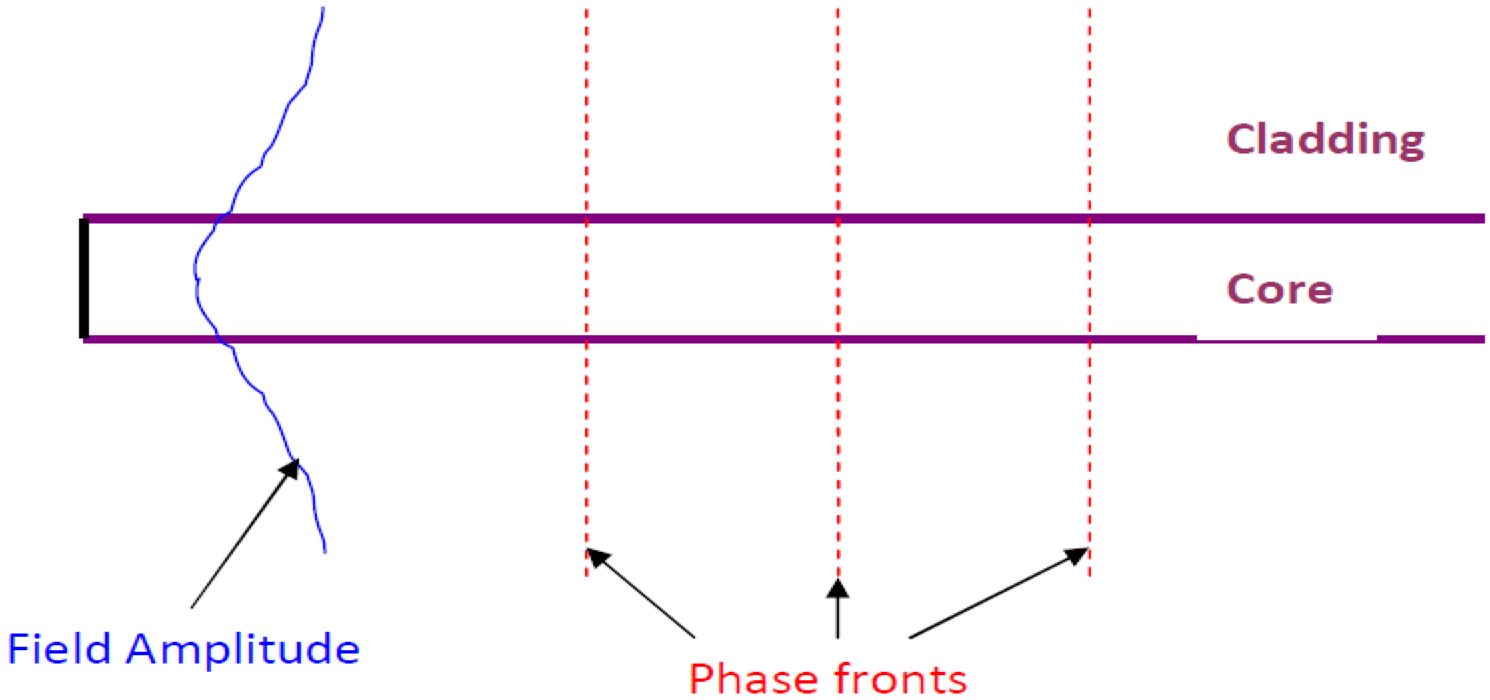
Nowadays many improvements and advancements have made these sources more reliable. A few of such comparisons of these two sources are given below.

Both these sources are modulated using either direct or external modulation techniques.

Low Loss Optical Fiber

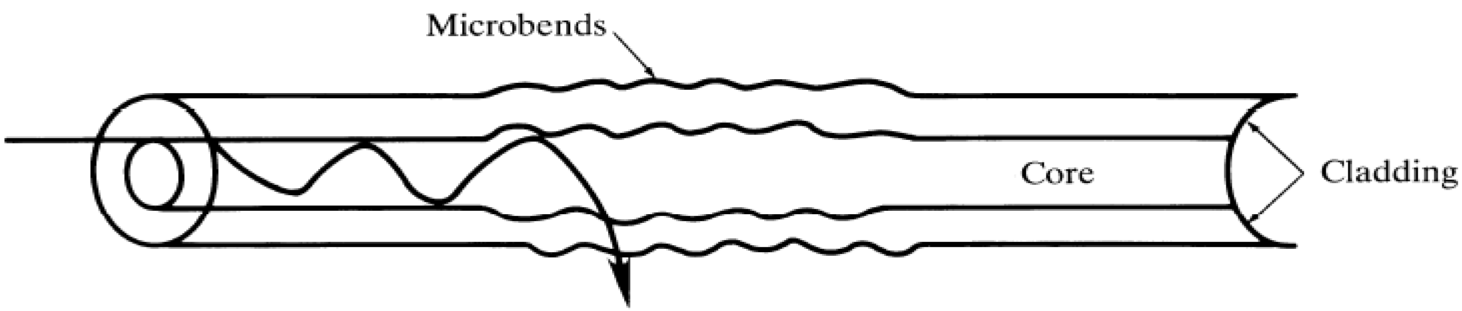
Optical fiber is a cable, which is also known as cylindrical dielectric waveguide made of low loss material. An optical fiber also considers the parameters like the environment in which it is operating, the tensile strength, durability and rigidity. The Fiber optic cable is made of high quality extruded glass (si) or plastic, and it is flexible. The diameter of the fiber optic cable is in between 0.25 to 0.5mm (slightly thicker than a human hair).

Phase Fronts in a Straight Fiber

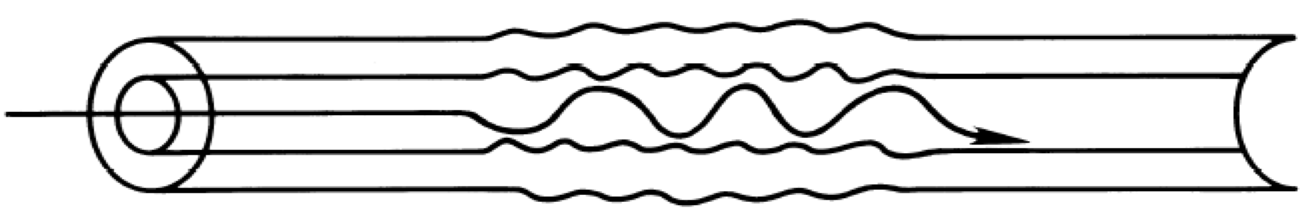


MICRO-BENDING LOSSES

While commissioning the optical fiber is subjected to micro-bending as shown in Fig.



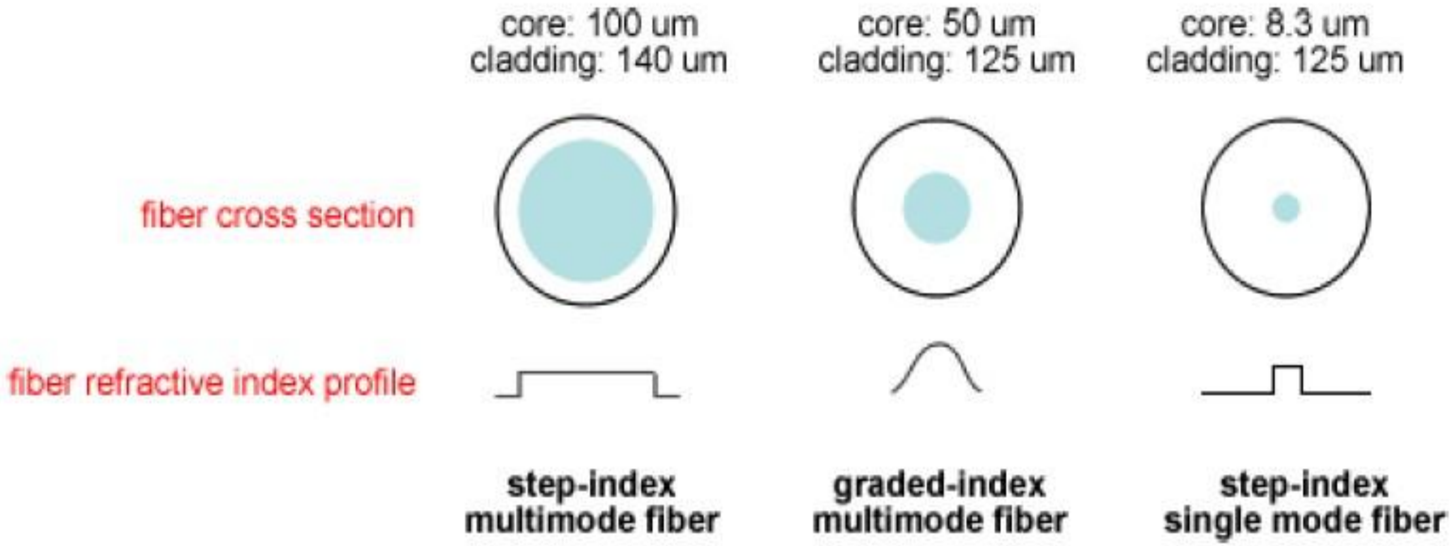
Power loss from higher-order modes

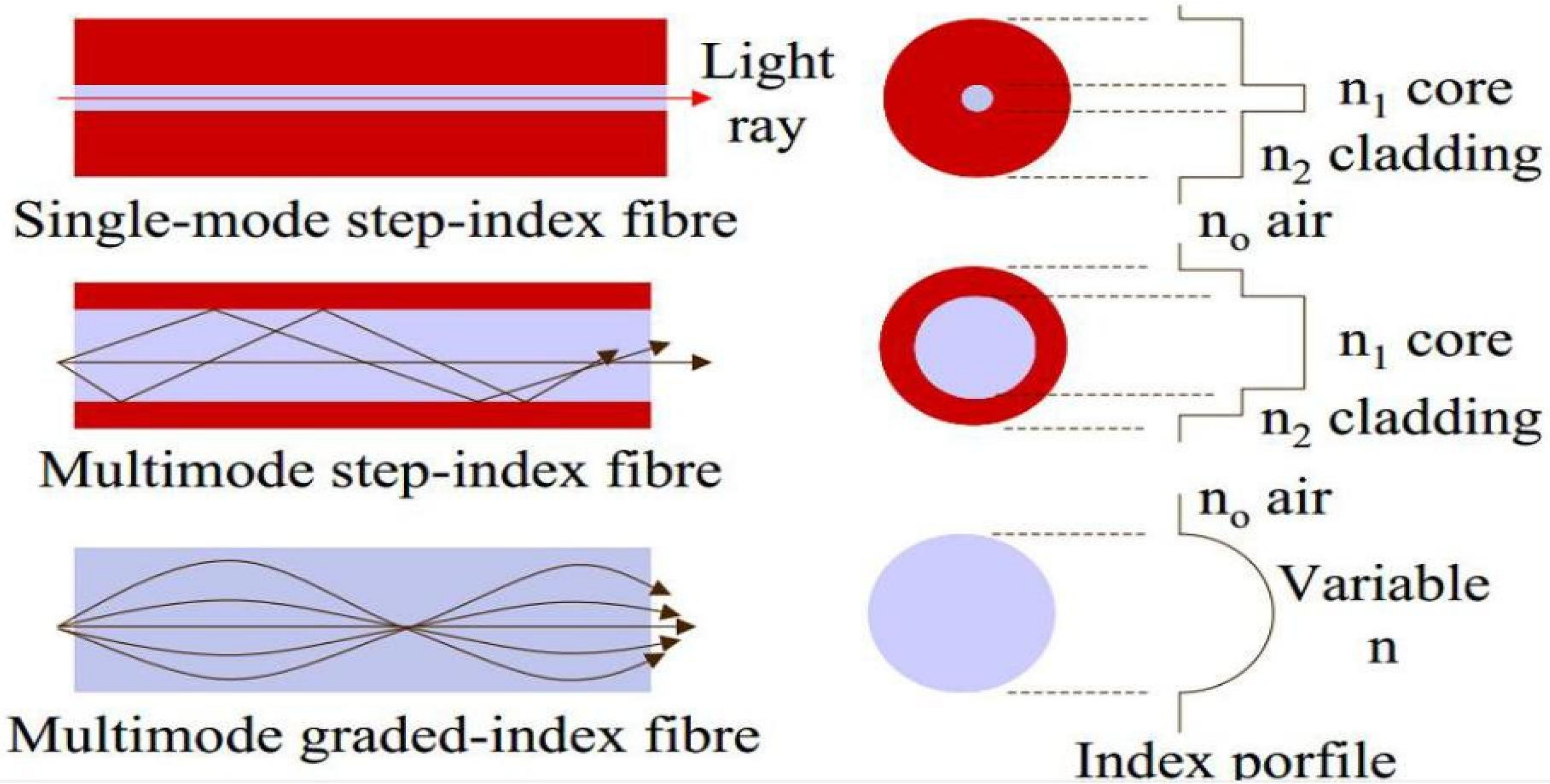


Power coupling to higher-order modes

Optical Fiber Index Profile

Index profile is the refractive index distribution across the core and the cladding of a fiber. Sor optical fiber has a step index profile, in which the core has one uniformly distributed index a the cladding has a lower uniformly distributed index. Other optical fiber has a graded ind profile, in which refractive index varies gradually as a function of radial distance from the fib center. Graded-index profiles include power-law index profiles and parabolic index profiles. T following figure shows some common types of index profiles for single mode and multimo fibers.

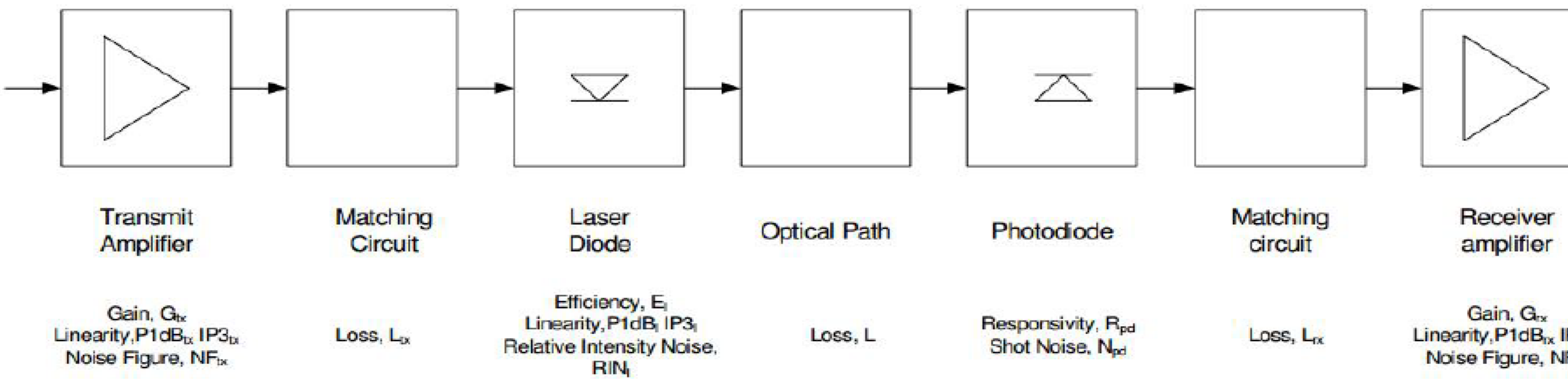




Multimode Step Index Fiber

Fibre Optic Link Budget

The FOL budget provides the design engineer with quantitative performance informat
about the FOL.It is determined by computing the FOL power budget and overall link gai



Fibre Optic Power Budget

The FOL power budget (PB) is simply the difference between the maximum and minim
signals that the FOL can transport.

UNIT-III

OPTICAL DETECTORS

CLOs	Course Learning Outcome
CLO1	Understand phase noise, switching and modulation characteristics.
CLO2	Define Optical detectors: pin detector, avalanche photodiode.
CLO3	Understand Principles of operation, concepts of responsively, sensitivity and quantum efficiency, noise in detection.

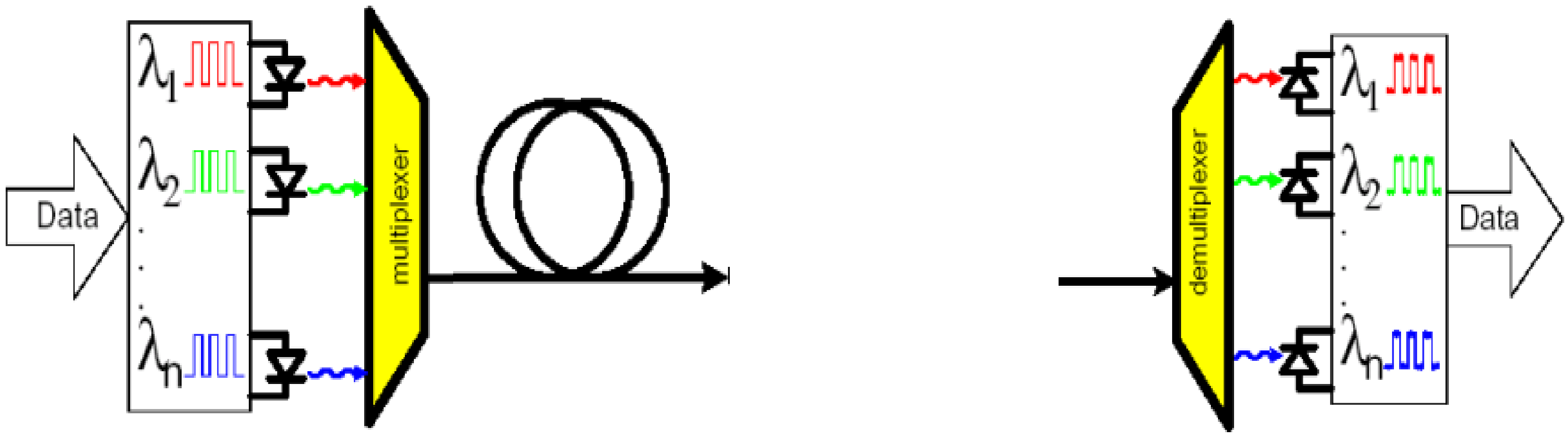
Optical Detectors

In the following we will discuss the operating principles and the application of photo detectors in optical communication systems.

Introduction

Optical receivers and transmitters are of essential importance for the overall performance of optical communication systems. The function of an optical detector is to convert the optical signal in an electrical signal, which can then be further processed. Schematic sketch of an optical transmitter and receiver of an optical communication system.

Ref: Agilent Technologies,



- Schematic sketch of an optical transmitter and receiver of an optical communication system.
- Ref: Agilent Technologies, Back to Basics in Optical Communications Technology.

Introduction

The improvement on optical receiver and transmitter side is of major interest to network operators, because less repeater are needed and the spacing between repeaters can be increased.

The following performance criteria of optical detectors are of major important for applications in optical communication systems:

- Sensitivity has to be matched to the emission spectra of the optical transmitter
- Linearity (Linear relationship between the intensity and the electrical signal)
- High quantum efficiency / high spectral sensitivity
- Fast response time
- Stability of performance (temperature sensitivity)
- Reliability and Robustness
- Low Noise
- Lost Cost

Classification of optical detectors

The first and by far the most important group are **diodes**. The group of diodes can again be separated in different subgroups: pn diodes, pin diodes, Schottky diodes and Avalanche photodiodes
The second and third group are photoconductors and photo transistors.

Classification of optical detectors

- Diodes
- Pn-diodes
- Pin diodes
- Avalanche photodiodes
- Schottky diodes
- Photo conductors
- Photo transistors

Optical detection principle

- The conversion of an optical into an electrical signal requires the absorption of the incident light.
- The absorption leads to an excitation of an electron from the valence to the conduction band. What is left in the valence band is a vacancy,which we call a “hole”.
- Therefore, we speak about the photo-generation of electron-hole pairs, because the absorption always leads to the generation of a hole and an electron.
- (That does not necessary mean that both carriers contribute to the electronic transport, but the generation creates both species.)

Sensitivity and Efficiency of optical Detectors

Like we determined the efficiency of the light emitting devices we can determine the (quantum) efficiency of detectors.

The Quantum efficiency

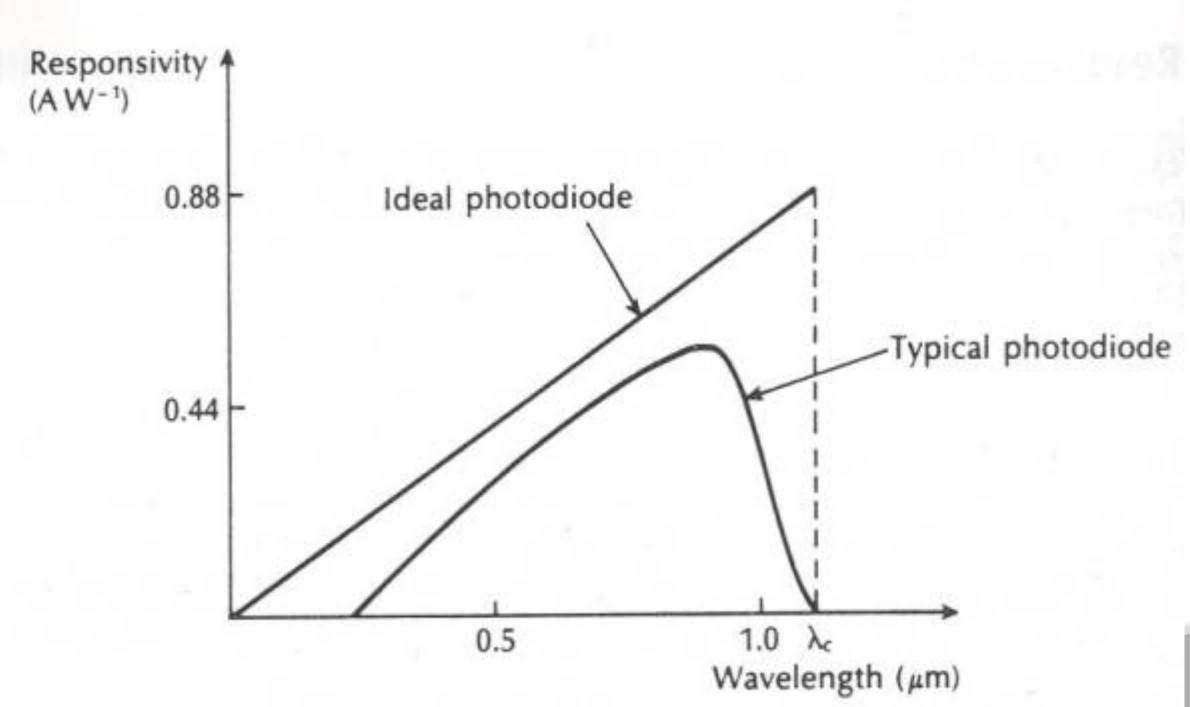
The quantum efficiency is defined by:

$$\eta = \frac{number\ of\ electrons\ collected}{number\ of\ incident\ photons} \qquad \text{Quantum efficiency}$$

One of the major factors which influences the quantum efficiency is the absorption coefficient. The quantum efficiency is generally below unity, but can be for its maximum very close to unity

Spectral responsivity

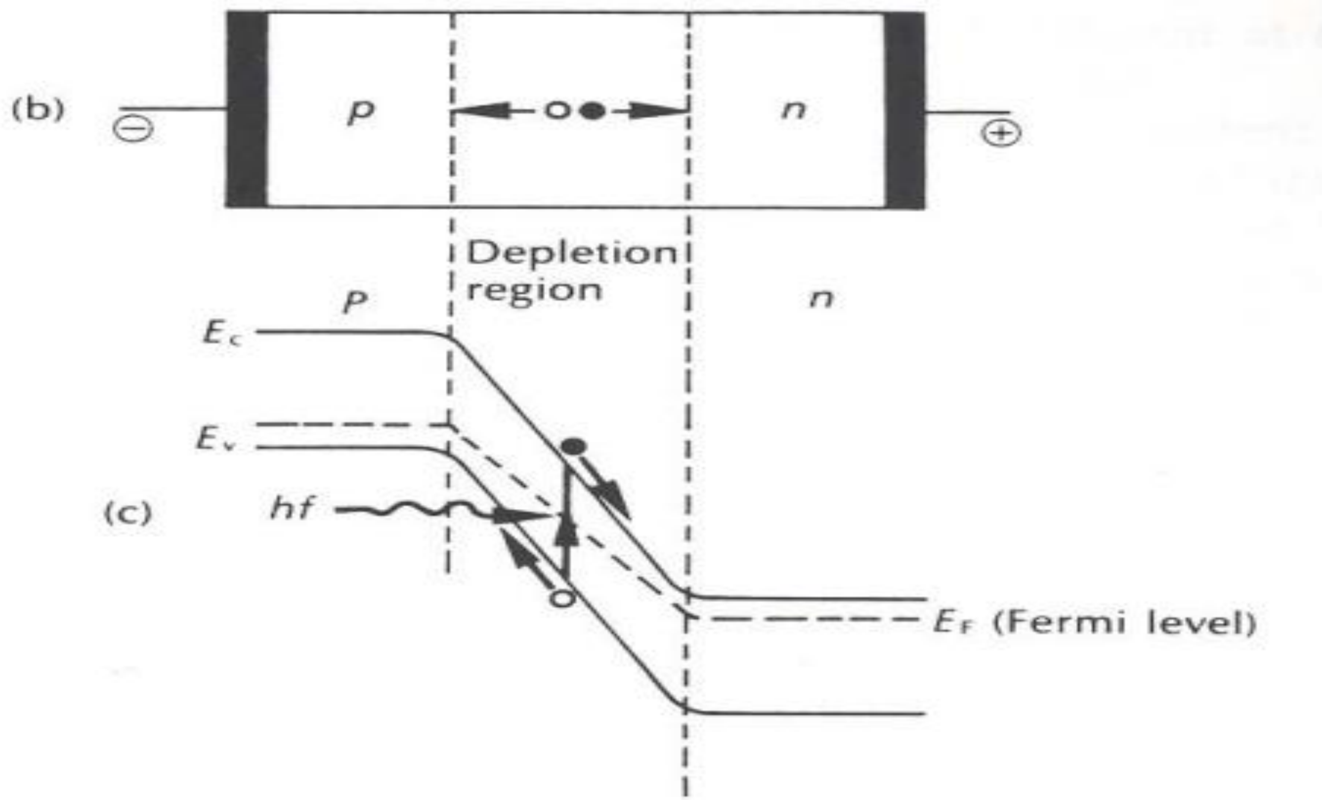
- It can be seen that the responsivity is increasing with the wavelength of the incident photons.
- The difference between the ideal and the real diode can be explained by thermal losses for lower wavelengths and a reduced absorption coefficient for higher wavelengths.



Operating principle of Photodiodes

- The electron-hole pairs generated in a photodiode are separated by the electric field.
- The electric field distribution in the diode is determined by an internal and an external electric field component.
- The internal field is created by the build-in potential which leads to the formation of a depletion region.
- The build-in potential is formed due to the difference in the Fermi level in the p- and the n-region.
- The external electrical field is due to the external applied bias voltage.

Operating principle of Photodiodes



Operation principle of a photodiode. A reverse bias voltage is applied to the pn photodiode.

Operating principle of Photodiodes

- The photocurrent of an optical detector should be linear.
- This means that a linear relationship exists between the intensity of the incident light and the photocurrent.
- In order to extract almost all photo-generated carriers out of the device a reverse bias voltage can be applied to the diode.
- The reverse bias voltage leads to an increase of the electric field in the depletion region and the depletion region gets wider.

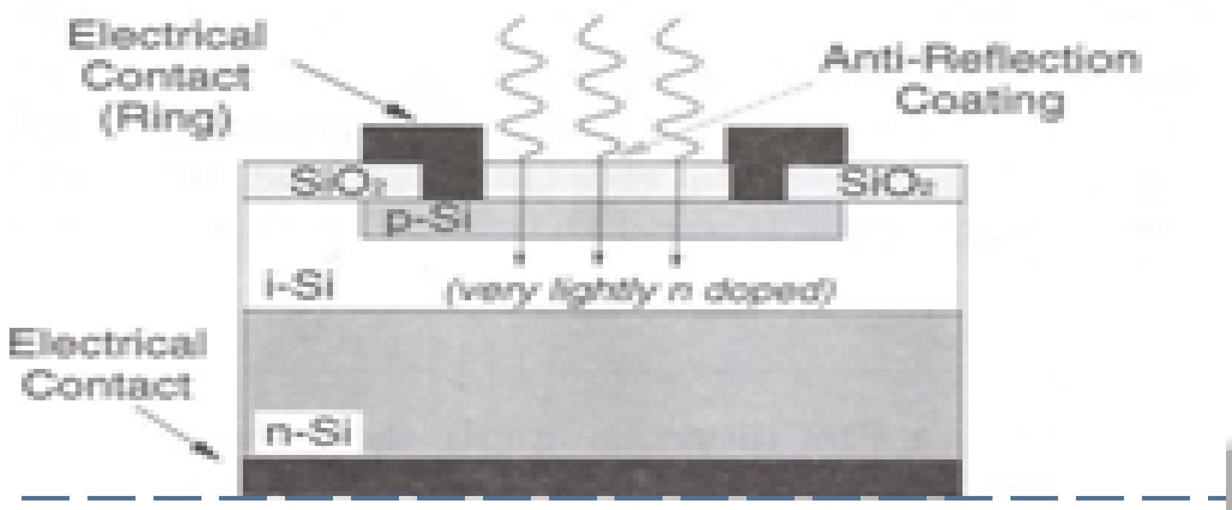
Diode Device Structure

Various diode device structures exist. In the following the realization and the characteristic device behavior of pn-diodes, pin diodes, Avalanche photodiodes and Schottky diodes will be discussed. Furthermore, the different devices will be compared in terms of their advantages and disadvantages.

Pin-diodes

- As a consequence the depletion region is extended across the intrinsic or lightly doped layer and therefore more photo-generated carriers contribute to the photocurrent.
- The pin-diode can be realized as an homo-junction or a hetero-junction.
- If the structure is realized in silicon the device will be usually a homo- junction.
- Under such conditions all three layers (p-,i- and n-region) have the same optical bandgap.
- Depending on the application the thickness and the individual layers can be adjusted.

- The thicker the i-layer the further the sensitivity can be extend in the near infrared part of the optical spectrum.
- If there is only an interest in detecting blue or green light the i-layer can be kept short.
- The pin diode shown on this slide is a crystalline silicon pin diode. Therefore,



Pin-diodes

- Typical materials used for the three optical communication bands:

Short wave band (800nm – 900nm)

- Silicon pin diodes are the best choice for the short wave band. The diodes are very inexpensive, reliable and easy to handle.

Medium Wave band (1250 nm - 1350nm)

- In this band germanium and different compound semiconductors are of interest.
- Germanium has a lower band gap energy of 0.67eV, so that it can theoretically be used up to 1600nm (but it is typically not used).
- Indium gallium arsenide phosphide (InGaAsP) is an alternative.

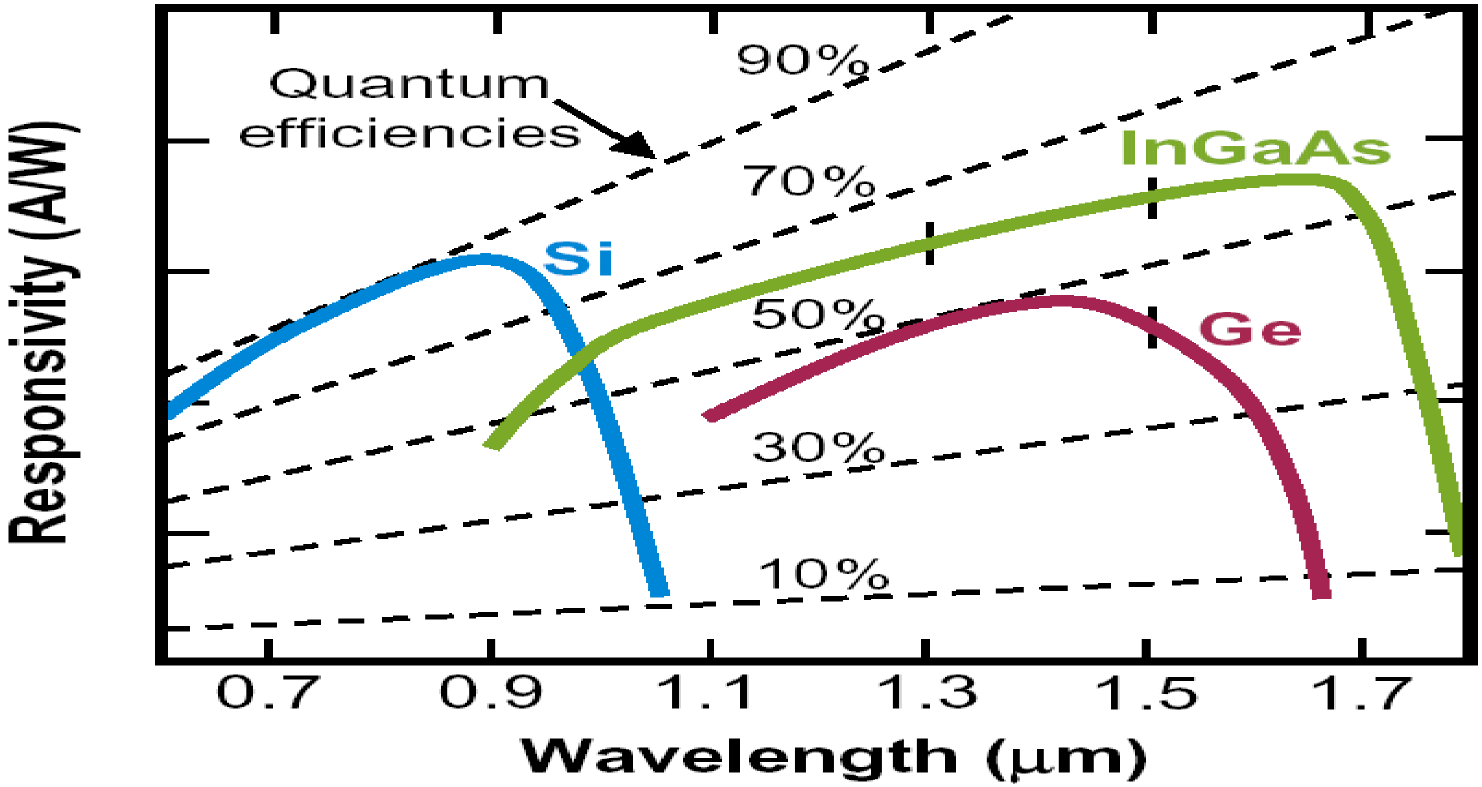
Pin-diodes

- The material has an optical band gap of0.89eV (depending on the composition of the material) and is perfectly suitable for the medium wavelength band.
- Of course all diodes based on compound semiconductors are significantly more expensive in manufacturing.

Pin-diodes

Long Wave Band (1500nm - 1600 nm)

- For the long wave band the optical band gap of the material has to be already very small.
- This causes problems. At room temperature already a large number of carriers is excited due to thermal excitation.
- This problem can be solved to a certain extend by using hetero structures.
- A material used here is usually InGaAs (indium gallium arsenide).
- InGaAs has a bandgap energy of 0.77 eV.

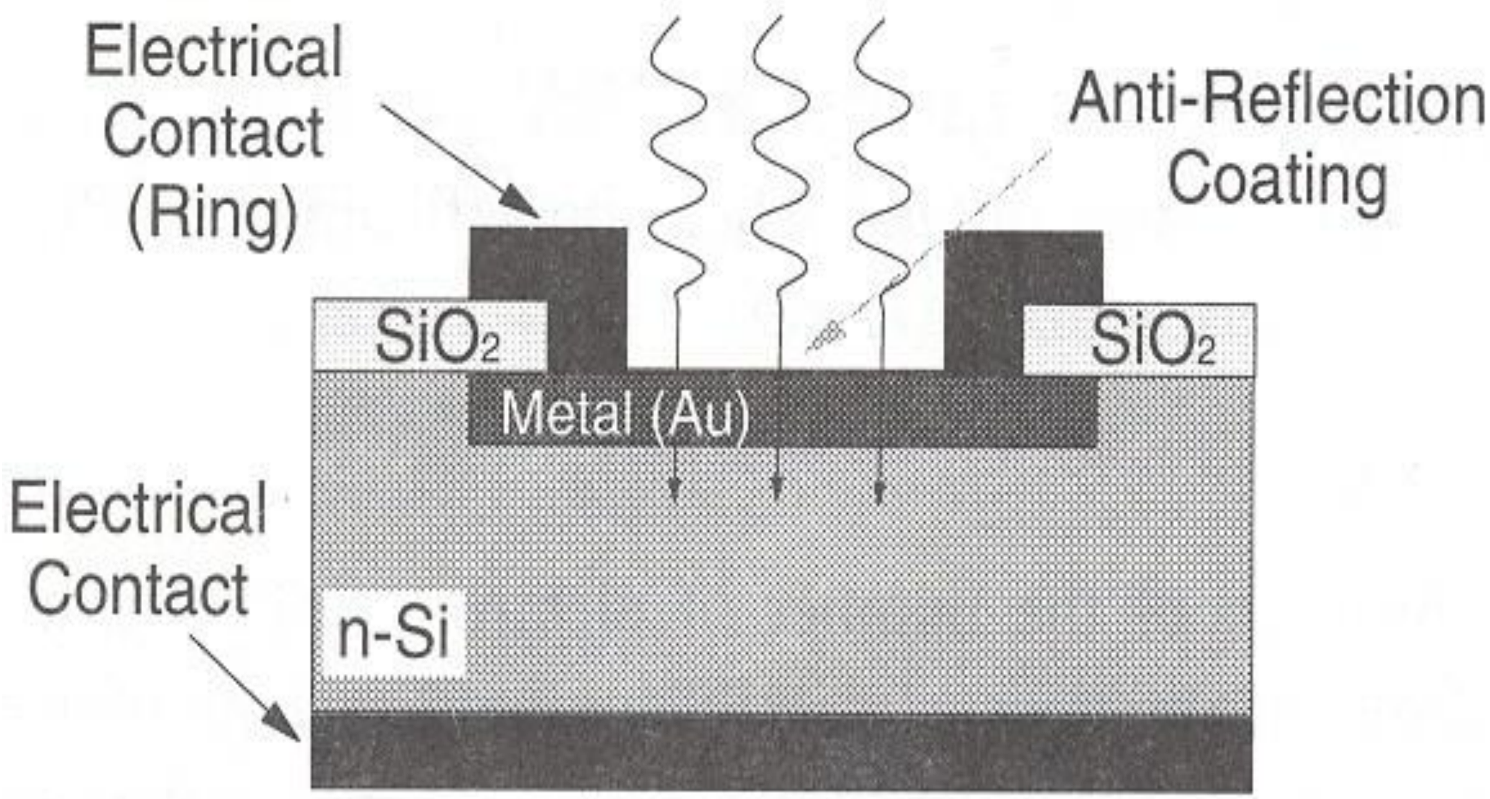


Sensitivity of pin diodes based on various material systems.

Schottky Barrier diodes

- During this lecture we concentrate on the device aspect of optical detectors.
- The sensitivity of the detector has to be matched with the optical spectrum of the incident light.
- Hence, different materials have to be applied for different optical communication bands (short, medium or long wave bdn).
- However, sometimes it is not possible to realized pn-diodes for a given wavelength band and/or the performance of the diodes is not sufficient to be applied as a detector in an optical communication system.

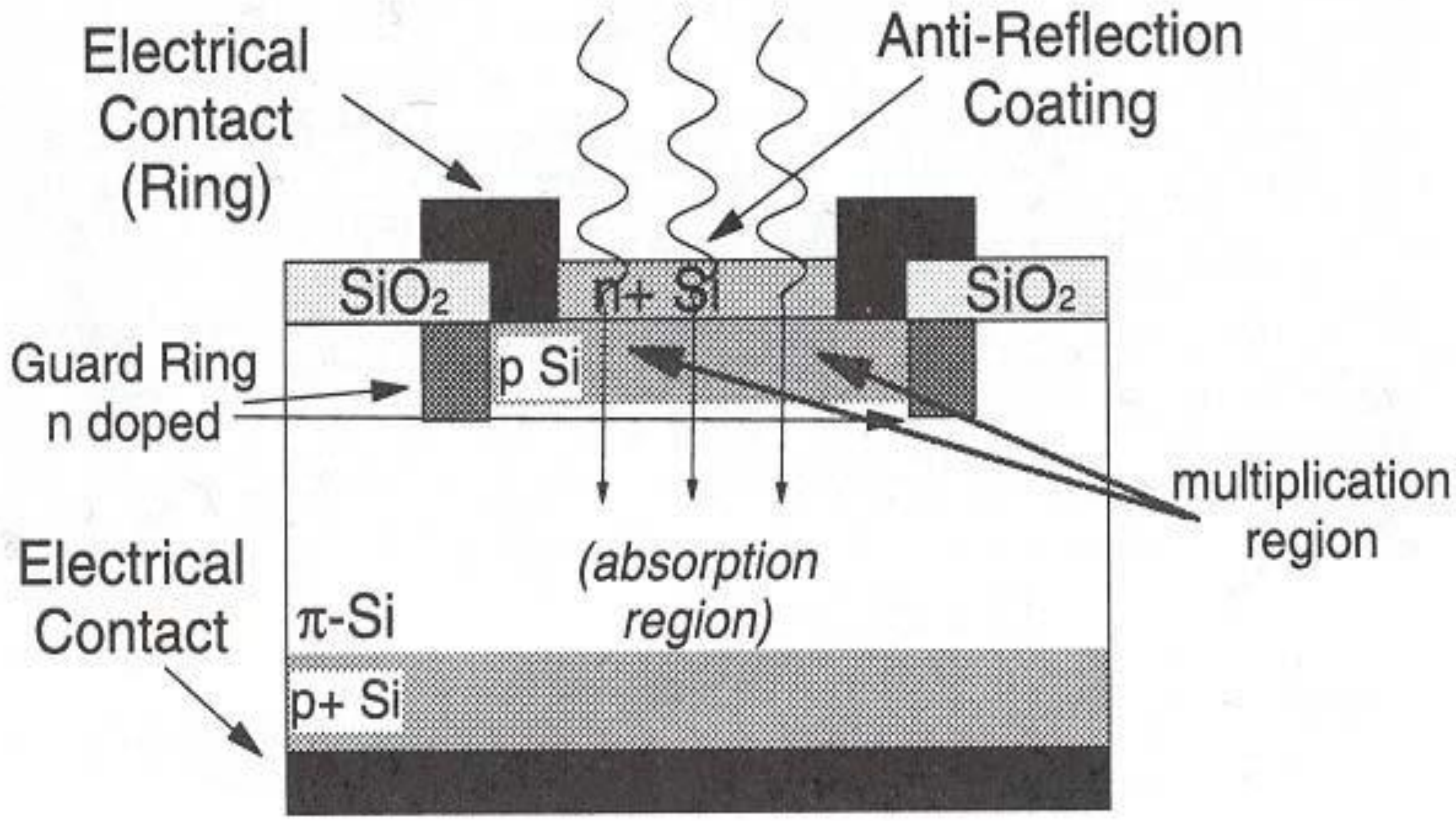
Silicon Schottky Barrier diode.



Avalanche Photodiode (APD)

- One way of increasing the sensitivity of the receiver is amplification.
- APDs amplify the signal during the detection process. The operating principle of a APD is based on the avalanche effect, where a highly accelerated electron excites another electron due to “impact ionization”.
- However, in the first step a photon has to be absorbed and a electron-hole pair has to be generated.
- The device consists of two regions. In region 1 of the device the electron hole pairs are generated and separated.
- In region 2 of the device the carriers are accelerated and „impact ionized“.

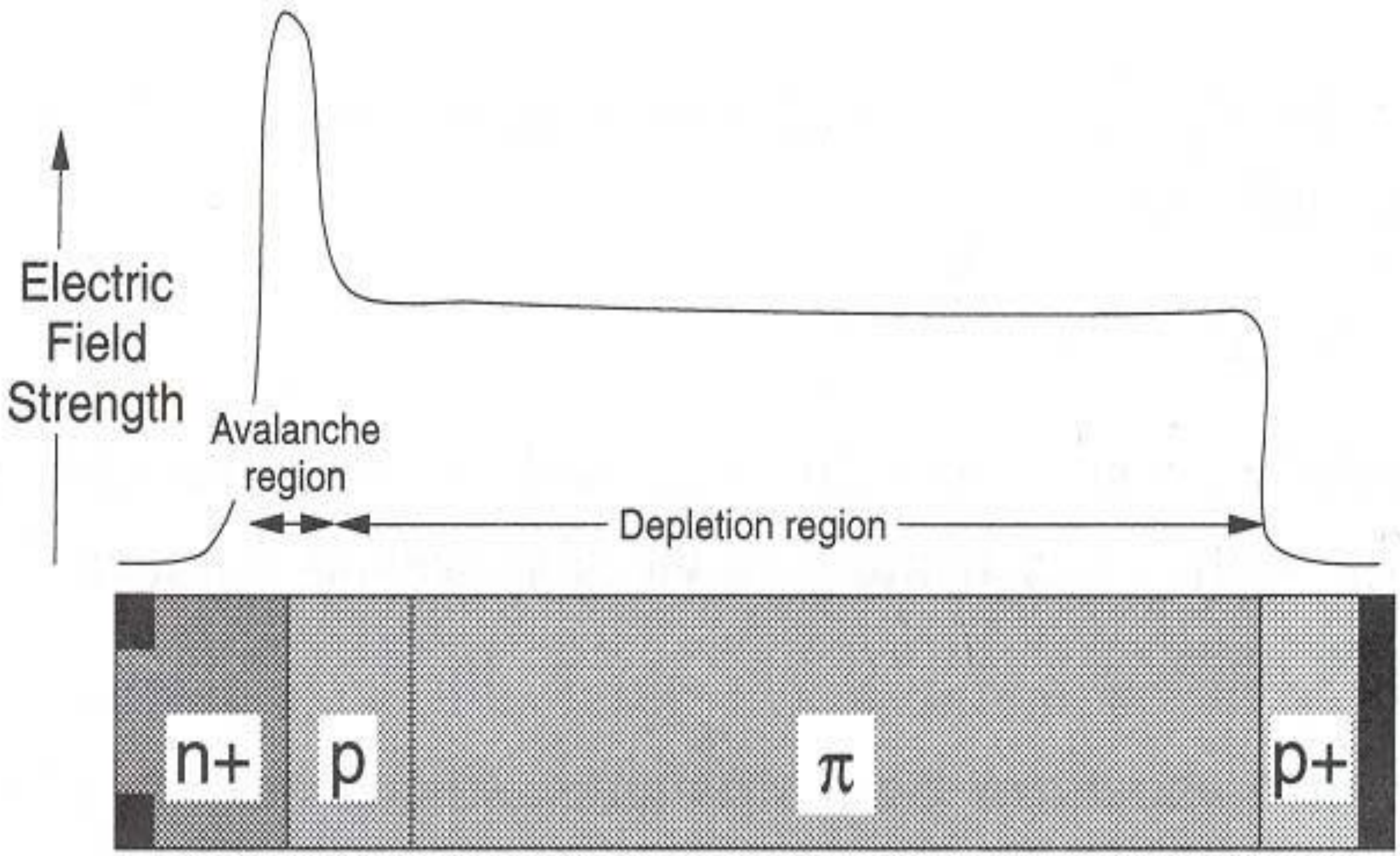
Avalanche Photodiode (APD).



Avalanche Photodiode (APD

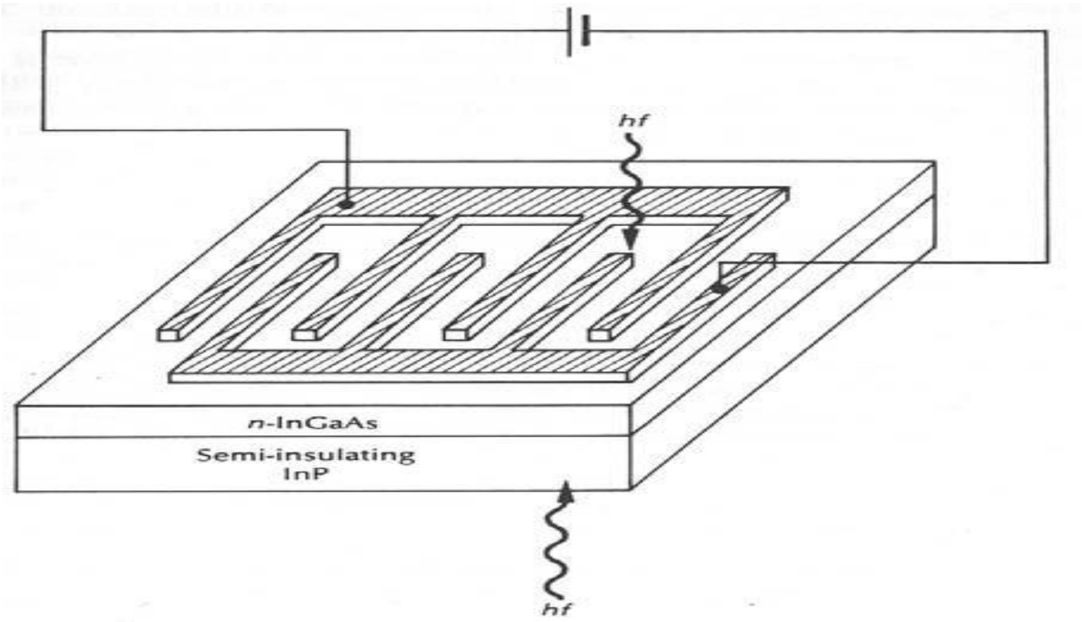
- The device operation works as following: Arriving photons pass through thin n^+p- junction.
- The carriers are absorbed in a □- region. The absorption leads to the generation of electron-hole pairs in this region.
- The electric field in the □-region is high enough to separate the carriers.
- The electric field across the □-region is not high enough for the charge carriers to gain enough energy for multiplication to take place.

Silicon Avalanche Photodiode (APD).



Photoconductive detectors

- Pn and pin diodes have a clear disadvantage which is the transient response.
- The transient response is limited by the capacitance of the diode or the transient time of the charges.
- The photoconductive detector is formed by two adjacent finger contact which are placed on a semiconducting material.



Photoconductive detectors

Due to the fact that the capacitance of the device is extremely low it should be possible to build very fast optical detectors. The transient time of detectors is limited by the drift velocity (velocity of the carriers caused by the applied electric field) of the carriers.

For the manufacturing it is important to form good ohmic contacts with the semiconductor. Otherwise Schottky barriers are formed which will limit the current flow.

The photoconductive detector is an unipolar device, which means that the current flow is either completely dominated by electrons or by holes. Diodes are bipolar devices, because electrons and hole contribute to the current transport.

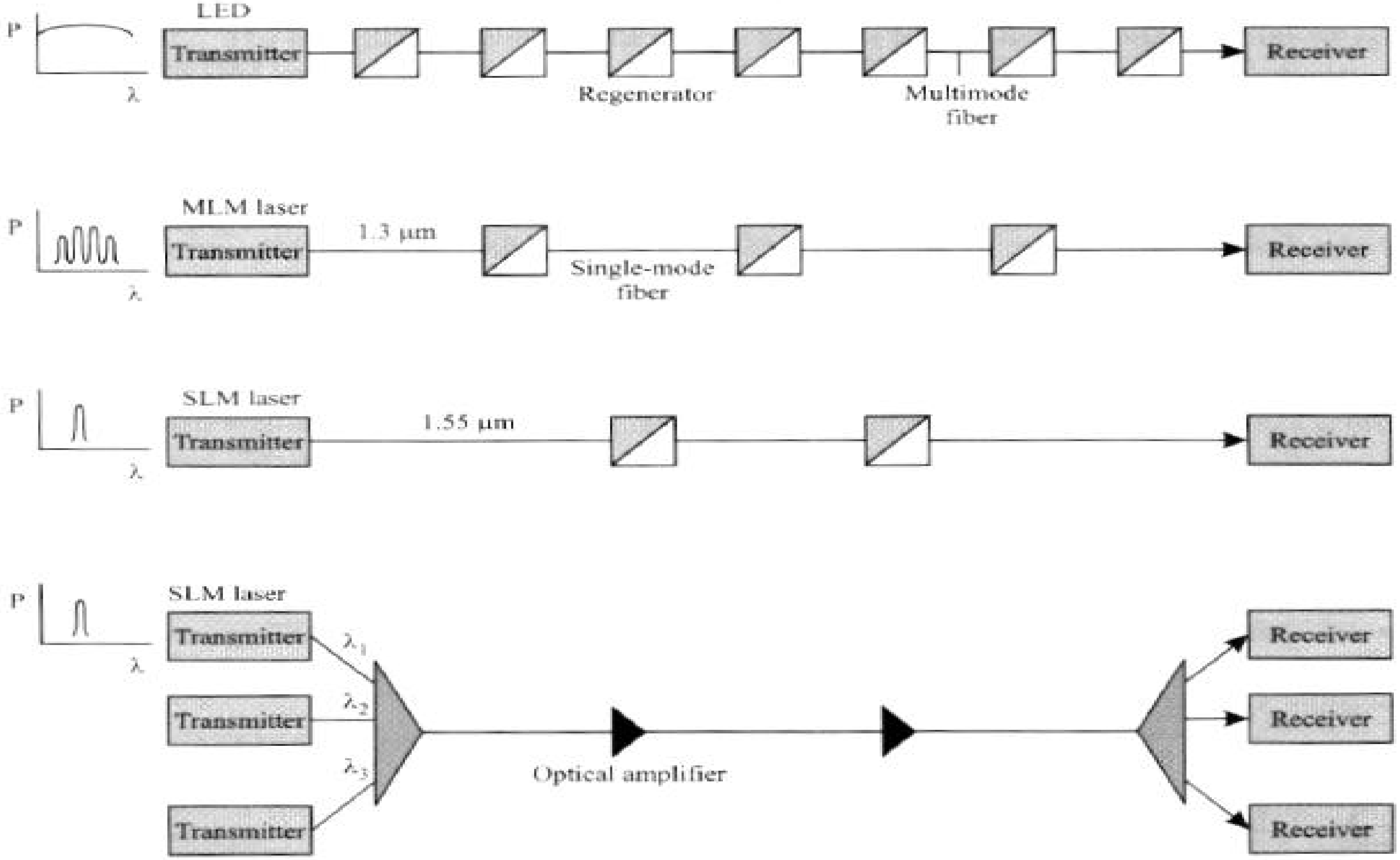
WDM Concept

Capacity upgrade of existing fiber networks (without adding fibers)

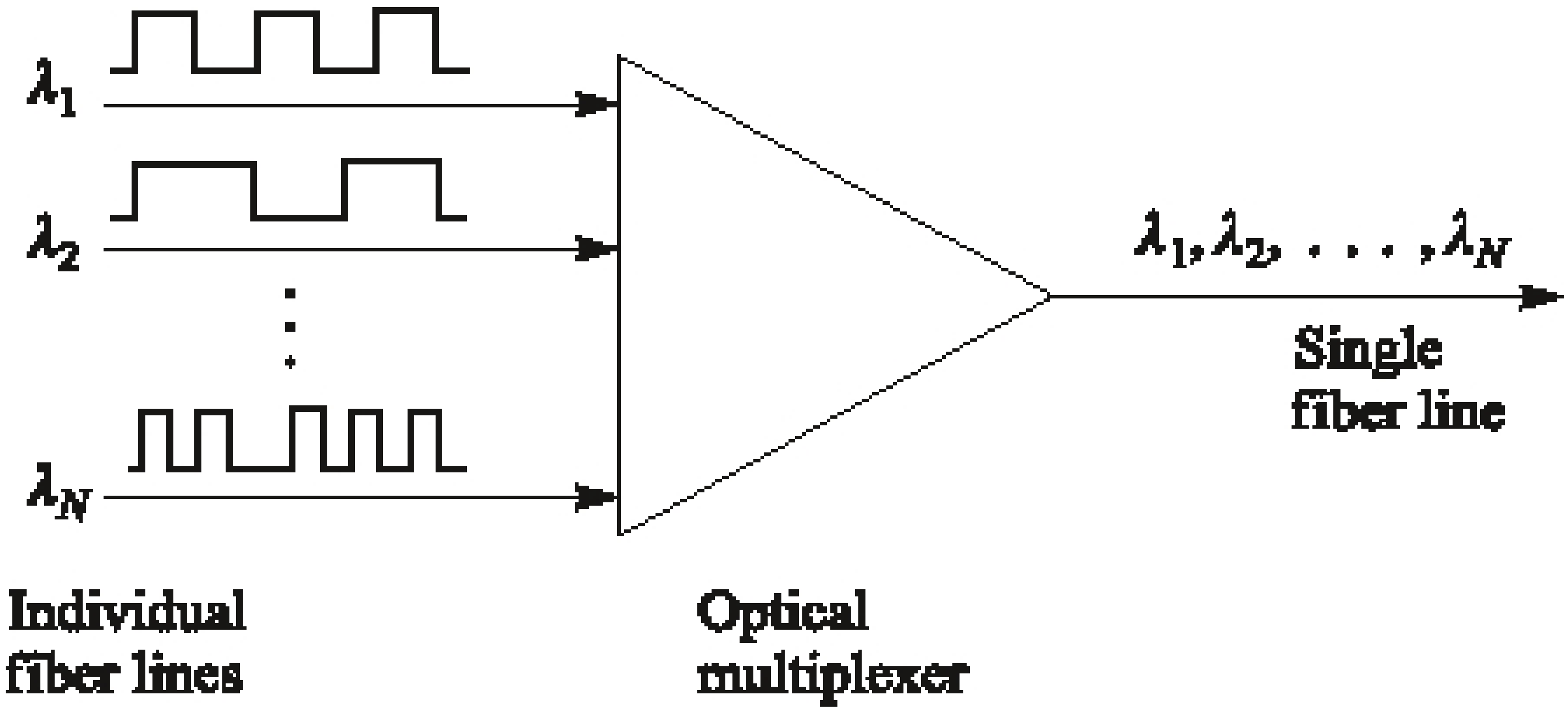
Transparency: Each optical channel can carry any transmission format (different asynchronous bit rates, analog or digital)

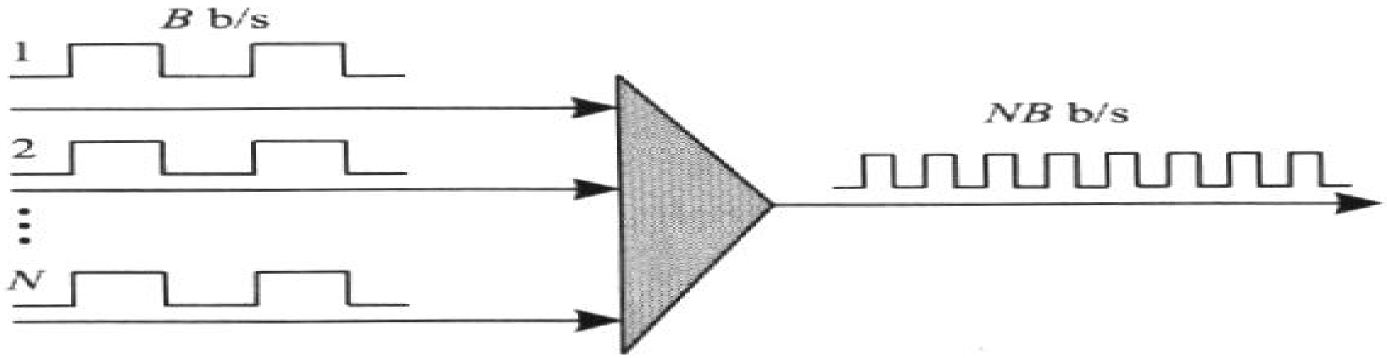
Scalability– Buy and install equipment for additional demand as needed

Wavelength routing and switching: Wavelength is used as another dimension to time and space

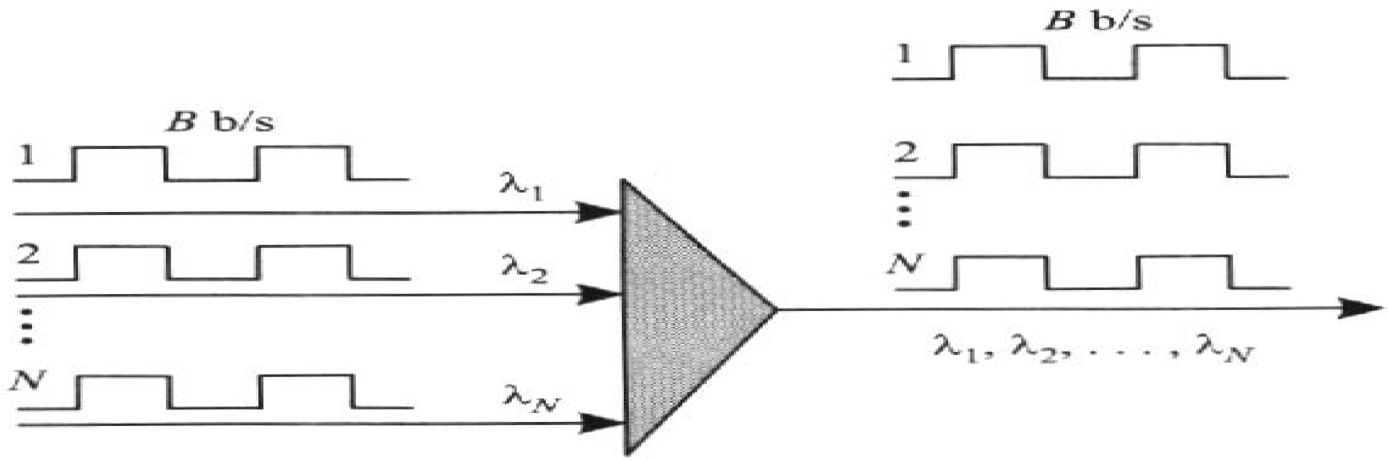

LED
P
λ
Transmitter
Regenerator
Multimode
fiber
Receiver
MLM laser
1.3 μm
Transmitter
Single-mode
fiber
Receiver
SLM laser
1.55 μm
Transmitter
Receiver
SLM laser
Transmitter
Transmitter
Transmitter
λ1
λ2
λ3
Optical amplifier
Receiver
Receiver
Receiver

Wavelength Division Multiplexing



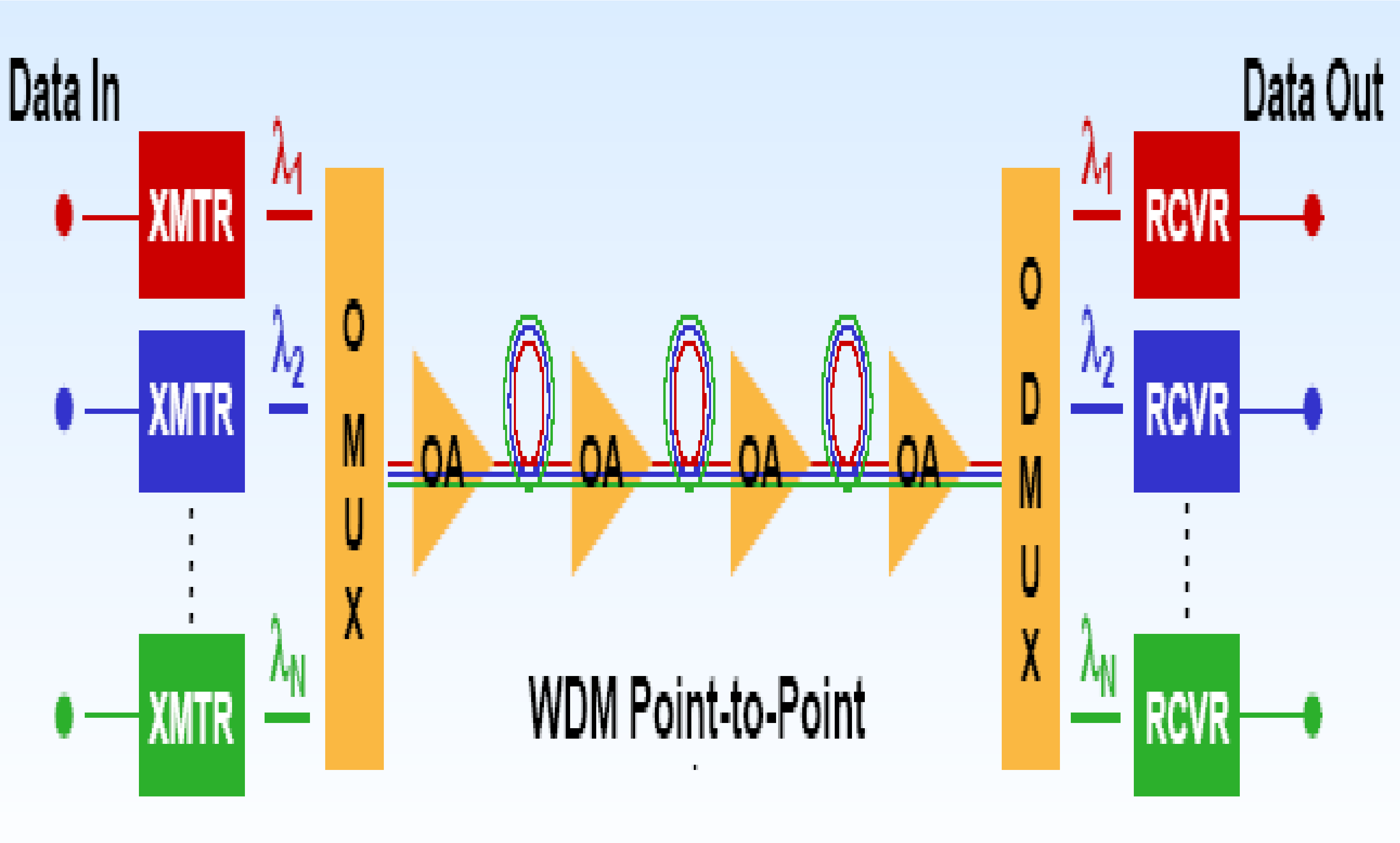


TDM or OTDM mux



WDM mux

Wavelength Division Multiplexing



WDM, CWDM and DWDM

- WDM technology uses multiple wavelengths to transmit information over a single fiber
- Coarse WDM (CWDM) has wider channel spacing (20 nm) – low cost
- Dense WDM (DWDM) has dense channel spacing (0.8 nm) which allows simultaneous transmission of 16+ wavelengths – high capacity

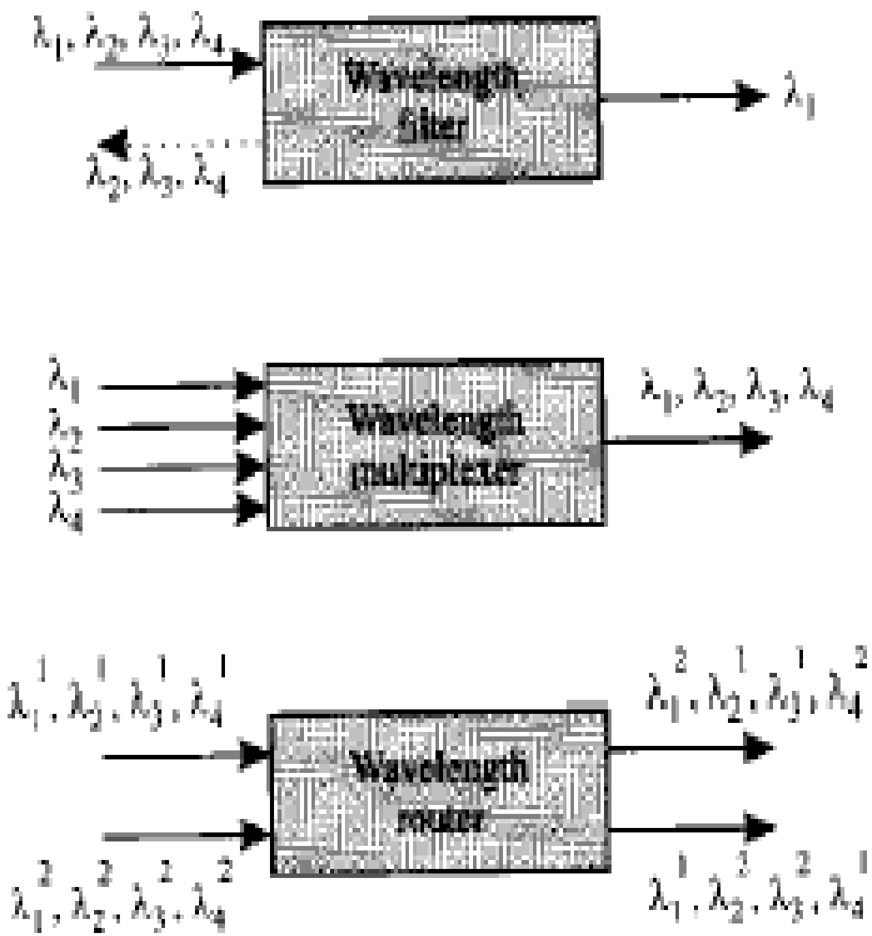
WDM and DWDM

- First WDM networks used just two wavelengths, 1310 nm and 1550 nm
- Today's DWDM systems utilize 16, 32,64,128 or more wavelengths in the 1550 nm window
- Each of these wavelength provide an independent channel (Ex: each may transmit 10 Gb/s digital or SCMA analog)
- The range of standardized channel grids includes 50, 100, 200 and 1000 GHz spacing
- Wavelength spacing practically depends on:
  laser linewidth
  optical filter bandwidth

Key Components for WDM

- Passive Optical Components
- Wavelength Selective Splitters
- Wavelength Selective Couplers
- Active Optical Components
- Tunable Optical Filter
- Tunable Source
- Optical amplifier
- Add-drop Multiplexer and De-multiplexer

Filter, Multiplexer and Router



- Applications
  - wavelength selection, channel add/drop
  - reduction of amplifier noise
  - basic building block of more advance components such as multiplexers and demultiplexers
- Requirements
  - low insertion loss
  - low polarization dependent loss
  - robust (temperature insensitive)
  - flat passbands, steep slopes
  - tunable (for dynamic operation)

UNIT-IV
OPTICAL AMPLIFIERS

CLOs	Course Learning Outcome
CLO1	Explain Multichannel Transmission technique-Multichannel Frequency Modulation Subcarrier multiplexing. WDM Concepts and Components.
CLO2	Understand semiconductor amplifier, erbium-doped fiber amplifier, Raman amplifier, Brillion amplifier.
CLO3	Understand principles of operation, amplifier noise, signal to noise ratio, gain, gain bandwidth, gain.

Why Optical Amplifiers?

Increase transmission distance

by increasing optical power coupled to transmission fiber(power booster)

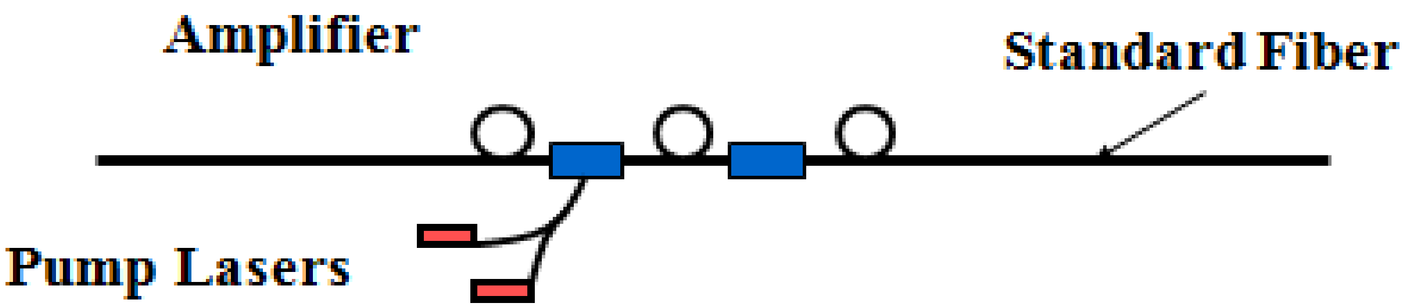
by compensating optical fiber losses(in-line amplifier, remote pump amplifier)

by improving receiver sensitivity (optical preamplifier)

- Function : Amplification of optical signal without conversion to electrical signal
- Ingredients : Pump energy, amplification medium

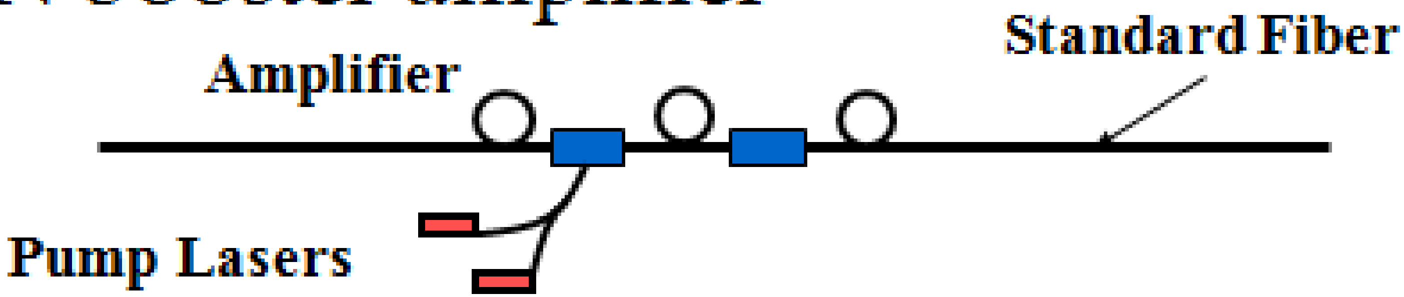
The Need of Optical Amplification

- **Erbium-Doped Fiber Amplifiers (EDFAs)** – application in long haul. Today's amplifier of choice.
- **Erbium-Doped Waveguide Amplifiers (EDWAs)** – application in metro and access networks
- **Raman Amplifiers** – application in DWDM
- **Semiconductor Optical Amplifiers (SOA)** – not fiber based type, application in metro and access networks



General Application of Optical Amplification

- **In-line amplifier:** Able to amplify an attenuated signal so that it can travel an additional length of fiber, is called an optical line amplifier.
- **Preamplifier:** is placed directly before the detector and may be integrated with it.
- **Power (booster) amplifier:** it is placed right after the source, and thus may also be integrated with it.
- **LAN booster amplifier**

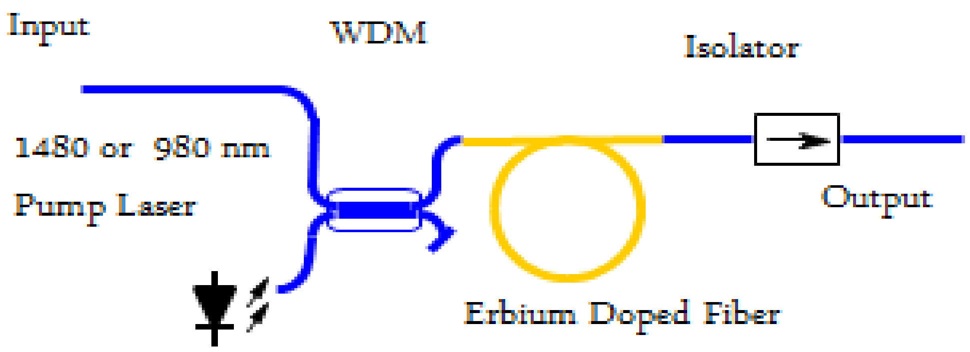


Improvement of System Gain

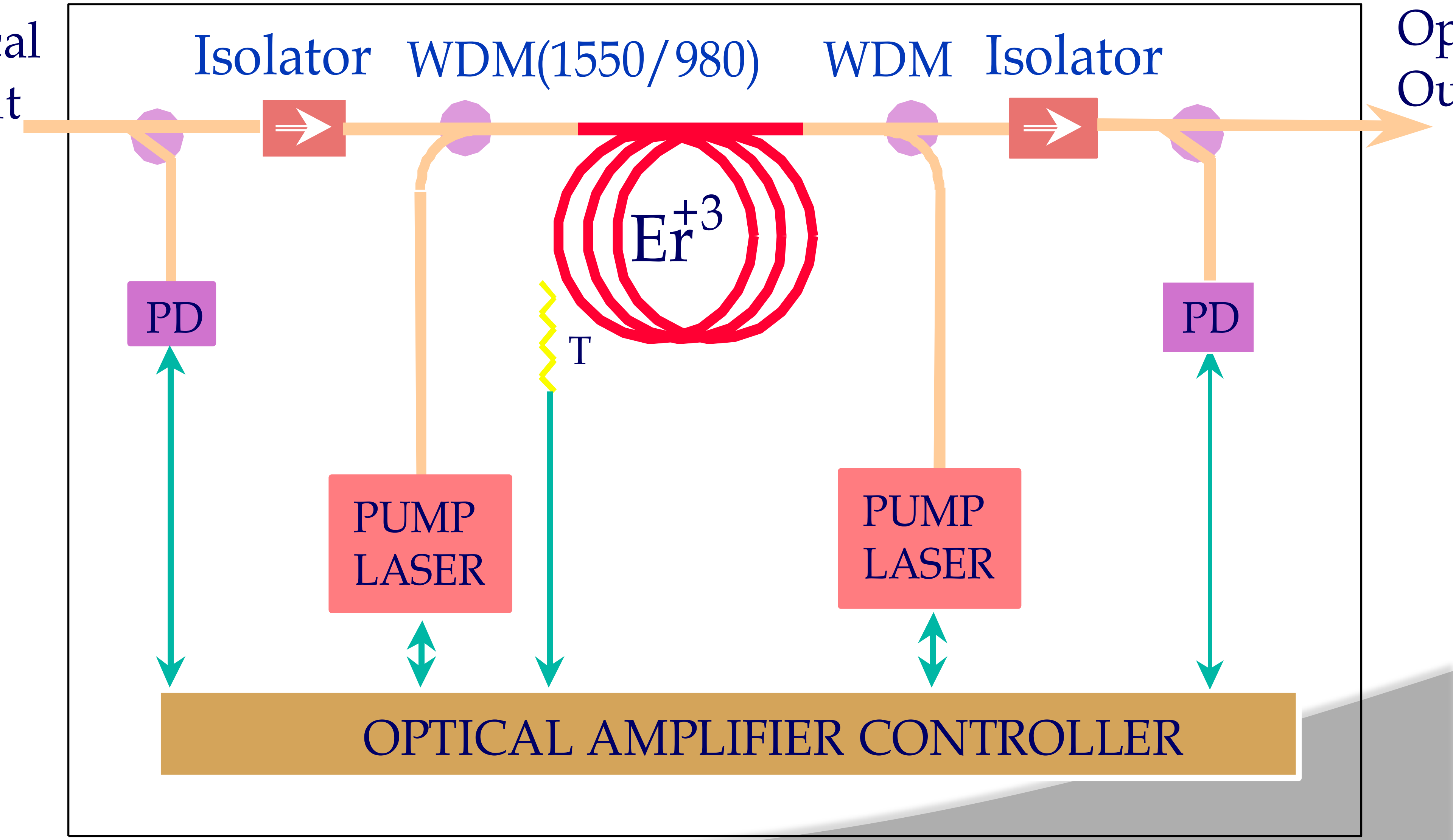
	Improvement in gain(dB)	Improvement in length(km)	Key technology
Booster amplifier Preamplifier	10 - 15 5 - 10 (APD)	40 - 60 20 - 40	High efficiency Low noise
In-line amplifier	10 - 15 (PIN) 15 - 30	40- 60 60 - 120	Low noise Supervisory
Remote pump amplifier	5 - 15	30 - 60	High pumping power

Basic EDF Amplifier Design

- Erbium-doped fiber amplifier (EDFA) most common
  - Commercially available since the early 1990's
  - Works best in the range 1530 to 1565 nm
  - Gain up to 30 dB



Erbium-doped Fibre Amplifier



When you actually look at an EDFA block diagram you see the input on the left the output on the right, photo diodes to measure input and output power levels, pump lasers which are used to excite this piece of erbium doped fiber to a higher energy state, and 1550 light is allowed to pass through.

The isolators are used to keep the 980 and 1480 pump wavelengths contained in the fiber but allow 1550nm light to pass through.

Issues of Amplifier Design

- Optimization
  - maximum efficiency
  - minimum noise figure
  - maximum gain
  - maximum gain flatness/gain peak wavelength
- Dynamic range, operation wavelength
- Gain equalization
- Control circuit
- Monitoring of amplifier performance

Typical Packaged EDFA

EDFAs In DWDM Systems

- Gain flatness requirements
- Gain competition
- Nonlinear effects in fibers

Erbium Doped Waveguide Amplifier (EDWA)

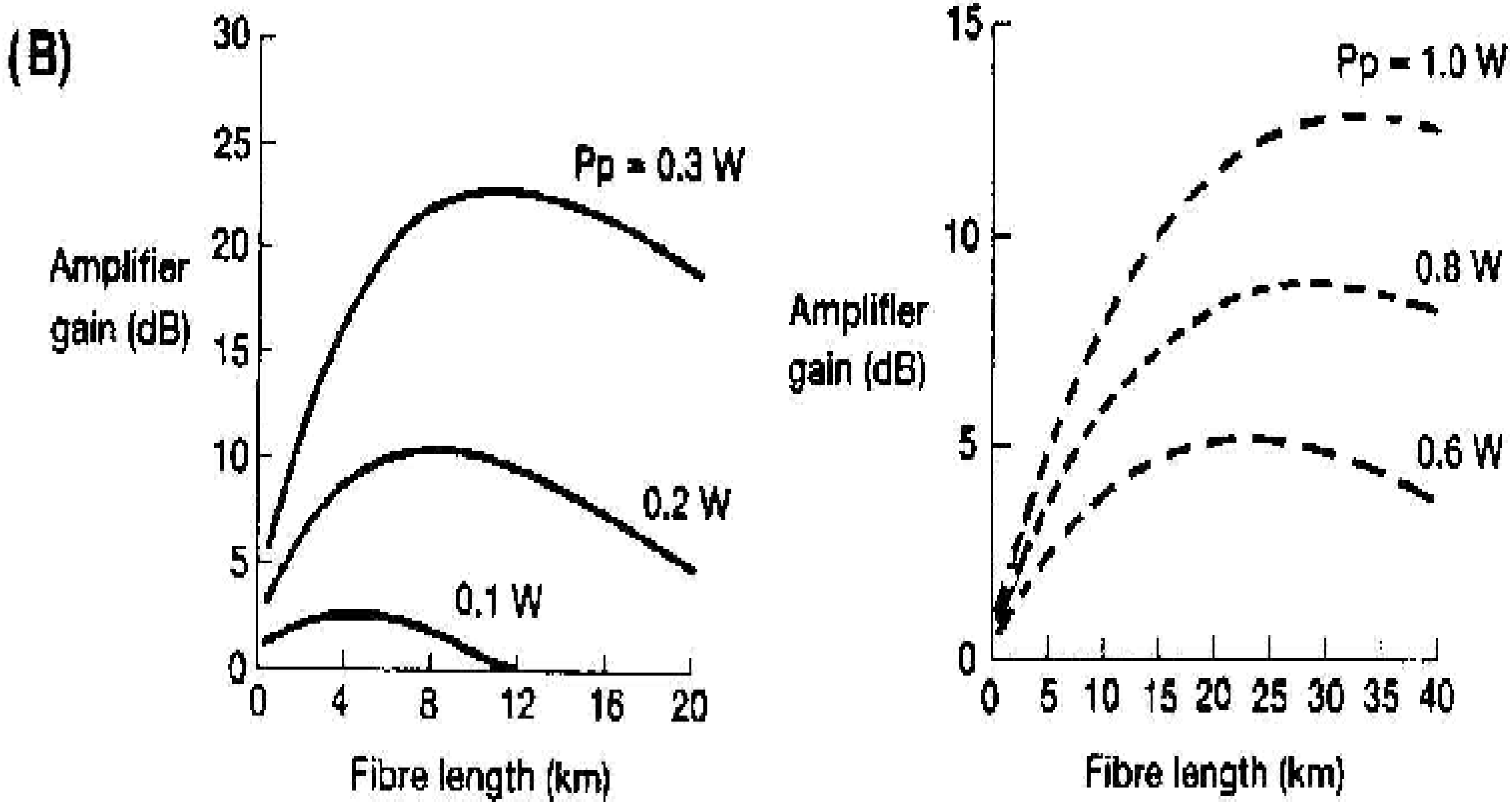
EDWA advantages

- EDWAs are inherently compact.
- One of the smallest gain block amplifiers to date, featuring 15-dB gain at 1,535 nm, fits in a 130x11x6-mm package.
- EDWAs also offer a better price/performance ratio than comparable EDFAs for access and metro network applications.

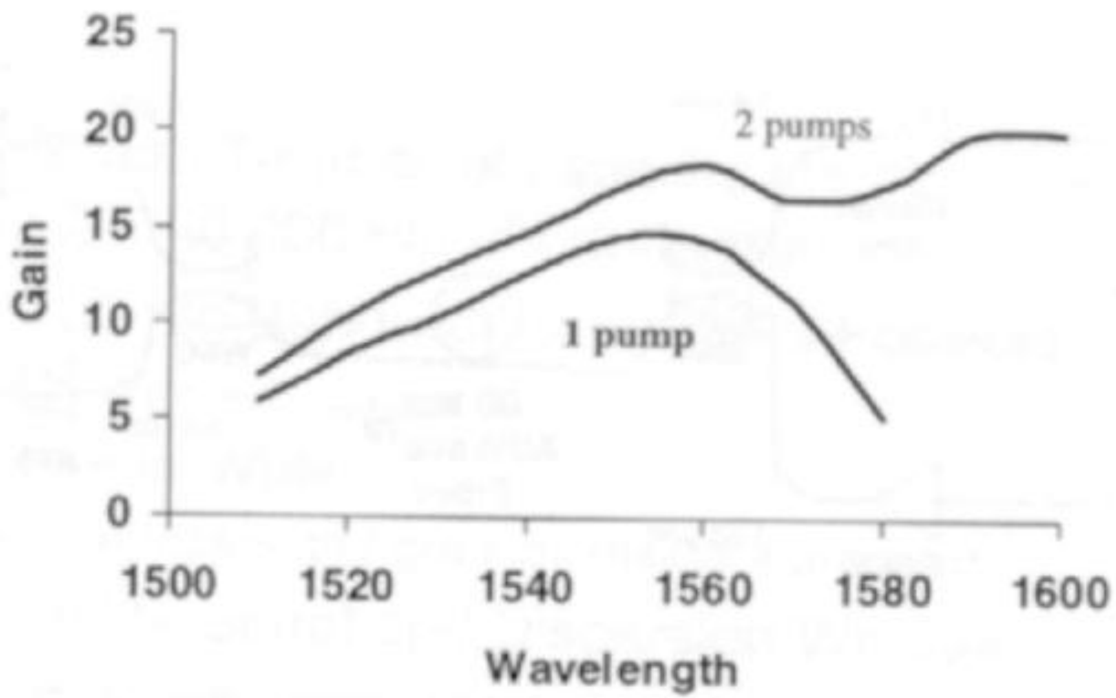
Raman Amplifier

- Raman Amplifier was demonstrated in the 1980s
- Unavailability of high-power diode laser pump source
- Why do you need it :
- amplify signals from 1270 to 1670 nm
- any optical fiber can serve as the amplifying medium
- Raman process itself provides high-power laser
- Disadvantage: Cross-talk

Raman Amplifier

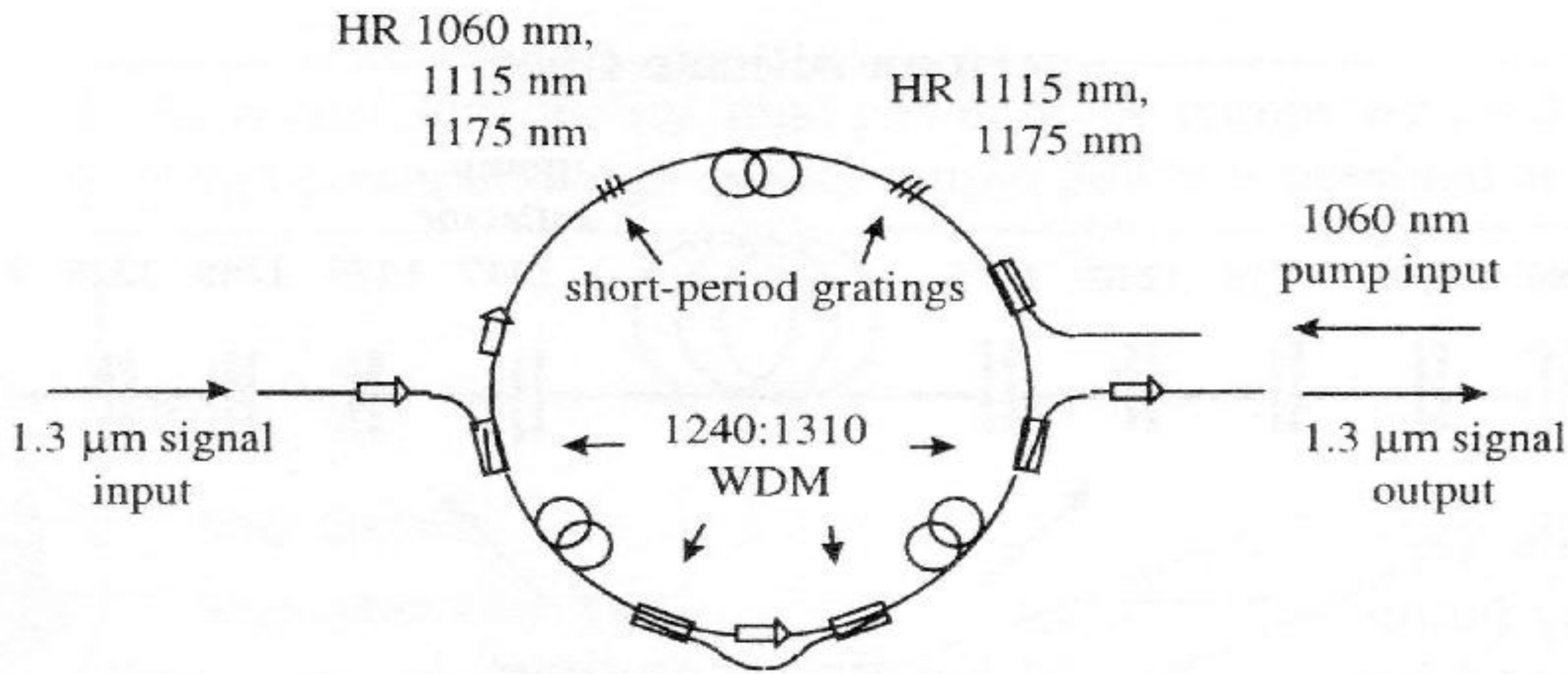


Raman Amplifier



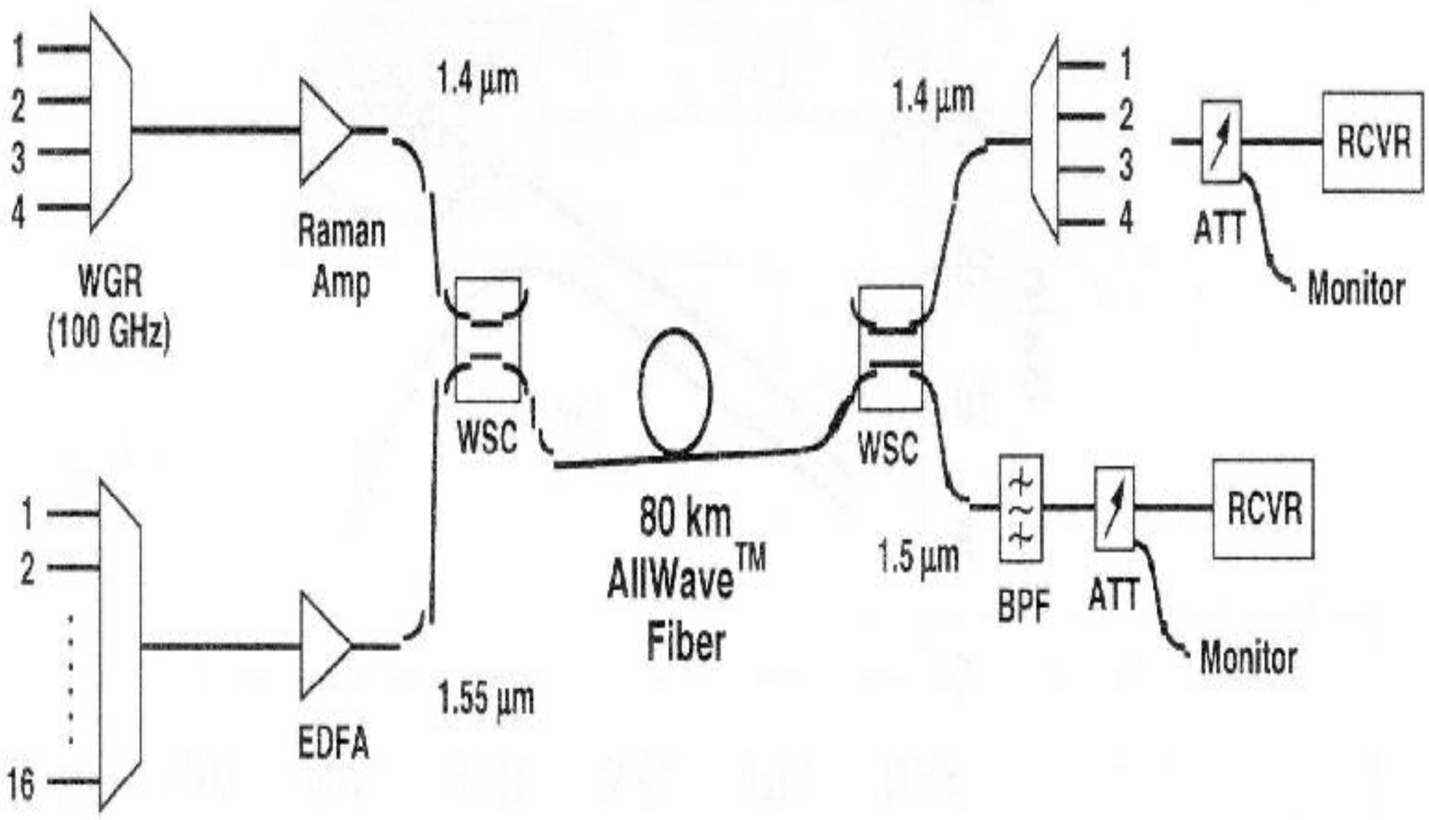
Wide bandwidth Raman amplifier can be realized using multiple pumps

Raman Amplifier



Multistage Amplifier
Counter propagating pump

EDFA+Raman



Combined Raman and EDFA transmission Experiment: DWDM (Lucent)

Raman Amplifier

- High-power laser sources are available by Raman process itself.
- 200 to 400 nm Bandwidth Amplifiers are possible
- Raman, EDFA combination
- Flat gain for WDM
- New fiber lasers and gratings make it practical
- System with Terabits of capacity are possible

General Types

- Doped fiber amplifiers
  - EDFA, TDFA, YDFA, PDFA
- Semiconductor Optical Amplifiers (SOA)
  - Tapered Amplifiers
    - BoosTA
  - Vertical Cavity SOA
- Raman Amplifier
- Chirped Pulse Amplification

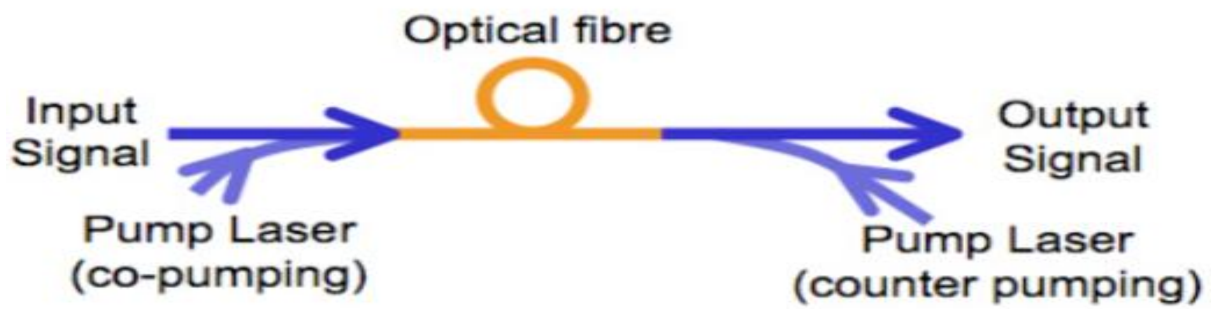
General Types

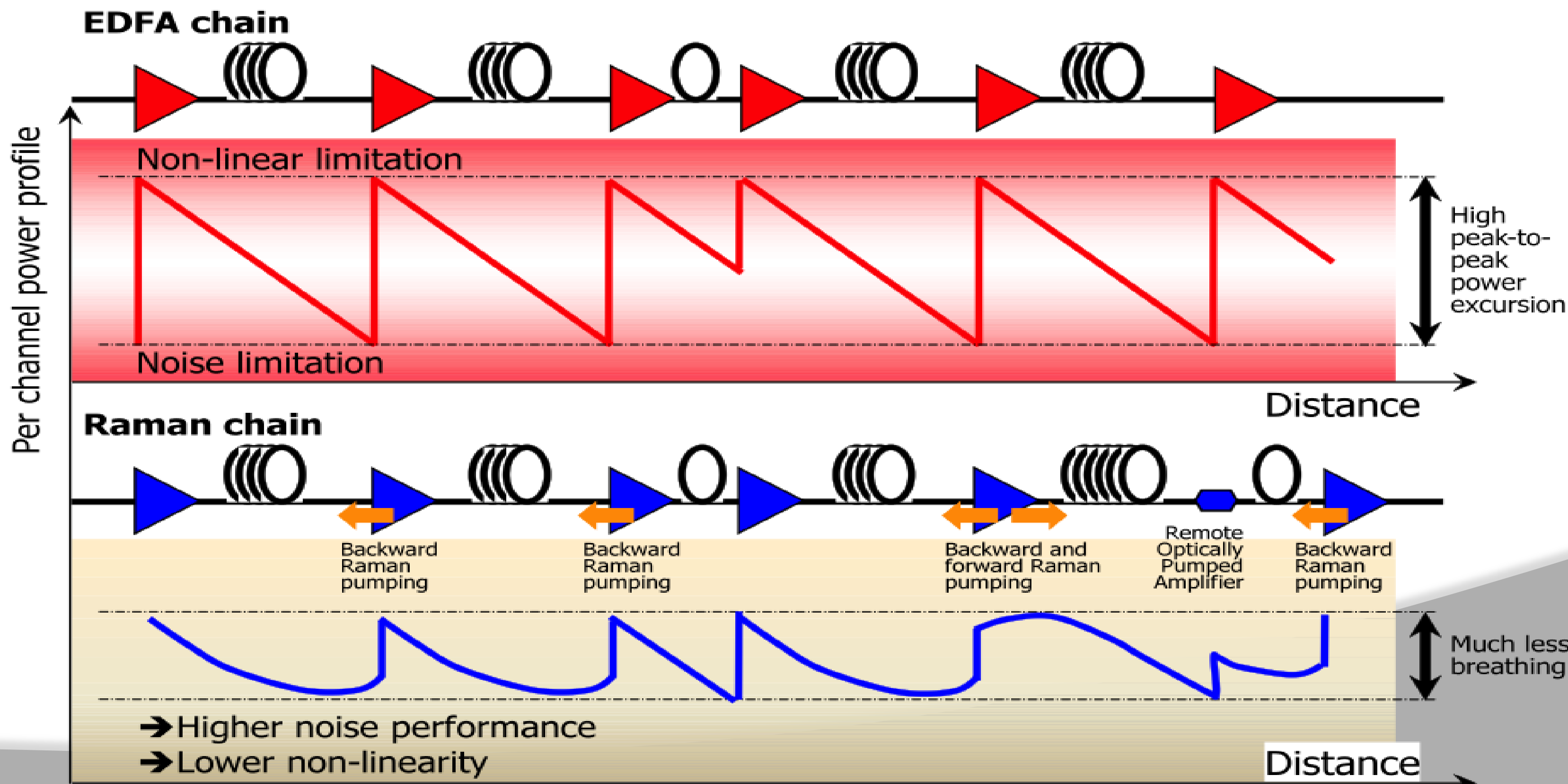
Property	EDFA	Raman	SOA
Gain (dB)	> 40	> 25	>30
Wavelength (nm)	1530-1560	1280-1650	1280-1650
Bandwidth (3dB)	30-60	Pump dependent	60
Max. Saturation (dBm)	22	0.75 × pump	18
Polarization Sensitivity	No	No	Yes
Noise Figure (dB)	5	5	8
Pump Power	25 dBm	>30 dBm	< 400 mA
Time Constant	10^{-2} s	10^{-15} s	2 x 10^{-9}
Size	Rack mounted	Bulk module	Compact
Switchable	No	No	Yes
Cost Factor	Medium	High	Low

Raman Amplifiers

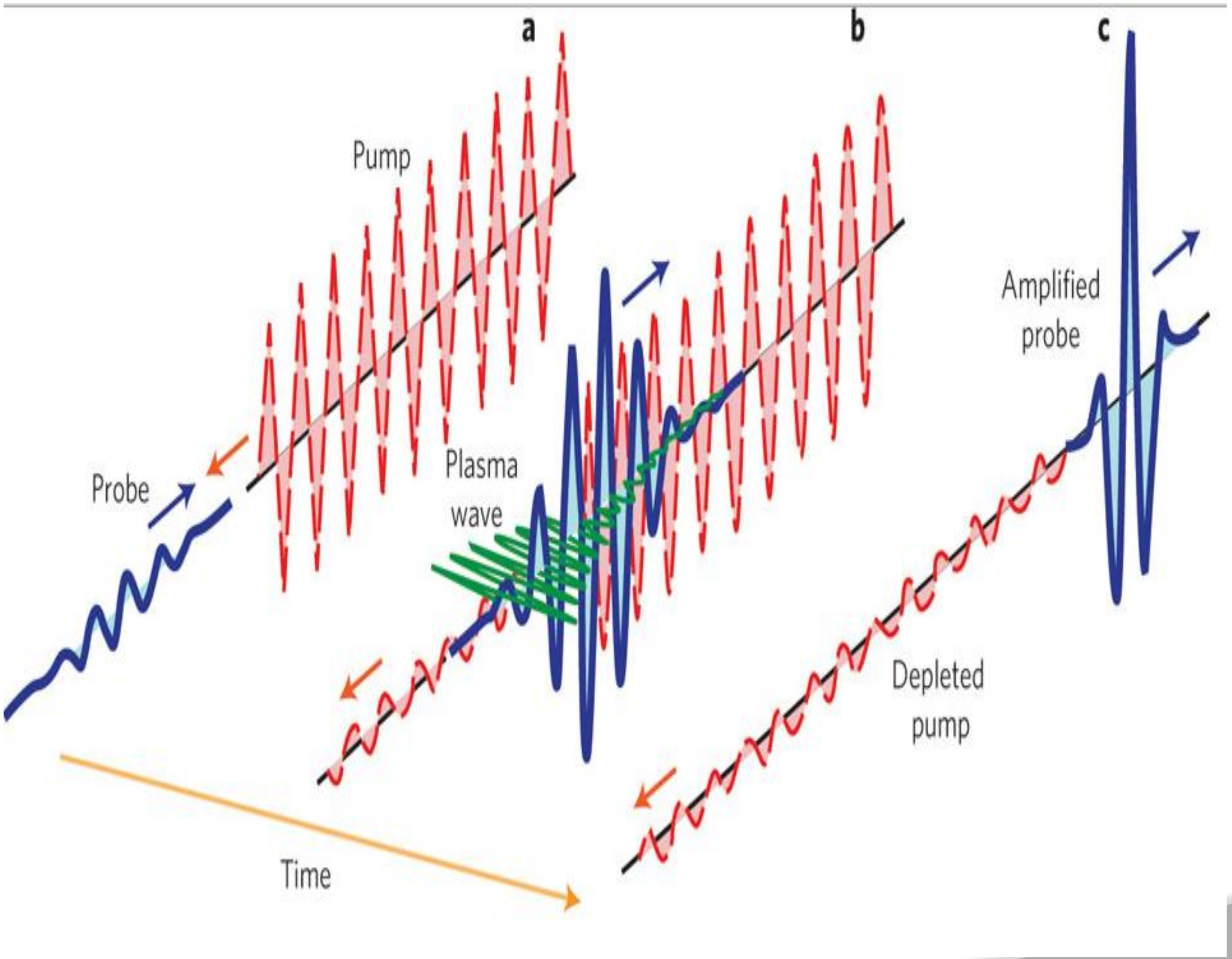
- Most of the time photons scatter elastically (Rayliegh Scattering)
- Some photons will scatter inelastically and lose energy
- Working Principles:
  - Nonlinear process: Stimulated Raman Scattering
  - Incident photon excites electron to virtual state
  - Electron de-excites down to the vibrational state
- Advantages
  - Any single mode fiber can be used
  - Lower cross talk between signals
  - Very broadband operation
- Disadvantages
  - High optical pump power
  - Low Gain ~ 10 dB
  - Long length of fiber required

Raman Amplifiers





Raman Amplifiers



UNIT-V
OPTICAL NETWORKS AND DISPERSION COMPENSATION

CLOs	Course Learning Outcome
CLO1	Explain noise dependencies, inter modulation effects, saturation induced crosstalk, wavelength range of operation.
CLO2	Design Optical networks-SONET/SDH, ATM, IP, wavelength routed networks, soliton communication system.
CLO3	Understand Fiber soliton, soliton based communication system design, high capacity and WDM soliton.

Introduction

- First Generation Optical Networks
  - Fiber Distributed Data Interface (FDDI)
  - Synchronous Optical Network/Synchronous Digital Hierarchy (SONET/SDH)
- Second Generation Optical Networks
  - Wavelength Division Multiplexing (WDM)
  - Optical Networking Components
  - Wavelength Routing Networks

Advantages of Optical Transmission

- Large bandwidth permits high data transmission, which also supports the aggregation of voice, video, and data
- Technological improvements are occurring rapidly, often permitting increased capacity over existing optical fiber
- Immunity to electromagnetic interference reduces bit error rate and eliminates the need for shielding within or outside a building
- Glass fiber has low attenuation, which permits extended cable transmission distance
- Light as a transmission medium provides the ability for the use of optical fiber in dangerous environments
- Optical fiber is difficult to tap, thus providing a higher degree of security than possible with copper wire
- Light weight and small diameter of fiber permit high capacity through existing conduits

Disadvantages of Optical Transmission

- Cable splicing:
  - Welding or fusing: you must clean each fiber end, then align and carefully fuse the ends using an electric arc.
    - Time consuming
    - Least amount of signal loss between joined elements.
  - Gluing
    - Bonding material that matches the refractive index of the core of the fiber.
    - Time consuming
    - Higher loss of signal power than fusing.
  - mechanical connectors
    - Considerably facilitate the joining of fibers,
    - More signal loss than do the other two methods
    - Can reduce the span of the fiber to a smaller distance.

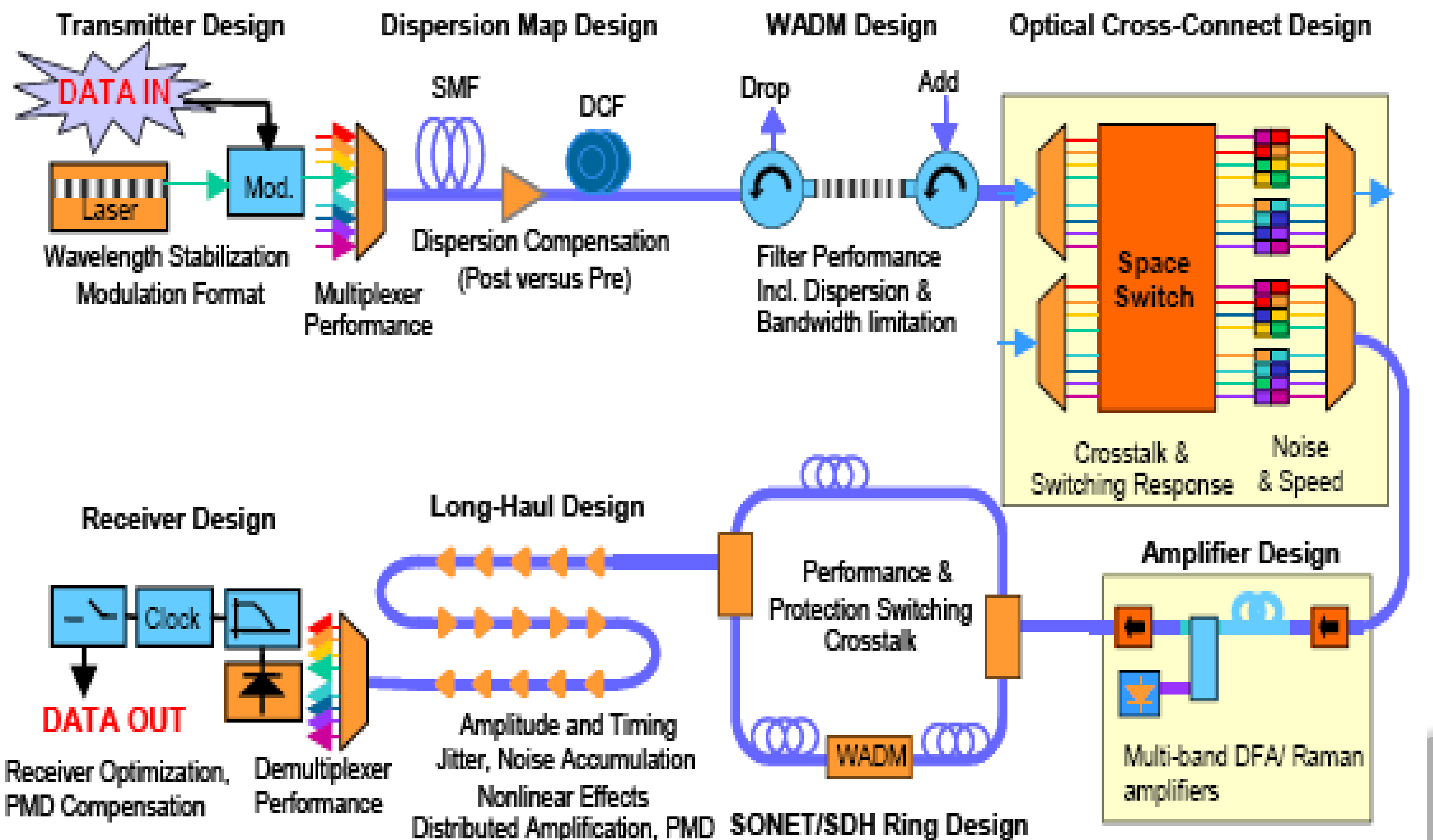
Fiber cost:

On a (bit/s)/km basis, the fiber cost will always be less than that for copper cable.

Some organizations may require only a fraction of the capacity of the optical fiber.

- It is often difficult to justify fiber to the desktop and similar applications where the cost of copper cable may be half or less than the cost of fiber.

The big picture



Fiber Distributed Data Interface (FDDI)

- Dates back to the early 1980s
- FDDI uses token-passing scheme
- Uses two fiber pairs, each operating at 100 Mbits/s.
- Data rates approaching 90% of its 100 MB/s operating rate
- FDDI was, and in some locations still is, commonly used at the Internet Service Provider (ISP) peering points that provide interconnections between ISPs.
- Relatively expensive

SONET/SDH(1)

Current transmission and multiplexing standard for high speed signals

- North America: Synchronous Optical Network (SONET)
- Europe, Japan and rest of the world: Synchronous Digital Hierarchy (SDH)

Prior to SONET and SDH: Plesiochronous Digital Hierarchy (PDH)

- 4KHz sampled at 8KHz quantized at 8 bits per sample → 64kb/s

Transmission rates for PDH

Level	North America [Mb/s]		Europe [Mb/s]		Japan [Mb/s]
0	DS0	0.064		0.064	0.064
1	DS1/T1	1.544	E1	2.048	1.544
2	DS2/T2	6.312	E2	8.448	6.312
3	DS3/T3	44.736	E3	34.368	32.064
4		139.264	E4	139.264	97.728

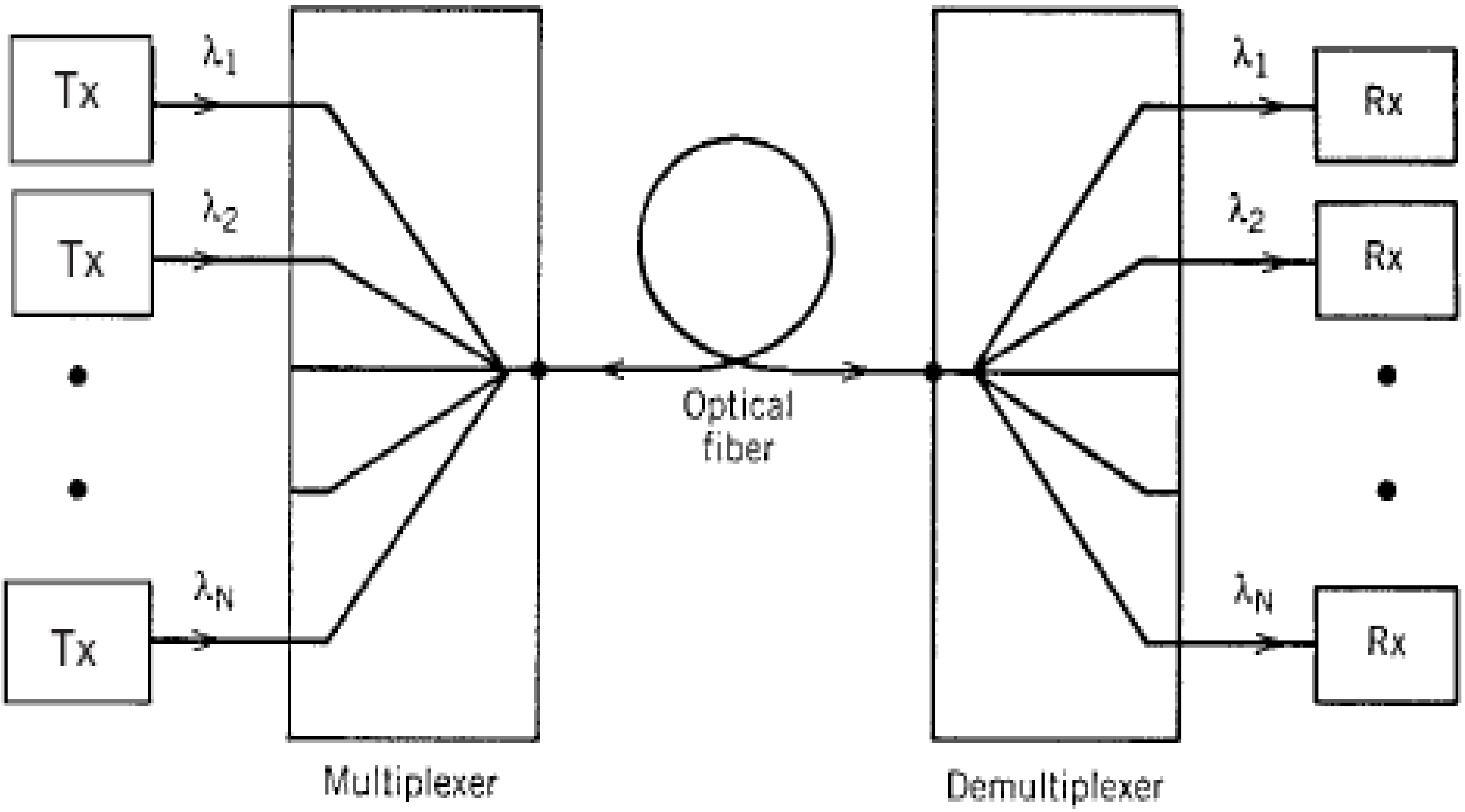
SONET/SDH(2)

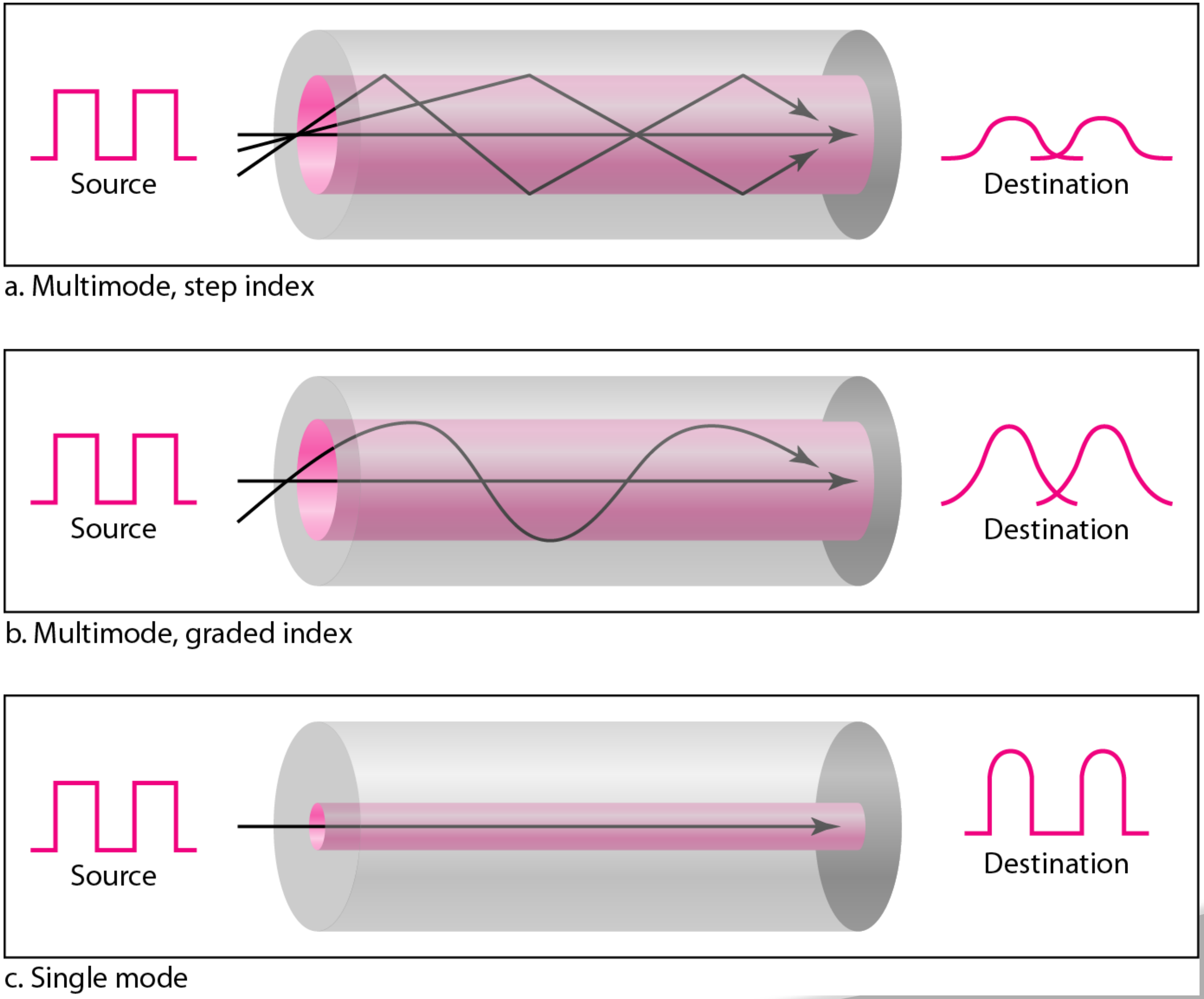
- PDH versus SONET/SDH
  - Multiplexing
    - PDH: Difficult to pick low bit rate stream from high bit rate stream
    - In PDH, clocks of lower bit streams are not perfectly synchronous
      - Higher rates are not integral multiples of 64Kb/s
        - Bit stuffing needed
        - Mulltiplexers and Demultiplexers complicated
    - In SONET/SDH a master clock is used→MUX and DEMUX much easier

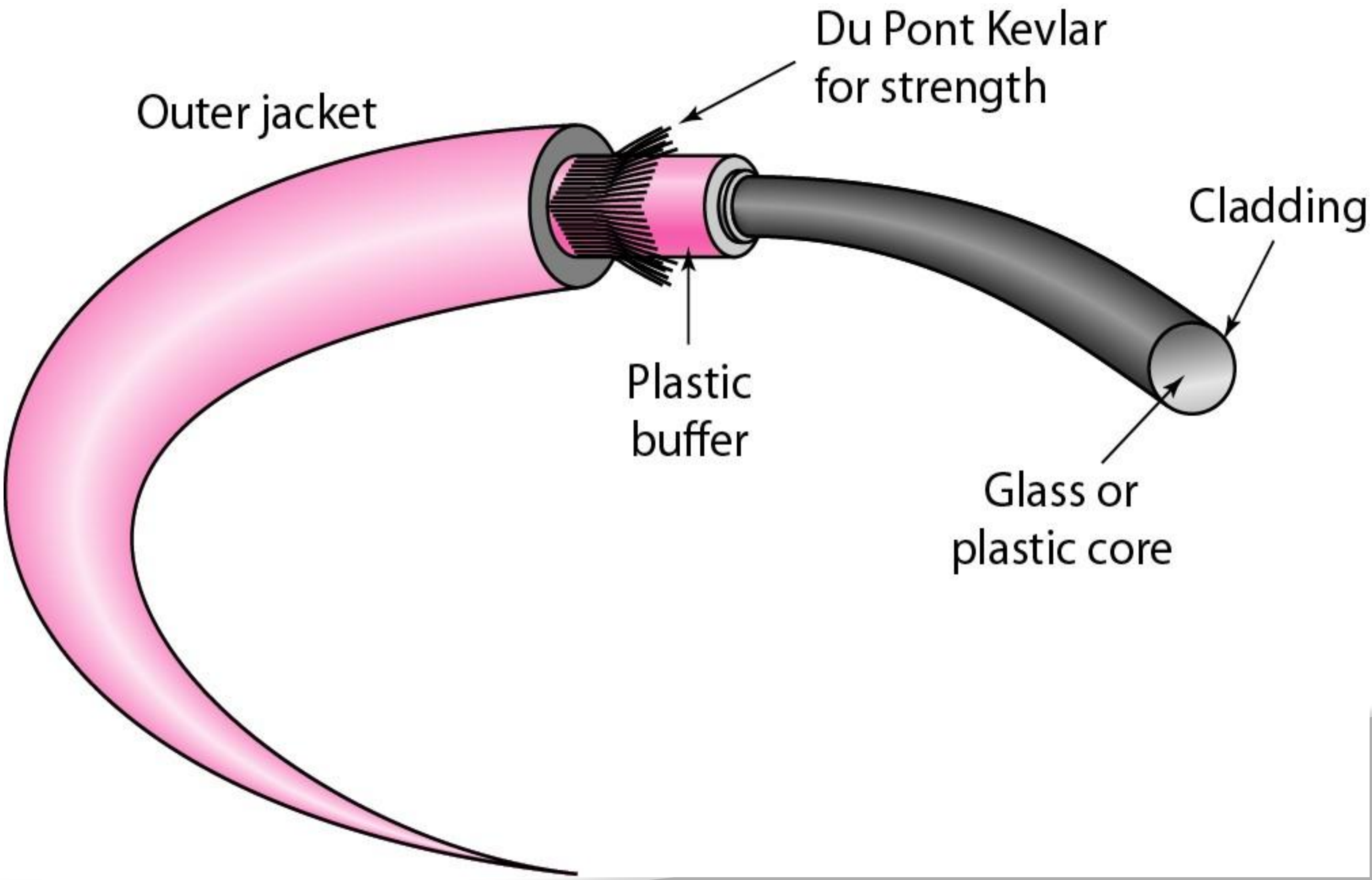
- Management
  - Unlike PDH, SONET/SDH standards are rich of management and traffic performance monitoring information
- Interoperability
  - SONET/SDH define standard optical interfaces
  - PDH: different vendors define different line coding, optical interfaces,...
- Networking
  - SONET/SDH: Service restoration time is less than 60 ms
  - PDH: restoration time is several seconds to minutes

WDM OPTICAL NETWORKS

- Considerable increase in traffic became a driving force for WDM and its evolution into dense WDM (DWDM).
- WDM refers to the technology of combining multiple wavelengths onto the same optical fiber.
- Each wavelength is a different channel.
- At the transmitting end, there are *W* independent transmitters. Each transmitter *Tx* is a light source, such as a laser, and is independently modulated with a data stream. The output of each transmitter is an optical signal on a unique wavelength λ_i , $i = 1, 2, . . . , W$.
- WDM: ~200 GHz spacing
- DWDM: ~50 GHz spacing

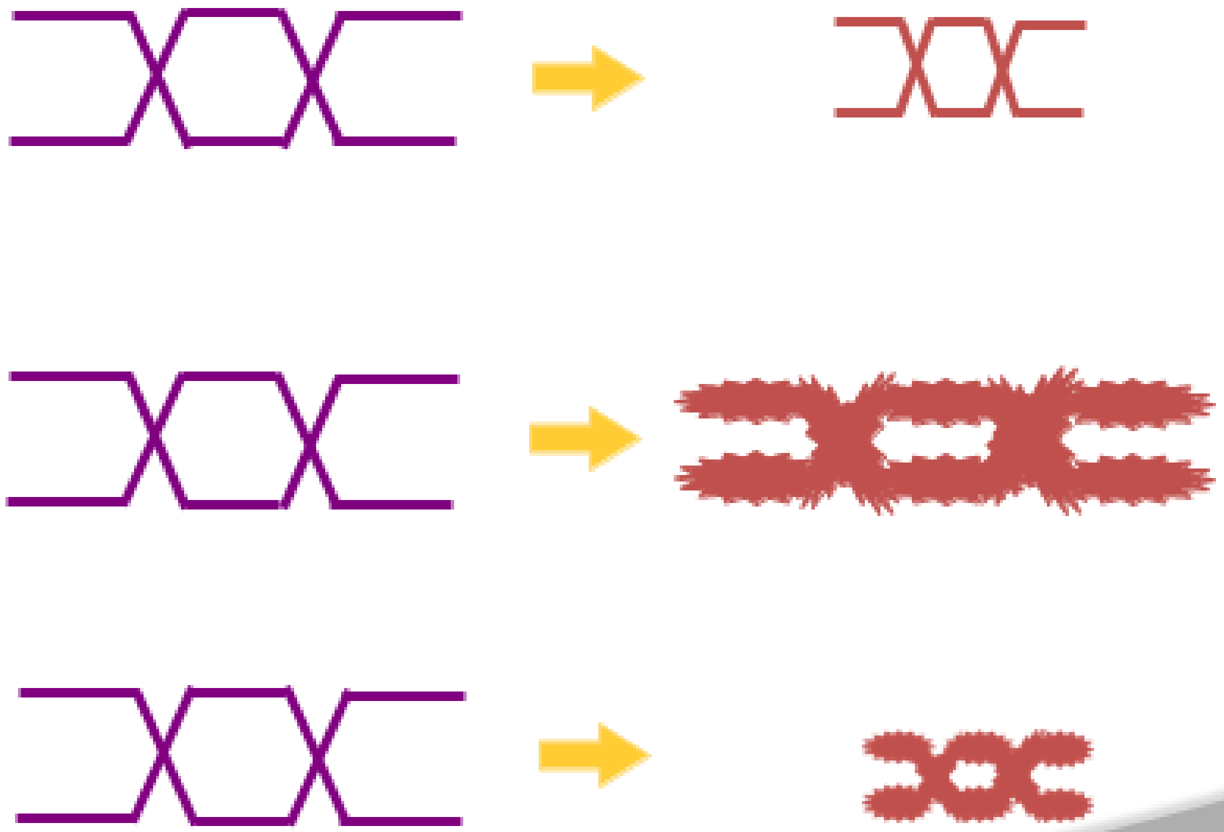

Tx
Tx
Tx
λ1
λ2
λN
Optical
fiber
λ1
λ2
λN
Rx
Rx
Rx
Multiplexer
Demultiplexer

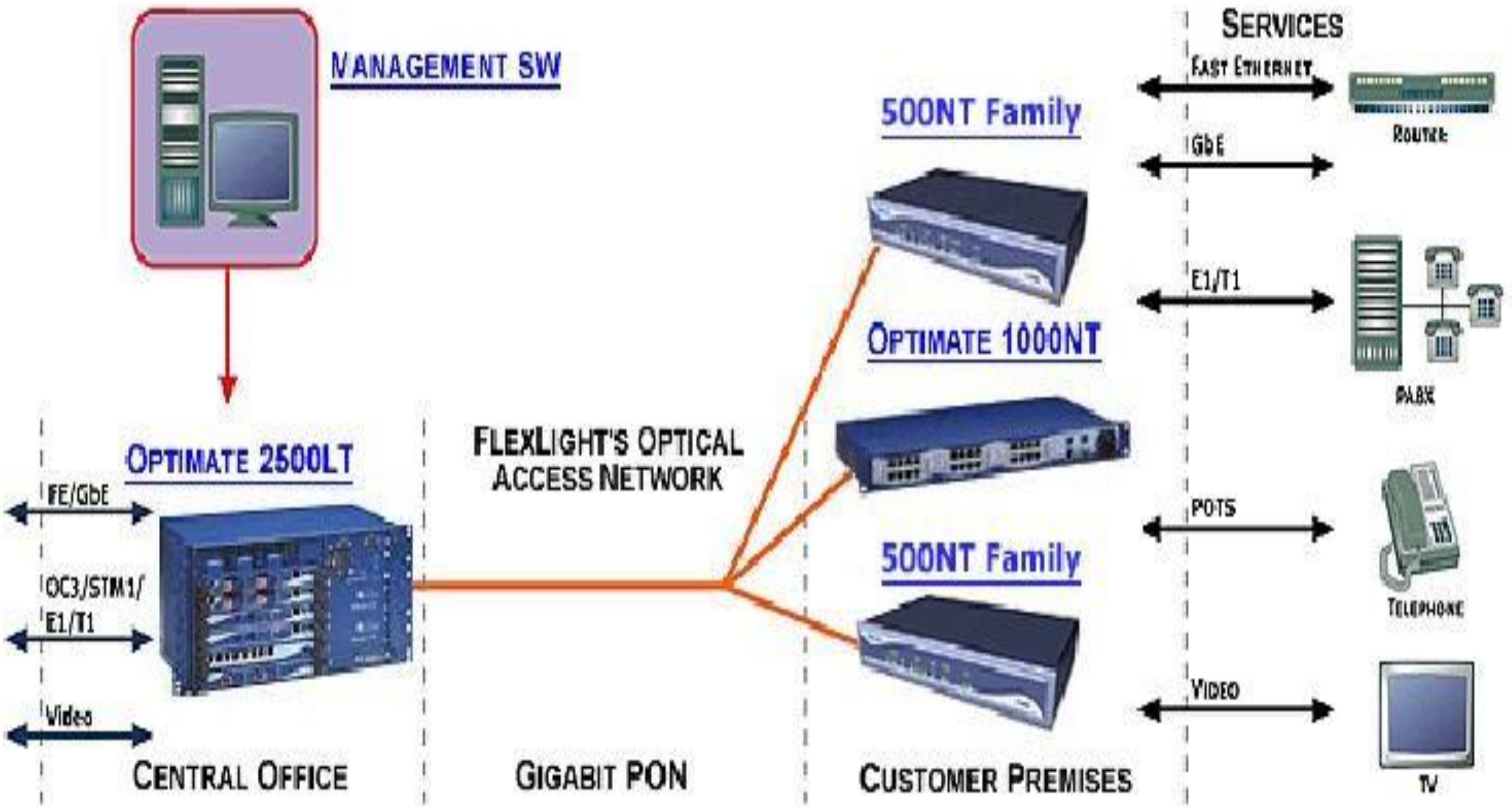

Source
Destination
a. Multimode, step index
Source
Destination
b. Multimode, graded index
Source
Destination
c. Single mode


Du Pont Kevlar
for strength
Outer jacket
Cladding
Plastic
buffer
Glass or
plastic core

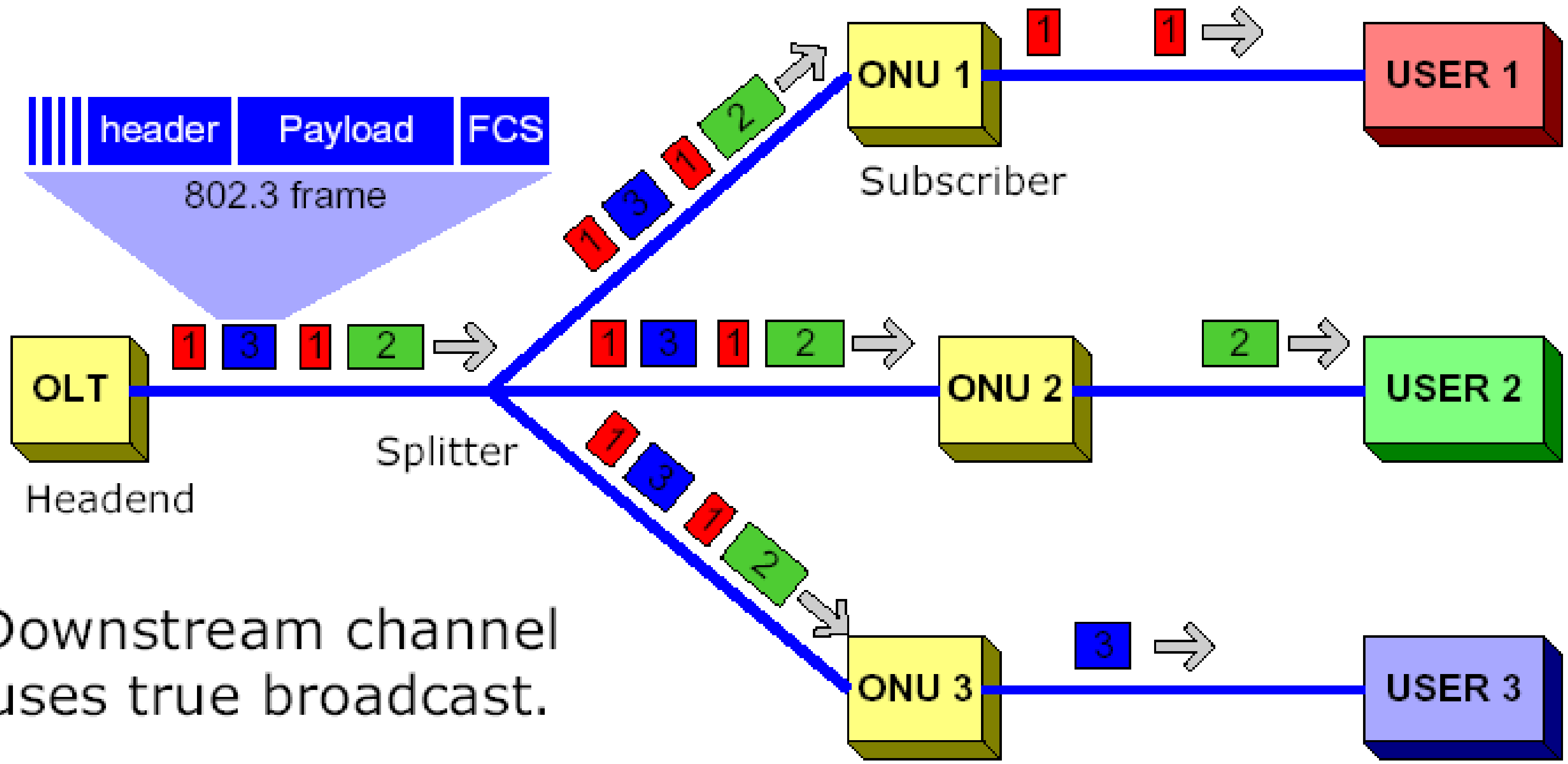
Optical Transmission Effects

Loss of transmission power due to long distance




MANAGEMENT SW
SERVICES
FAST ETHERNET
ROUTER
500NT Family
GbE
E1/T1
PABX
OPTIMATE 1000NT
FLEXLIGHT'S OPTICAL ACCESS NETWORK
OPTIMATE 2500LT
FE/GbE
POTS
OC3/STM1/
E1/T1
500NT Family
TELEPHONE
Video
VIDEO
TV
CENTRAL OFFICE
GIGABIT PON
CUSTOMER PREMISES

EPON Downstream

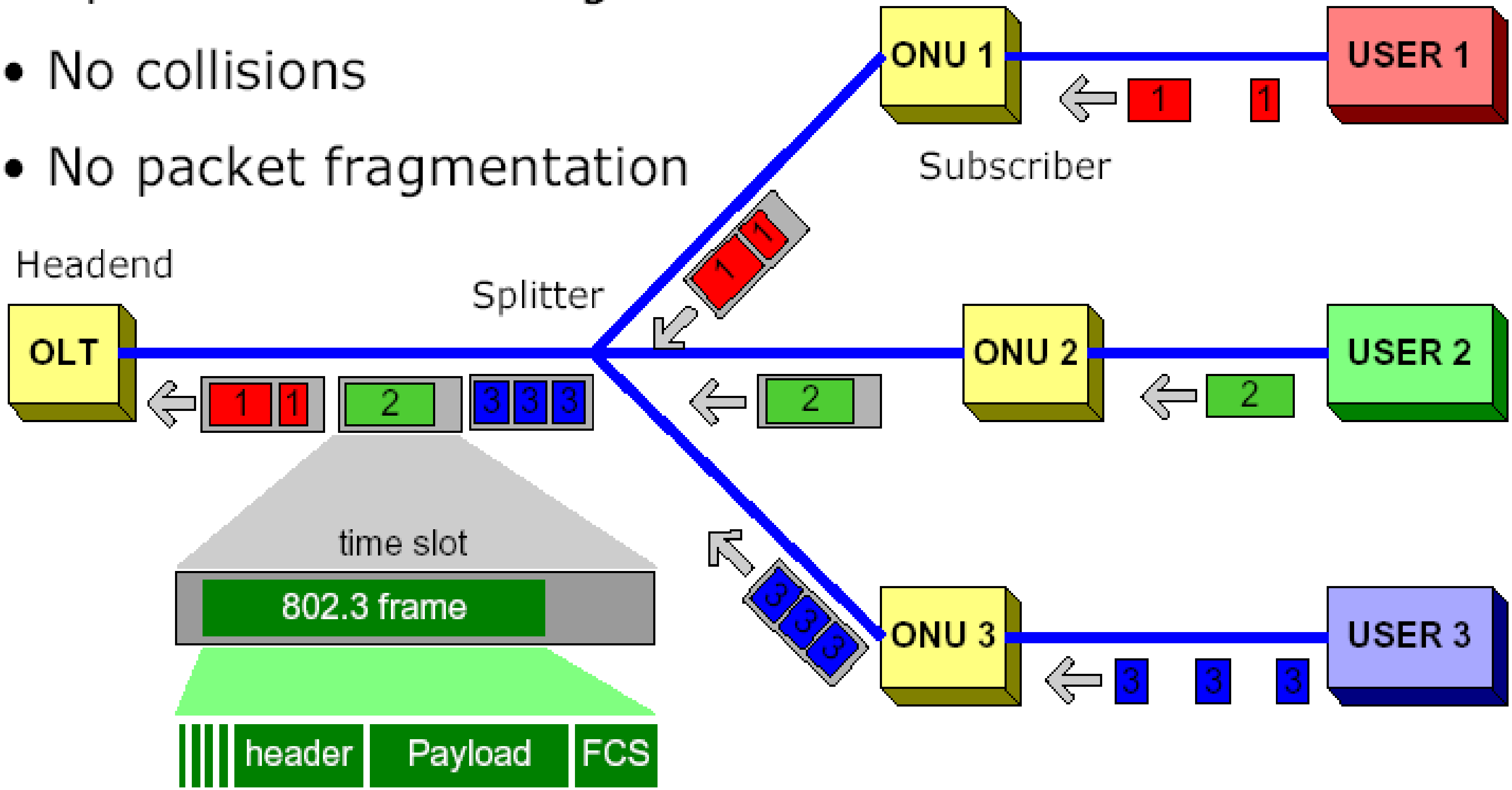


- Downstream channel uses true broadcast.
- 802.3 Frames extracted by MAC addresses.

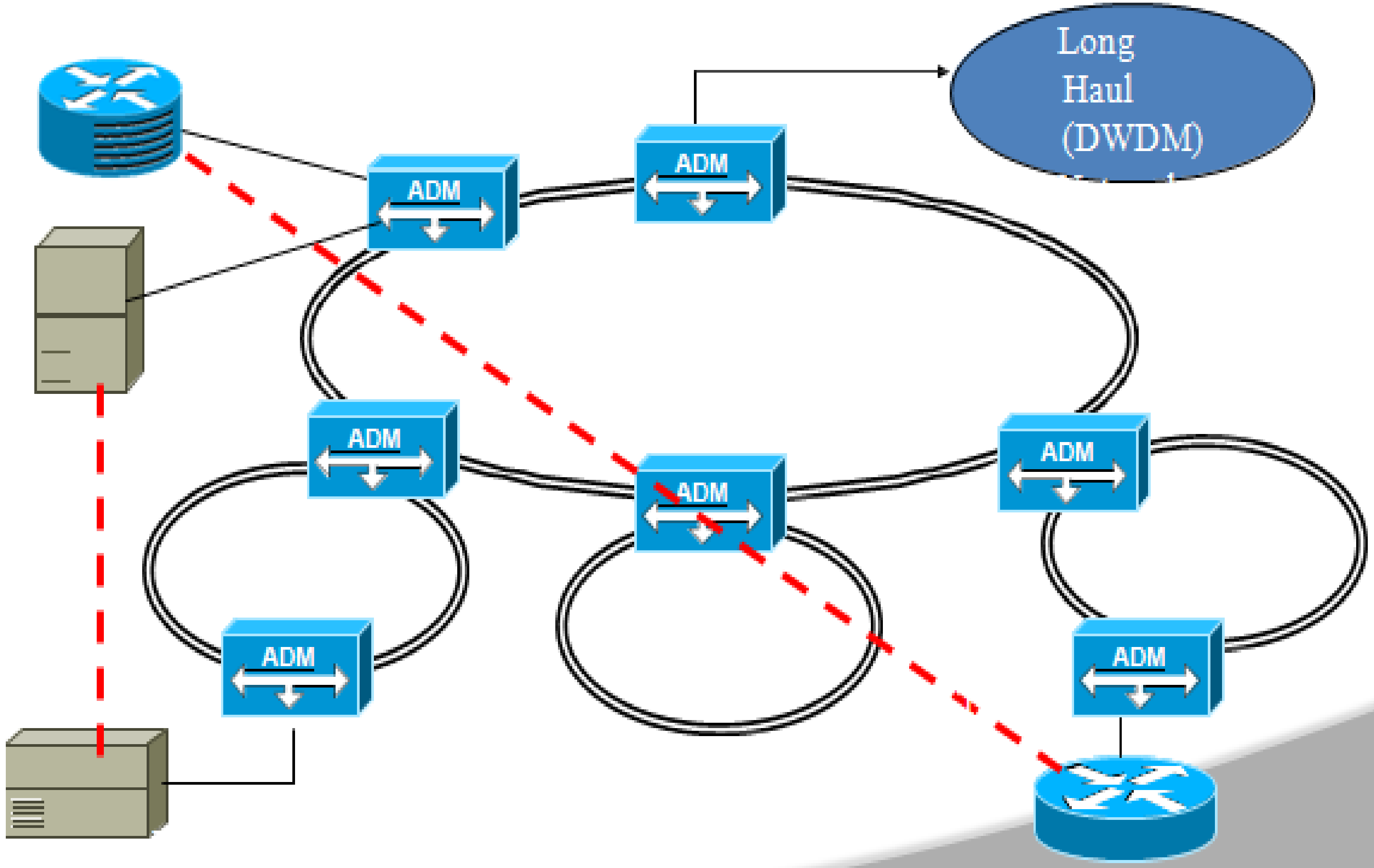
OLT = Optical Line Terminal
ONU = Optical Network Unit

EPON Upstream

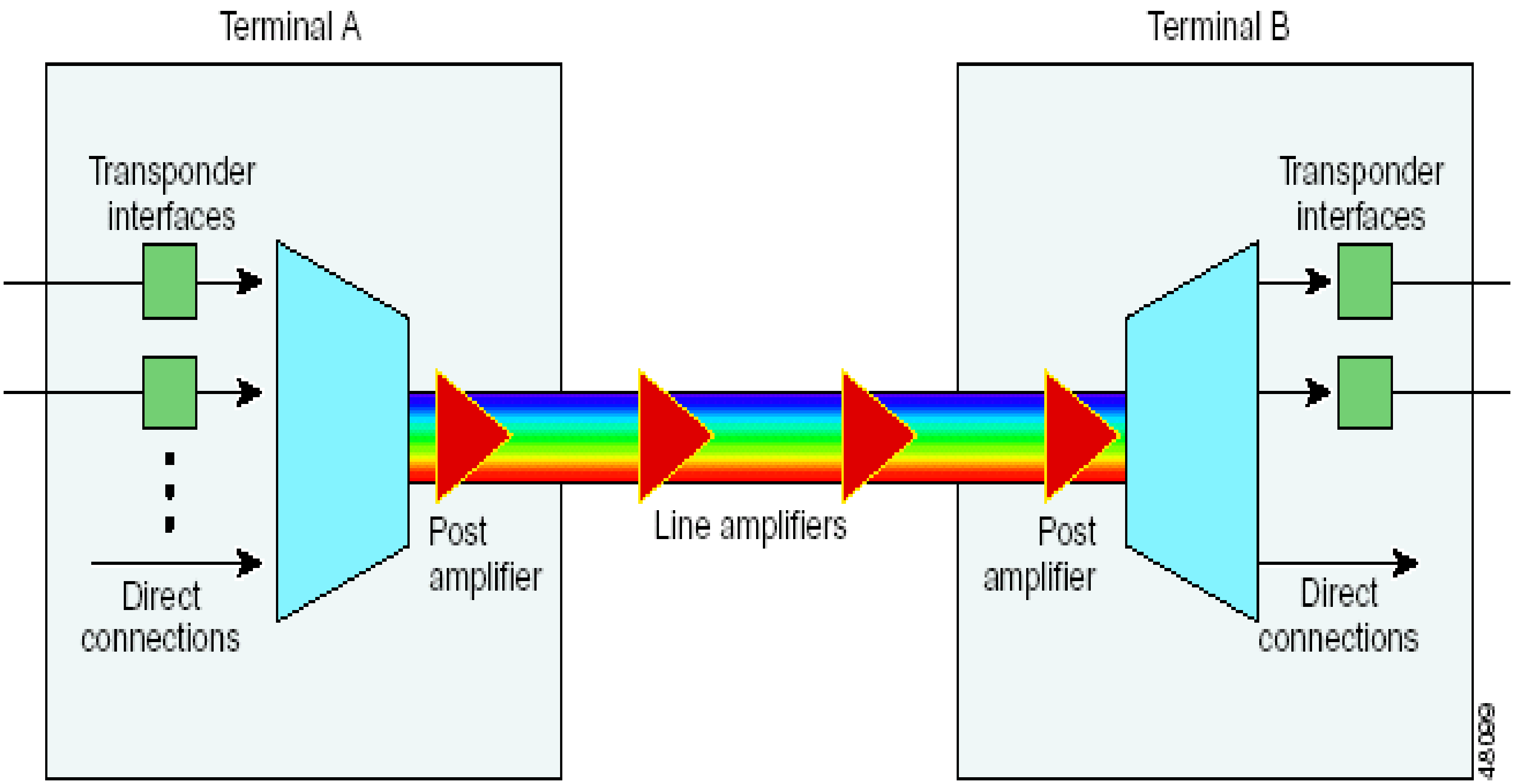
- Upstream time slicing
- No collisions
- No packet fragmentation



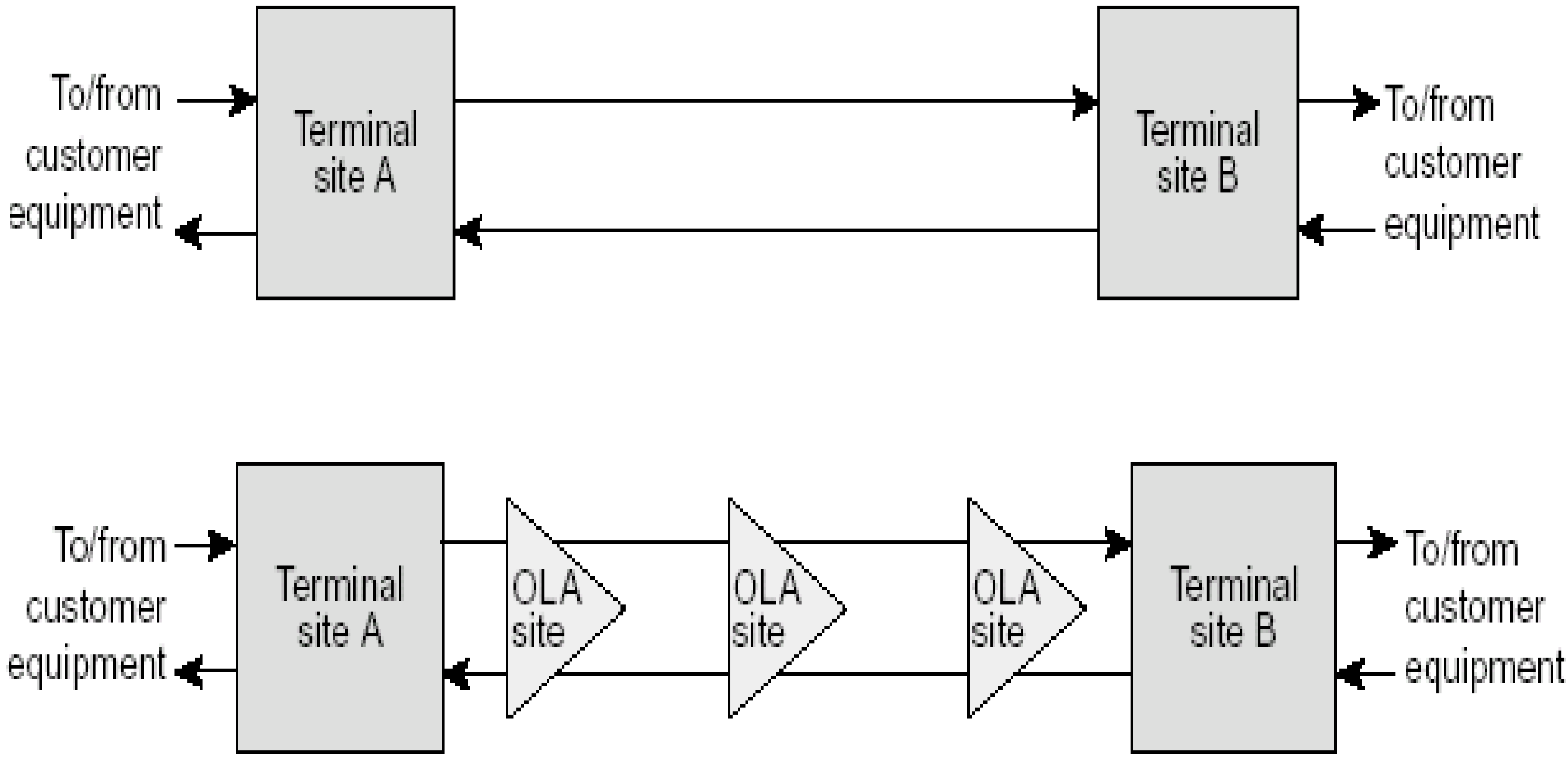
SONET in Metro Network



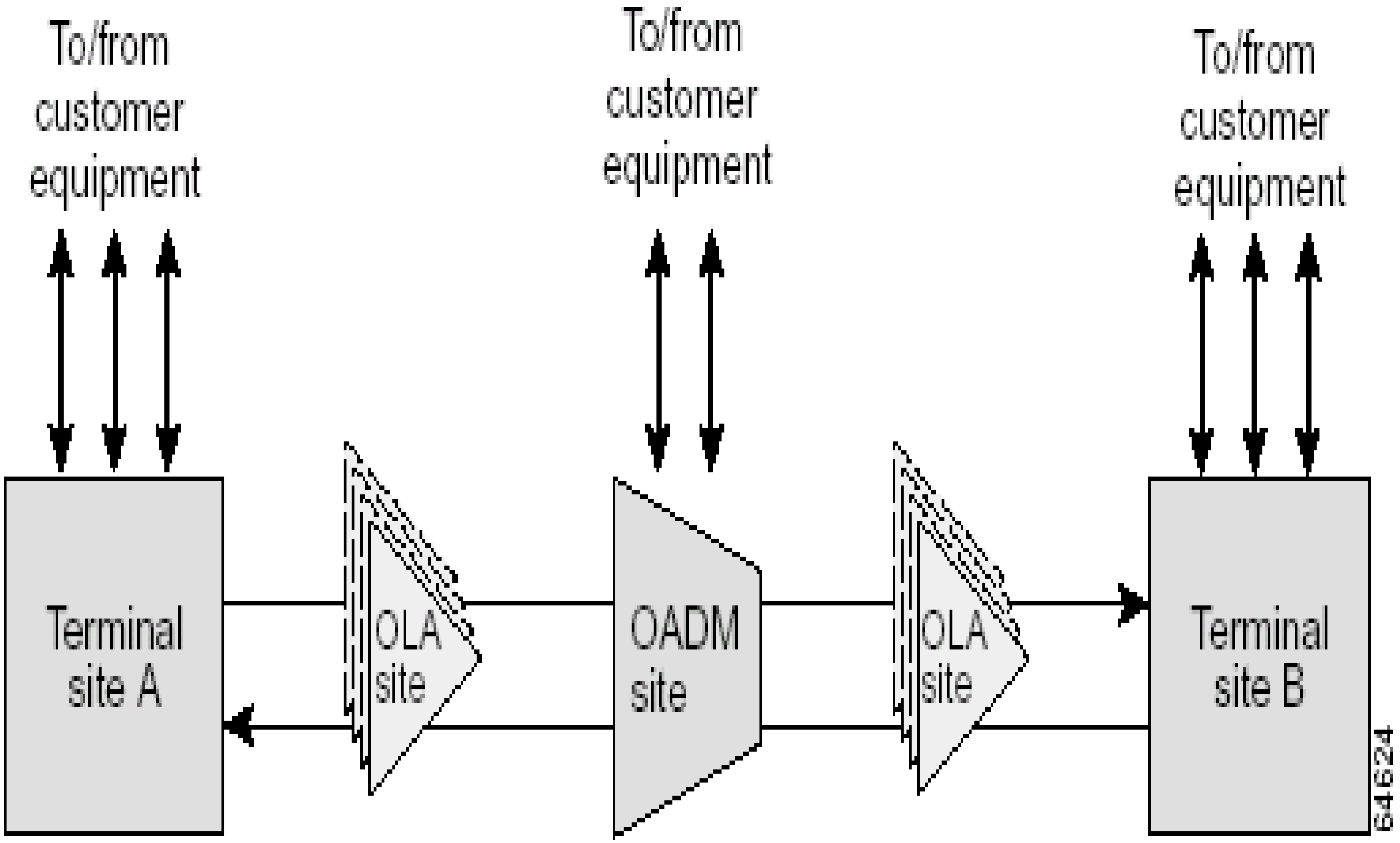
DWDM Network



DWDM Network (point-to-point)



DWDM Network Add-and-Drop



Soliton based transmission

- What is Optical Communication?
- Advantages &Disadvantages of Optical Communication
- Optical soliton
- Soliton based transmission
- Advantages & Disadvantages of soliton
- Conclusion
- References

What is Optical Communication

- The communication in which light is used to carry the signal to remote end instead of electric current

- Optical Communication relies on optical fibers to carry signals to the destination

Block Diagram of Optical Fiber Communication System

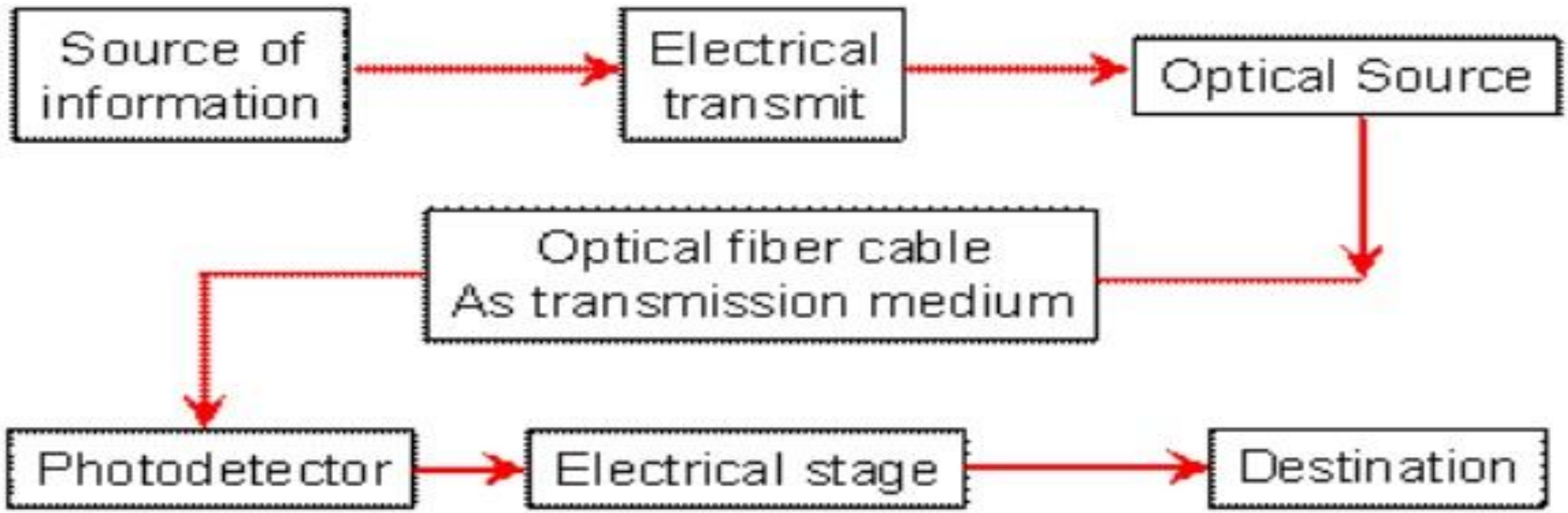


Figure: Basic Block Diagram of Optical Communication System

Optical Soliton

- Solitons are very narrow, high intensity stable optical pulses. High peak power and special shapes

- During propogation,the shape of soliton remains unchanged.

- Soliton pulses reduce the effect of chromatic dispersions.

- Chromatic dispersions:

- 1.Group velocity dispersion
- 2.Self phase modulation
-

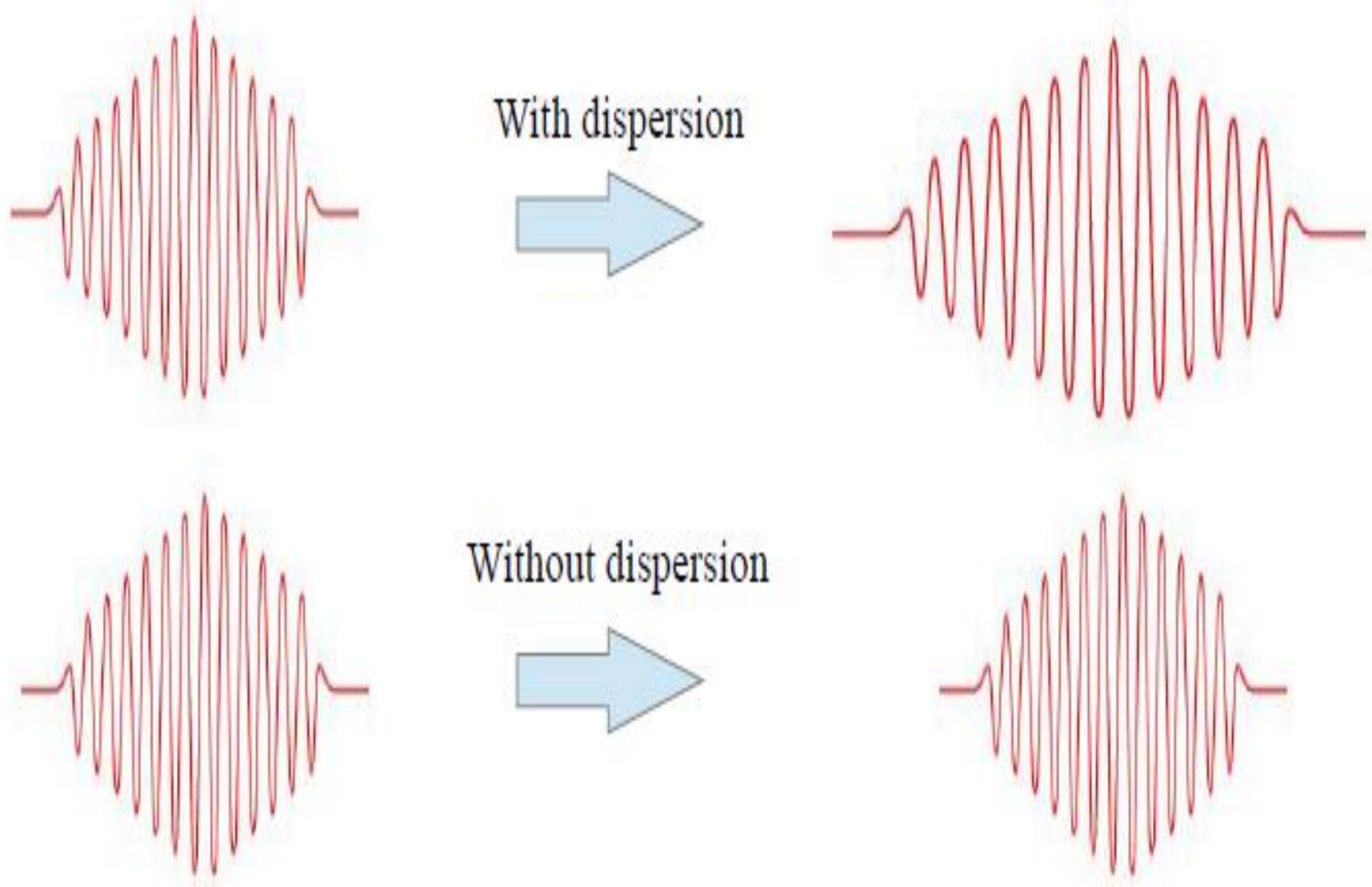
Effect of Chromatic Dispersion

Dispersion is the time domain spreading or broadening of the transmission signal light pulses - as they travel through the fibre

Chromatic Dispersion Causes

1. Pulse Broadening
2. Bit Error

Group velocity dispersion



Self phase modulation

Criteria to be satisfied for the soliton

- Appropriate peak power
- Should be unchirped

Soliton based transmission

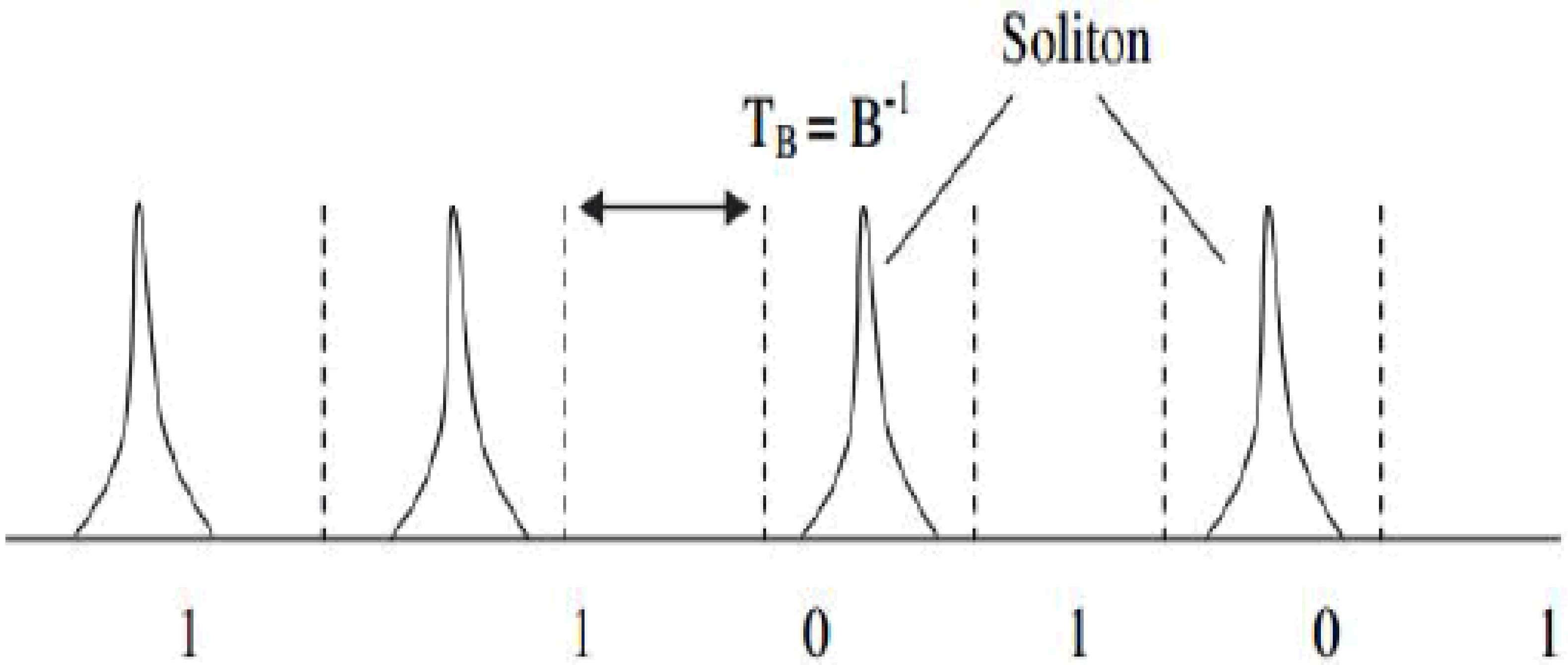


Fig.5: Soliton bit stream in an RZ format [3]

Advantages and disadvantages

Advantages:

1.Dispersions are reduced

2.Pulse shape can be maintained

3.Transmission speed can be increased

4.Opens the way to ultrahigh speed superhighways

Conclusion

- Soliton based optical fiber communication systems are more suitable for long haul communication because of their very high information carrying capacity.


Thank you