Lecture 1& Lect. 2

Physics of Optical Elements Introduction to Optical Fiber Communication System

By Prof. Dr. Zainab Naser Jameel
Communication Engineering Department
Second Class Optical & Wireless Division
University of Technology-Iraq

Reading List

1- J .M . Senior , Optical Fibre Communications , 2009 .

2- G. Keiser , Optical Fibre Communications , 2000 .

3- G . P . Agrawal , Fiber-Optic Communication Systems, 2010 .

Transmission Media

- Transmission Medium, or channel, is the actual physical path that data follows from the transmitter to the receiver.

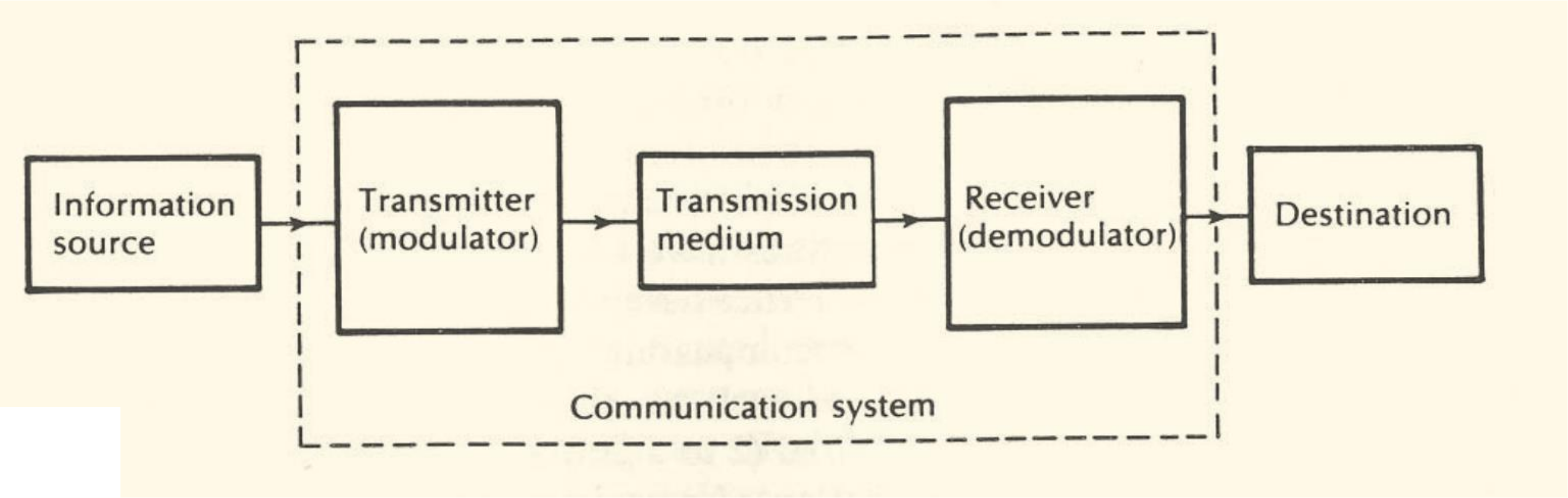
- Copper cable is the oldest , cheapest , and the most common form of transmission medium .

- Optical Fiber is being used increasingly for high-speed applications.

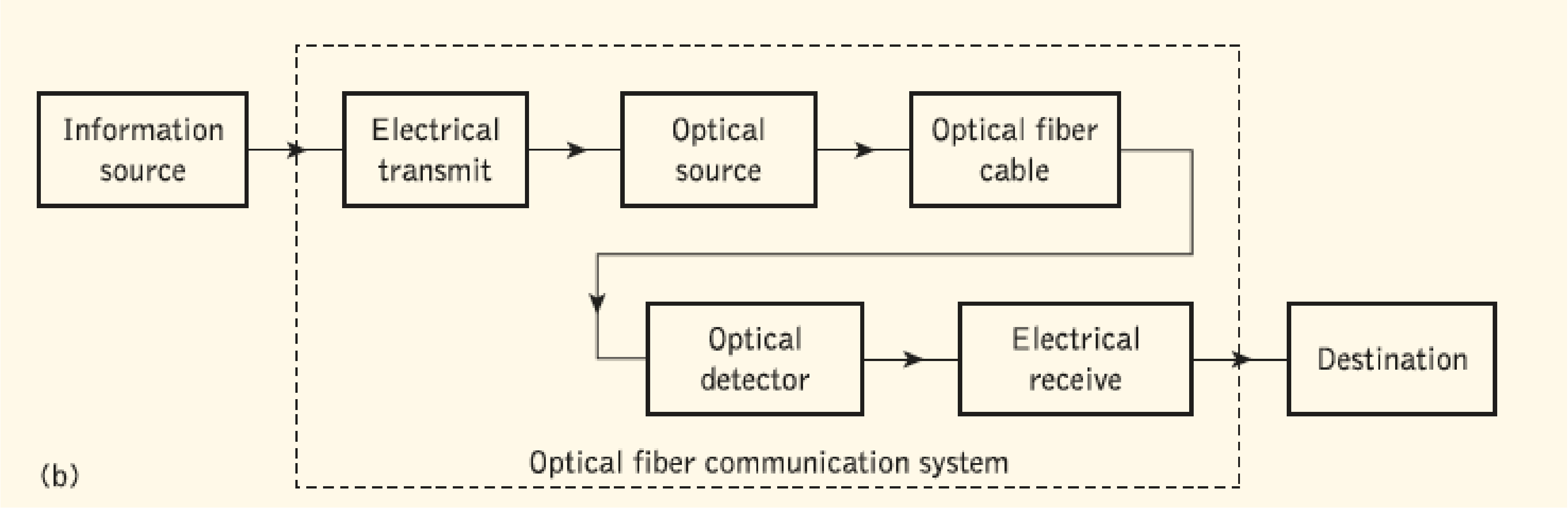
Advantages of optical fiber communication

1- Enormous potential bandwidth .
2- Small size and weight.
3- Electrical isolation.
4- Immunity to interference and crosstalk.
5- Signal security.
6- Low transmission loss.
7- Ruggedness and flexibility.
8- System reliability and ease of maintenance.
9- Potential low cost.

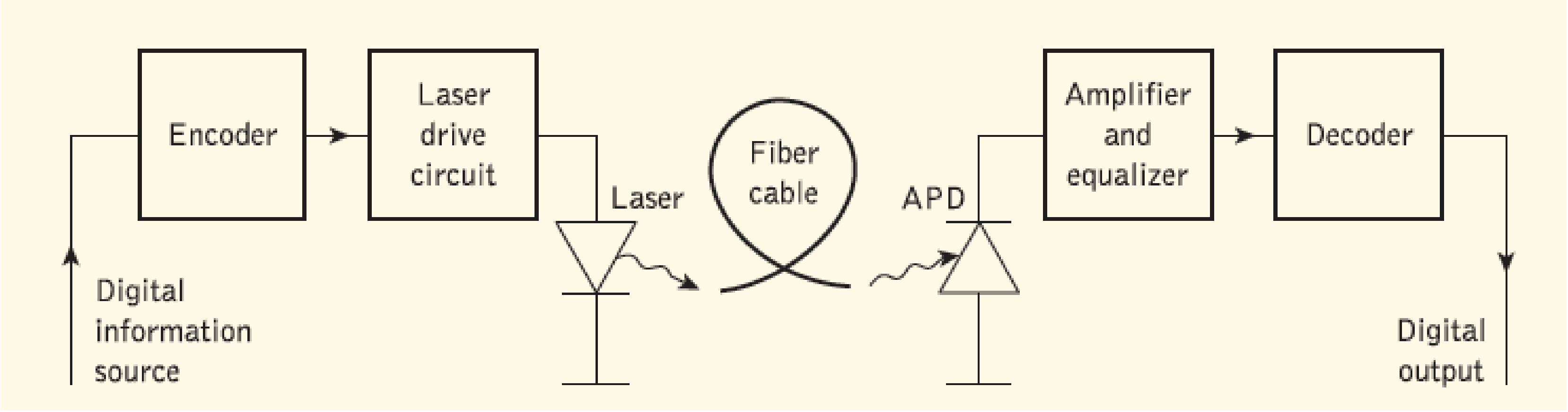
General Communication systems



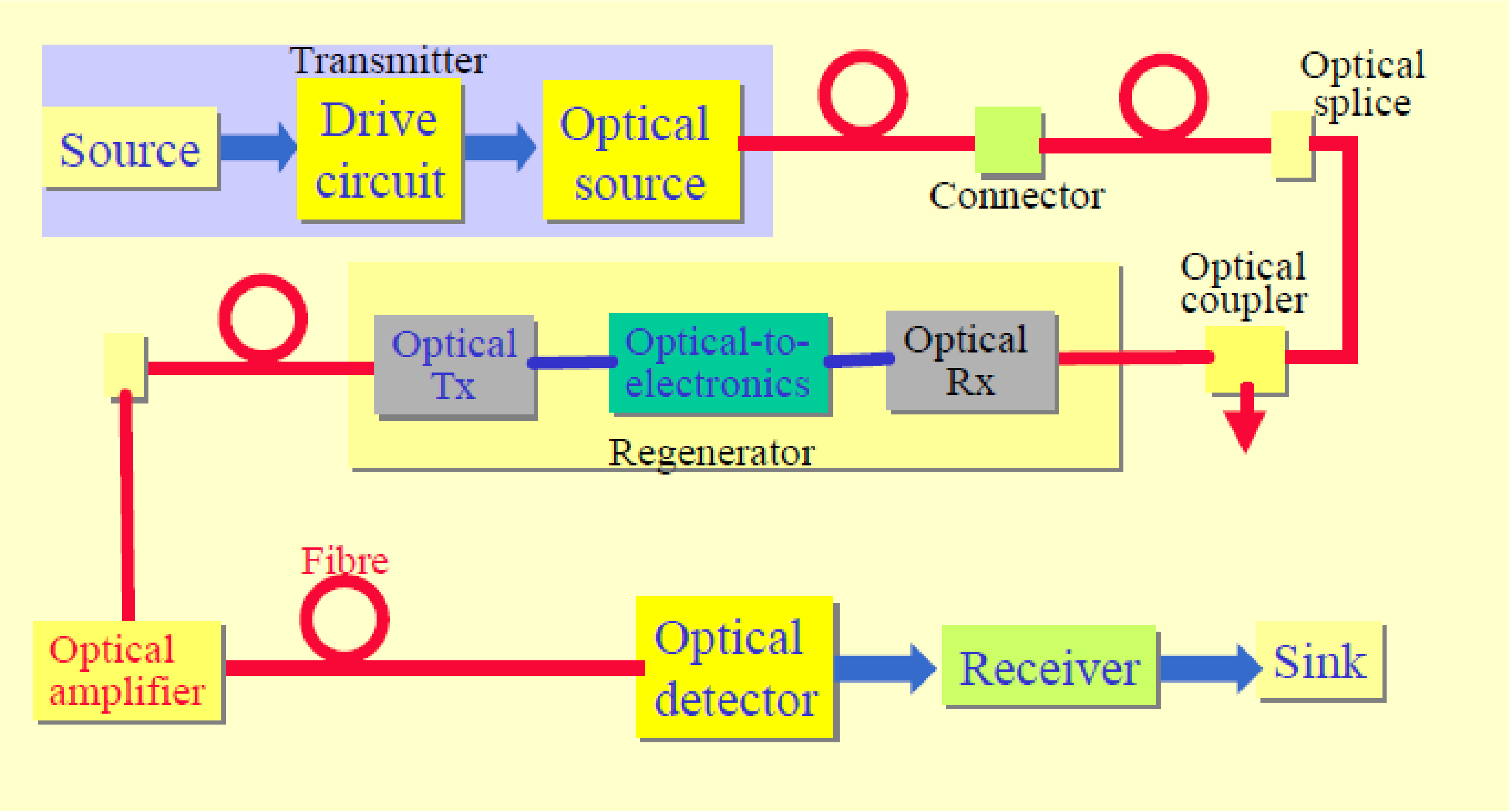
The optical fiber communication system



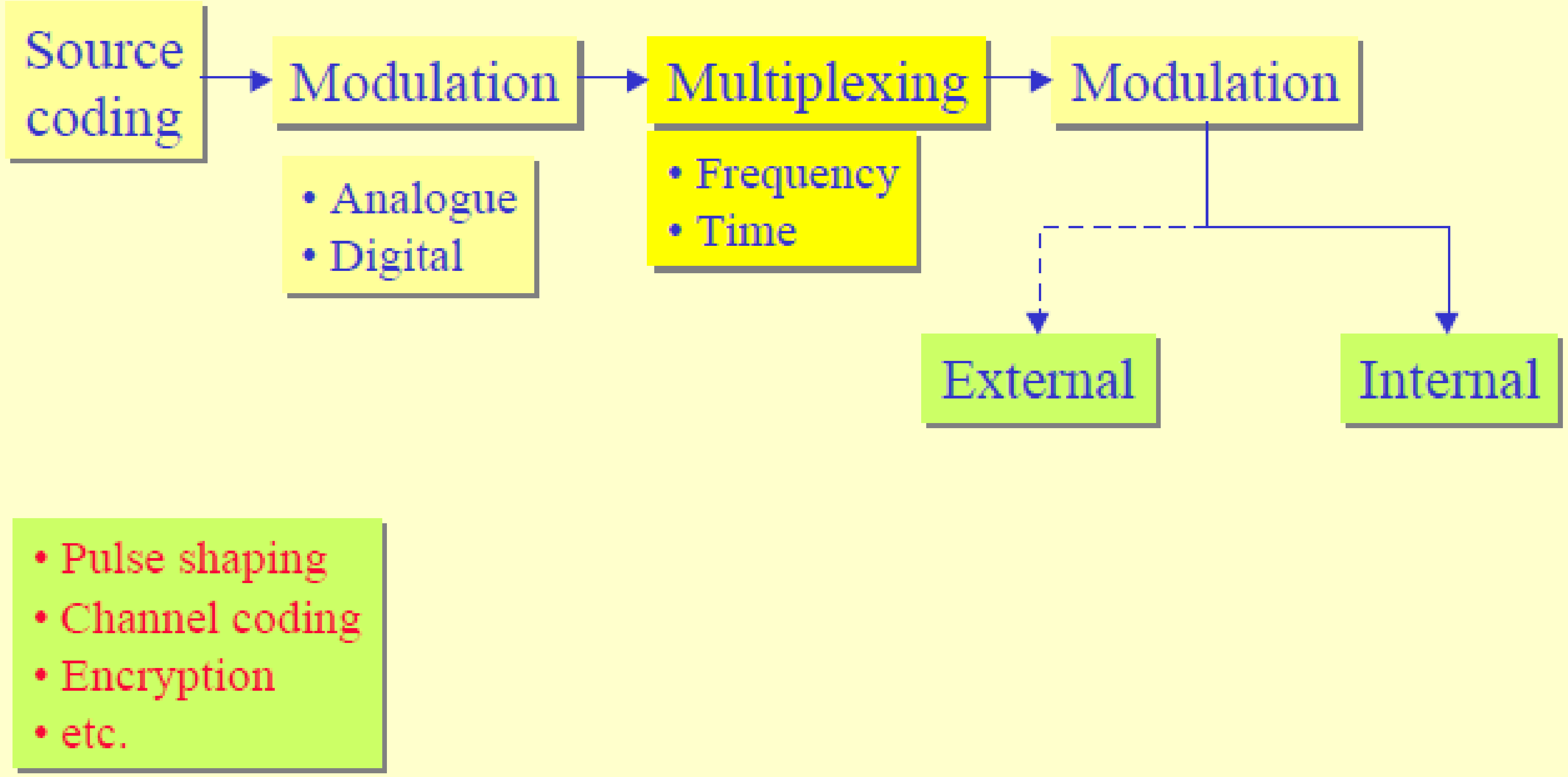
A digital optical fiber link using a semiconductor laser source and an avalanche photodiode (APD) detector



Optical Communication systems

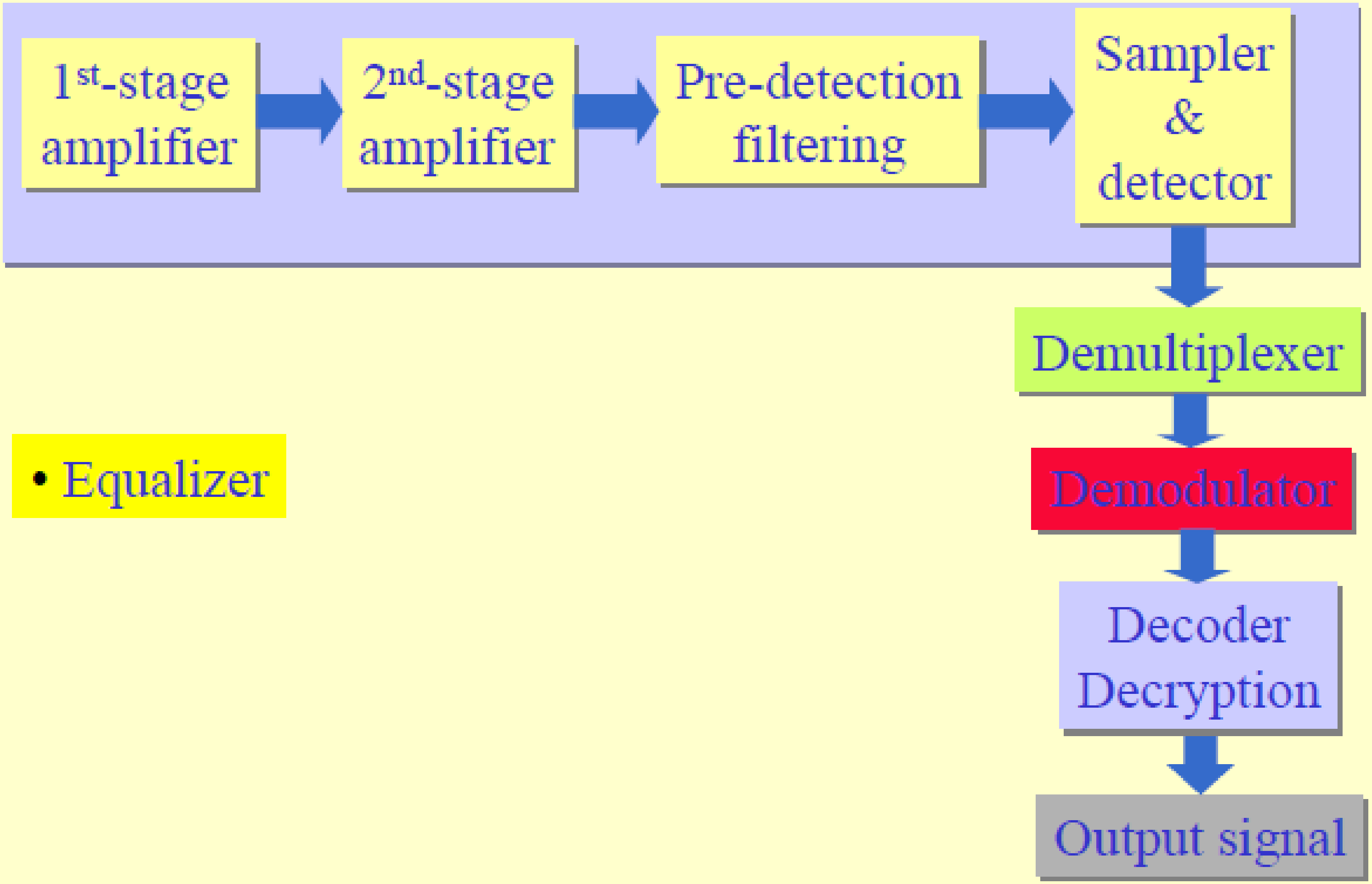


Source



Source coding
Modulation
Multiplexing
Modulation
• Analogue
• Digital
• Frequency
• Time
External
Internal
• Pulse shaping
• Channel coding
• Encryption
• etc.

Receiver



- Equalizer

Challenges Ahead

- Modulation and detection and associated high speed electronics
- Multiplexer and demultiplexer
- Fibre impairments:
  - . Loss
  - . Chromatic dispersion
  - . Polarization mode dispersion
  - . Optical non-linearity
  - . etc.

Evolution of Light wave systems

1st Generation: The development of low-loss fibers and semiconductor lasers (GaAs) in the 1970's.

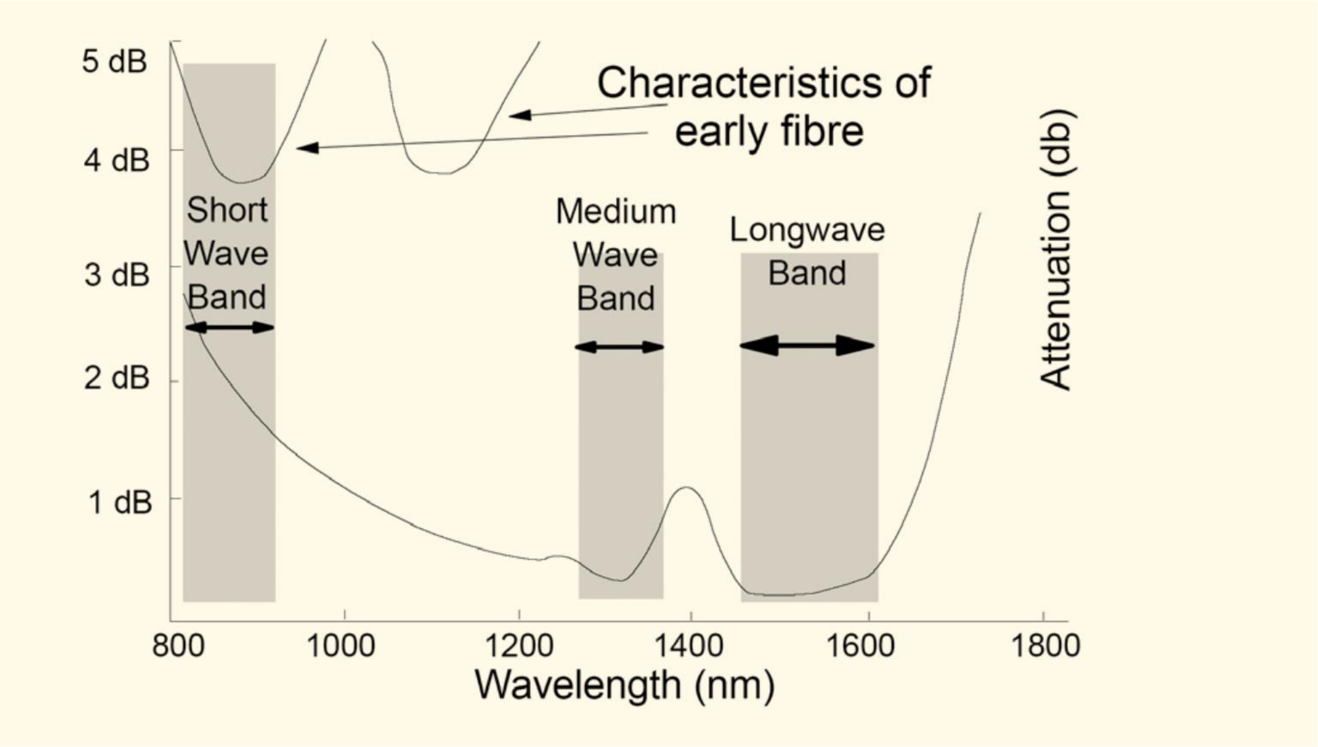
A Gallium Aresenide (GaAs) laser operates at a wavelength of 0.8μm.

The optical communication systems allowed a bit rate of 45Mbit/s and repeater spacing of 10km.

Example of a laser diode.

2nd Generation:

The repeater spacing could be increased by operating the lightwave system at 1.3µm. The attenuation of the optical fiber drops from 2-3dB/km at 0.8µm down to 0.4dB/km at 1.3µm. Silica fibers have a local minima at 1.3µm.

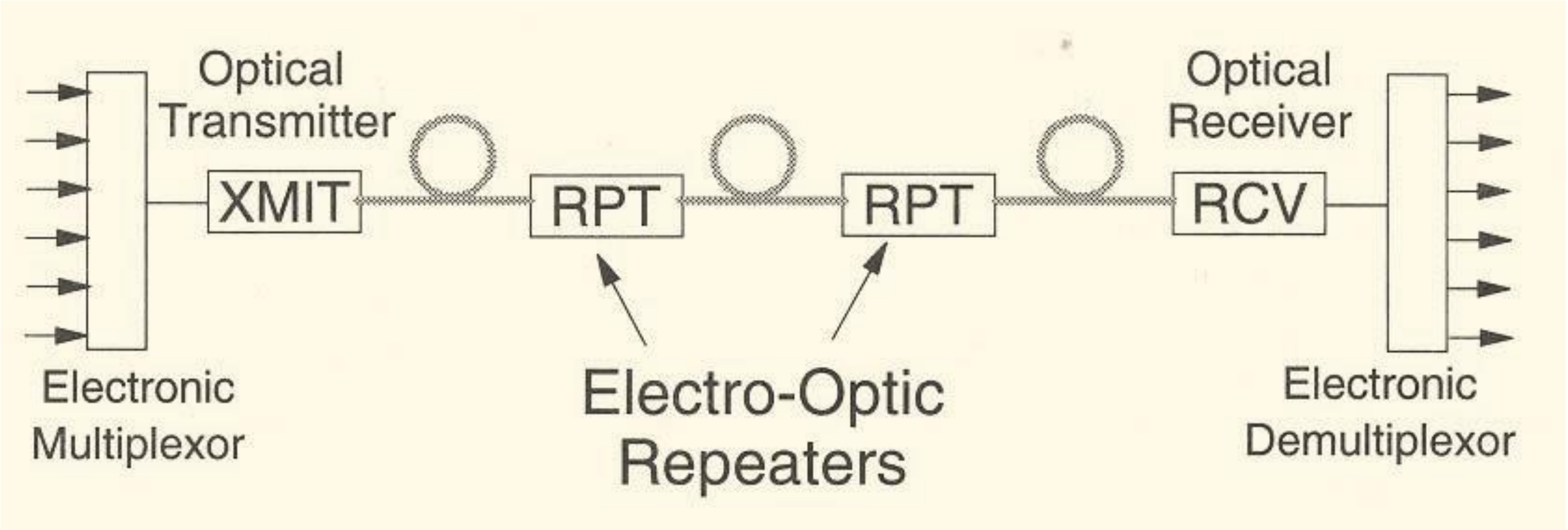


The transition from 0.8μm to 1.3μm leads to the 2nd Generation of lightwave systems. The bit rate- distance product can be further increased by using single mode fibers instead of multi-mode fibers.

Single mode fibers have a distinctly lower dispersion than multi mode fibers.

Lasers are needed which emit light at 1.3 μm.

3rd Generation: Silica fibers have an absolute minima at 1.55µm. The attenuation of a fiber is reduced to 0.2dB/km. Dispersion at a wavelength of 1.55µm complicates the realization of light wave systems. The dispersion could be overcomed by a dispersion-shifted fibers and by the use of lasers, which operate only at single longitudinal modes. A bit rate of 4Gbit/s over a distance of 100km was transmitted in the mid 1980's.

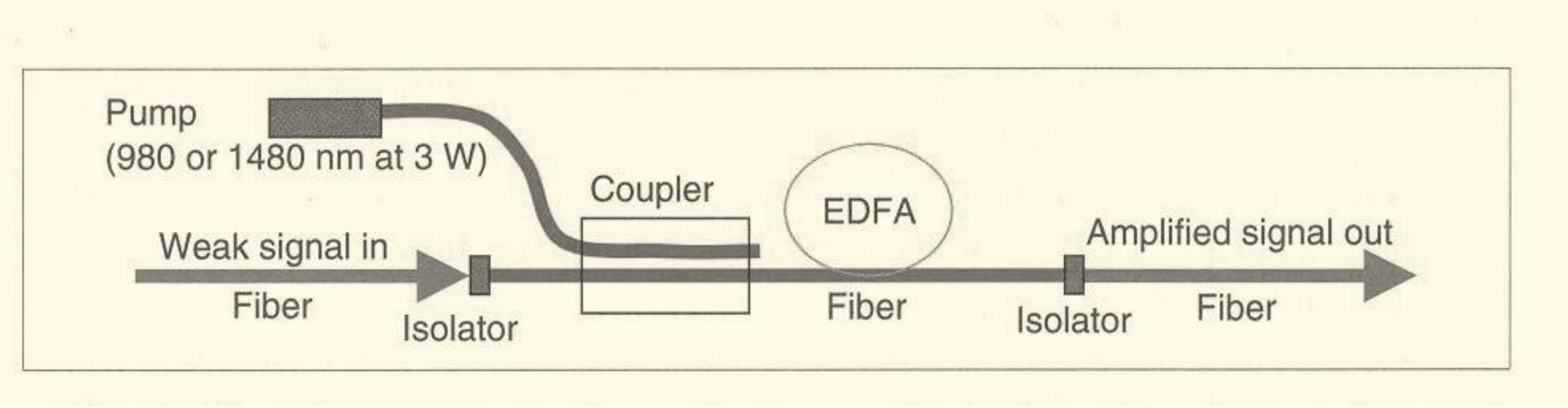


Traditional long distance single channel fiber transmission system.

Ref.: H. J.R. Dutton, Understanding optical communications

The major disadvantage of the 3rd Generation optical communication system is the fact that the signals are regenerated by electrical means. The optical signal is transferred to an electrical signal,the signal is regenerated and amplified before the signal is again transferred to an optical fiber.

4th Generation: The development of the optical amplifier lead to the 4th Generation of optical communication systems.

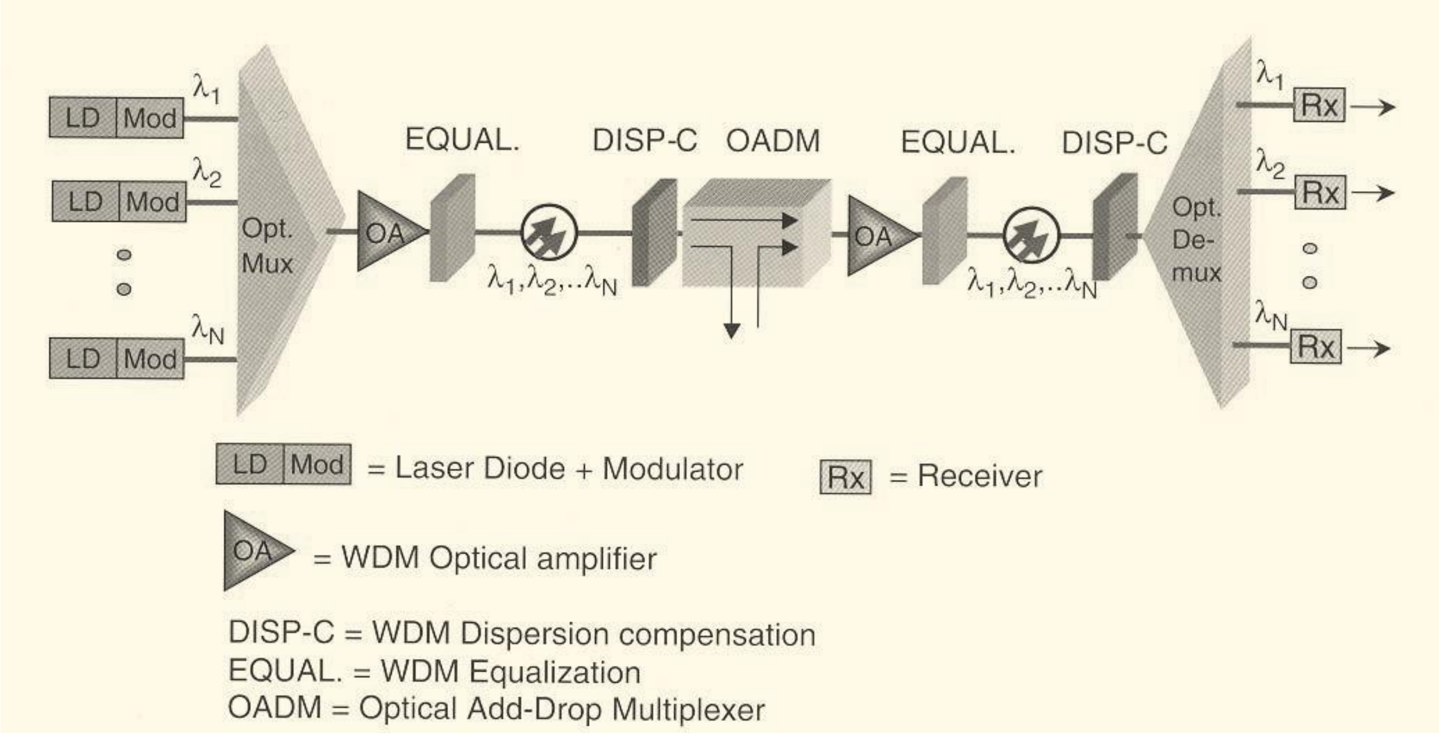


Schematic sketch of an erbium-doped fiber amplifier (EDFA).

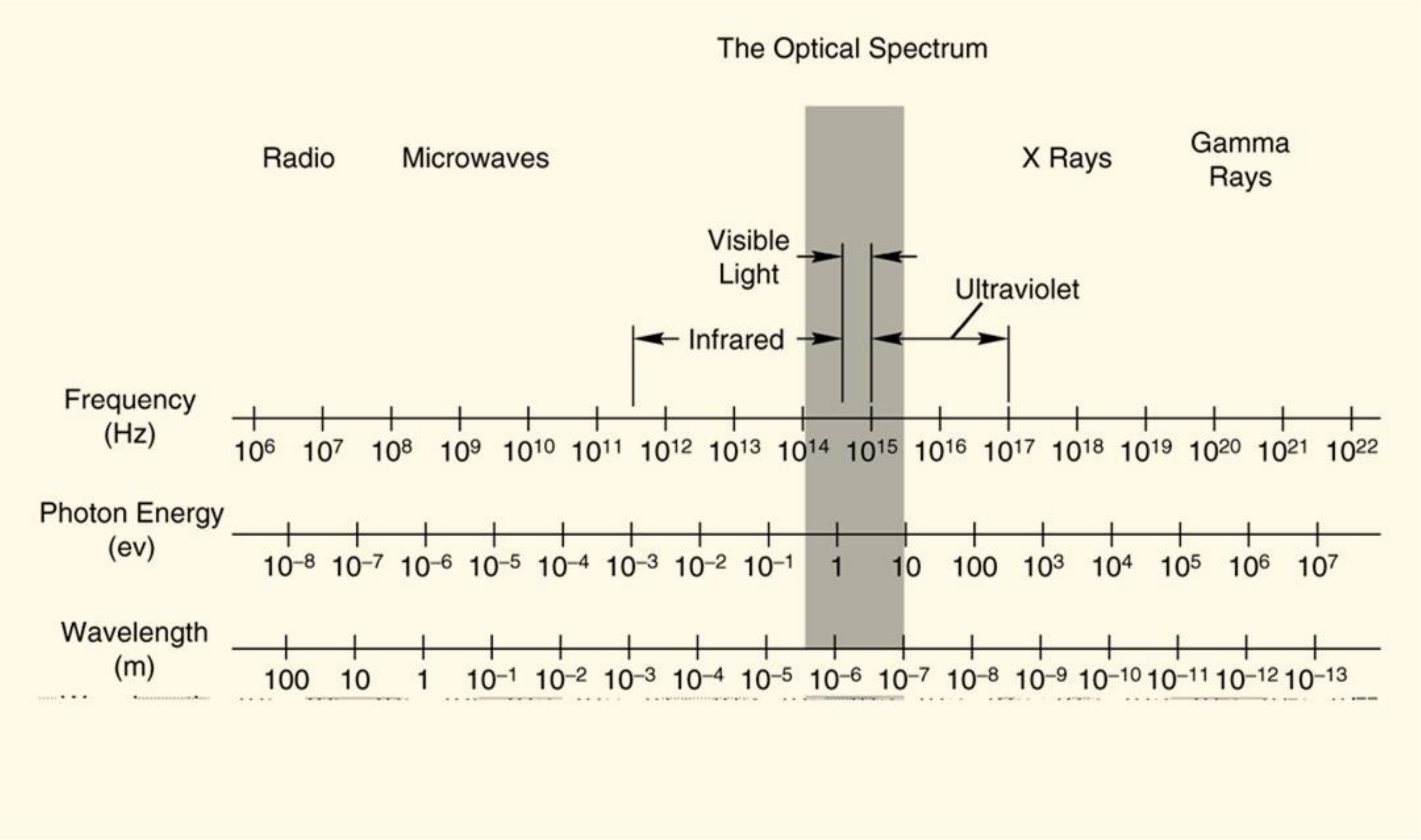
Ref.: S.V. Kartalopoulos, Introduction to DWDM Technology

State of the Art optical communication system:

Dense Wavelength Division Multiplex (DWDM) in combination of optical amplifiers. The capacity of optical communication systems doubles every 6 months. Bit rates of 10Tbit/s were realized by 2001.



Electromagnetic spectrum



Basic Optical - Material Properties

- The basic optical property of a material, relevant to optical fibers, is the index of refraction. The index of refraction (n) measures the speed of light in an optical medium. The index of refraction of a material is the ratio of the speed of light in a vacuum to the speed of light in the material itself. The speed of light (c) in free space (vacuum) is 3×10^8 meters per second (m/s). The speed of light is the frequency (f) of light multiplied by the wavelength of light. When light enters the fiber material (an optically dense medium), the light travels slower at a speed (v). Light will always travel slower in the fiber material than in air. The index of refraction is given by:

$$n = c / v$$

Group Velocity

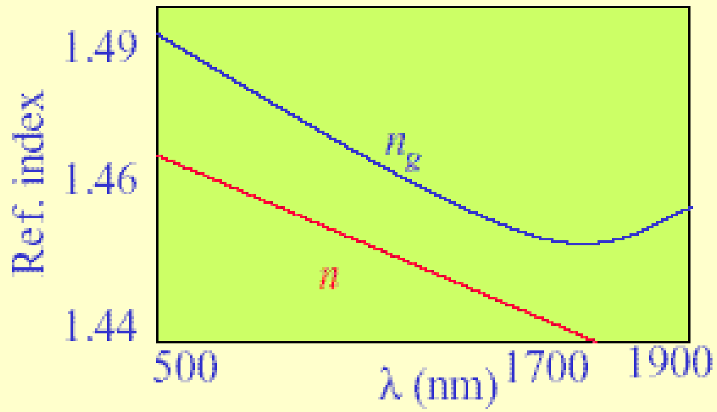
- A pure single frequency EM wave propagate through a wave guide at a

  Phase velocity $v_p = c / n$

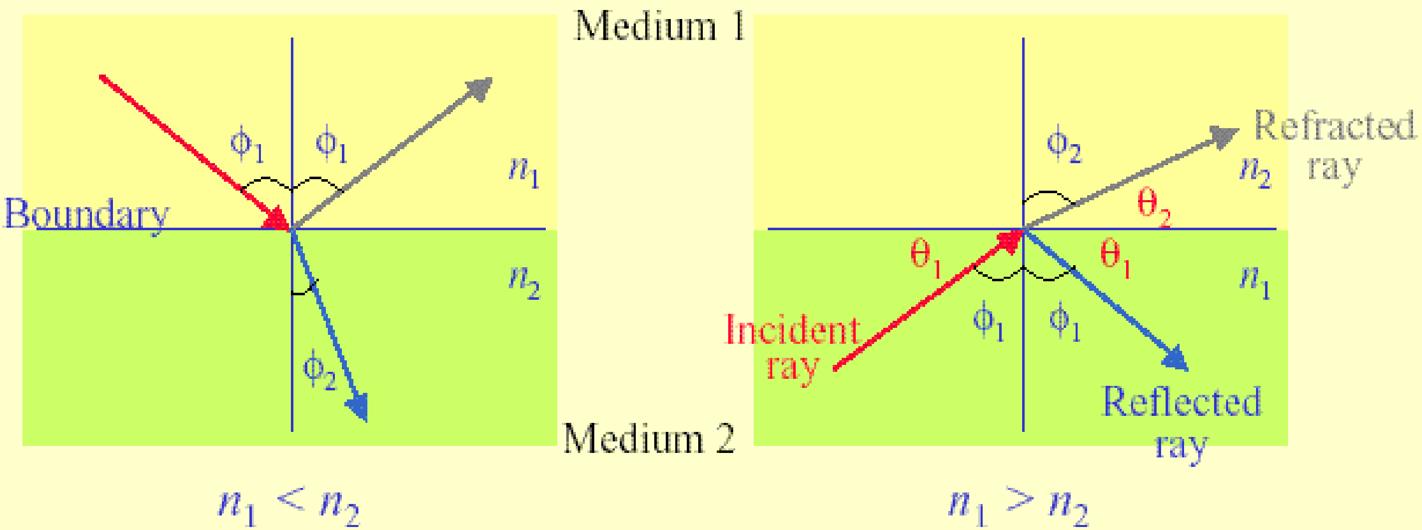
- However, non-monochromatic waves travelling together will have a velocity known as Group Velocity: $v_g = c / n_g$

Where the fibre group index is:

$$n_g = n - \lambda \frac{dn}{d\lambda}$$



Reflection and Refraction of Light



Using the **Snell's law** at the boundary we have:

$$n_1 \sin \phi_1 = n_2 \sin \phi_2$$

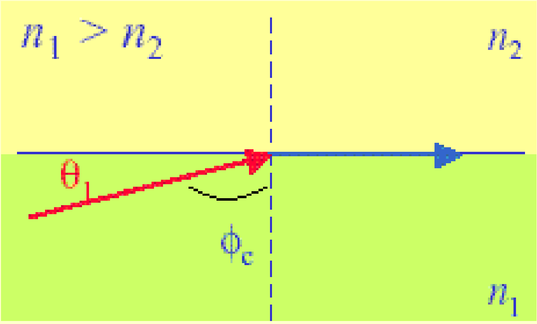
or

$$n_1 \cos \theta_1 = n_2 \cos \theta_2$$

ϕ_1 = The angle of incident

Total Internal Reflection

- As ϕ_1 **increases (or θ_1 decreases) then there is no reflection**
- The incident angle $\phi_1 = \phi_c$ = **Critical Angle**

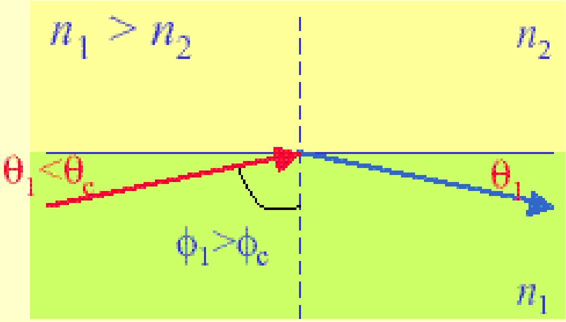


- Beyond the critical angle, light ray becomes **totally internally reflected**

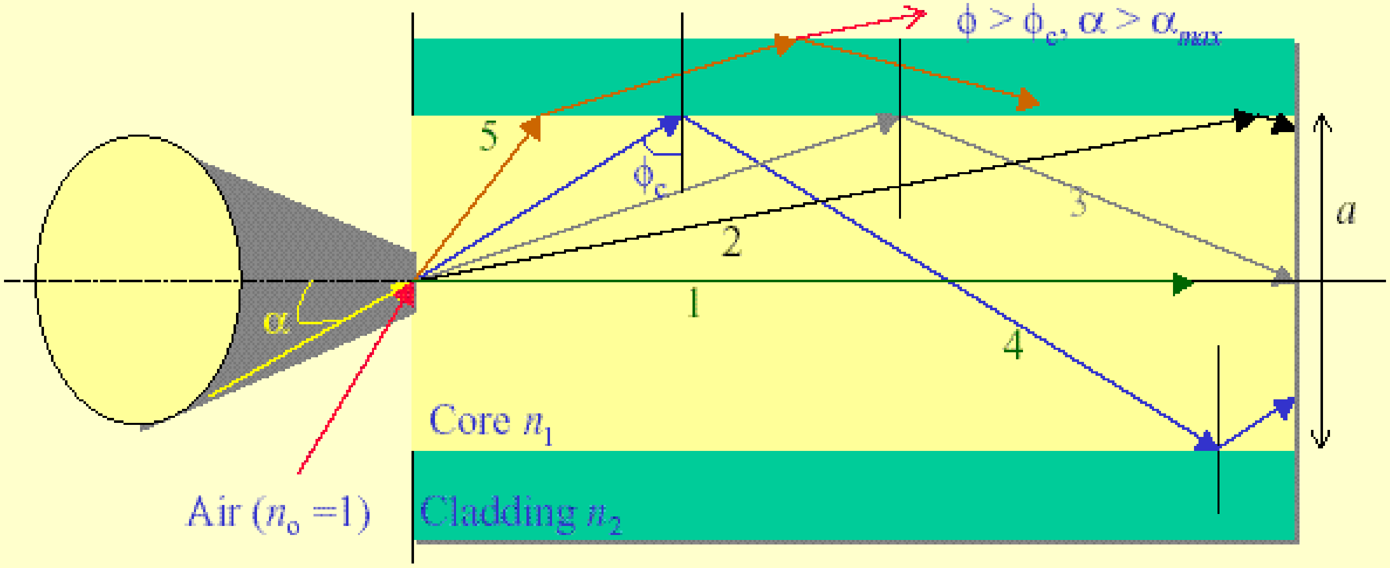
When ϕ_1 **= 90º (or** $\theta_c = 0º$)

$$n_1 \sin \phi_1 = n_2$$

Thus the critical angle $\phi_c = \sin^{-1}\left(\frac{n_2}{n_1}\right)$



Ray Propagation in Fibre - *Bound Rays*



From Snell's Law: $n_0 \sin \alpha = n_1 \sin (90 - \phi)$

$\alpha = \alpha_{max}$ when $\phi = \phi_c$ **Thus,** $n_0 \sin \alpha_{max} = n_1 \sin \phi_c$

Or $$n_0 \sin \alpha_{max} = n_1 (1 - \sin^2 \phi_c)^{0.5}$$

Since $$\phi_c = \sin^{-1}\left(\frac{n_2}{n_1}\right)$$

Then $$n_0 \sin \alpha_{\max} = n_1\left[1-\left(\frac{n_2}{n_1}\right)^2\right]^{0.5} = \left[n_1^2 - n_2^2\right]^{0.5}$$

$$\left[n_1^2 - n_2^2\right]^{0.5} = Numerical\ Aperture\,(NA)$$

NA determines the light gathering
capabilities of the fibre

Therefore $n_0 \sin \alpha_{max} = \mathrm{NA}$

Fibre acceptance angle $\alpha_{\max} = \sin^{-1}\left(\frac{NA}{n_0}\right)$

Note $\frac{n_1 - n_2}{n} = \Delta$ Relative refractive index difference

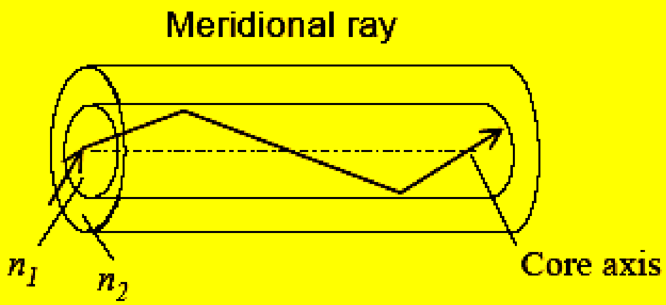
Thus $NA = n_1(2\Delta)^{0.5}$ $0.14 < \mathrm{NA} < 1$

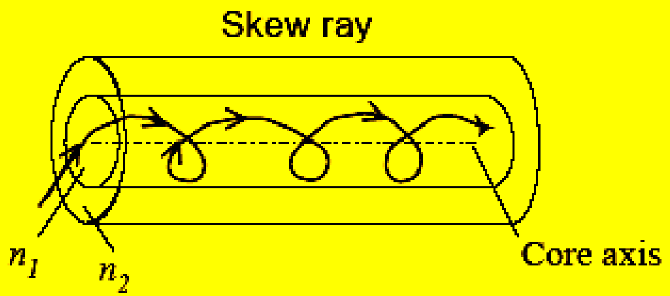
Ray Transmission in Fibers

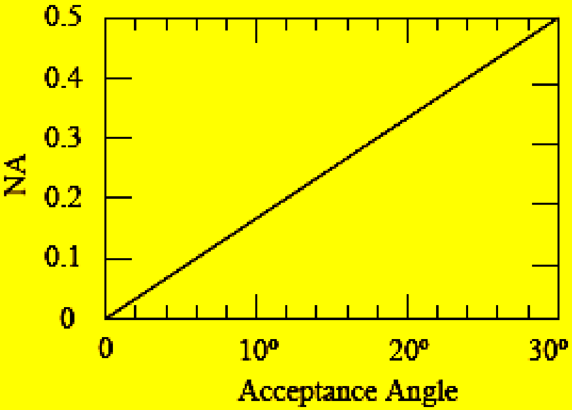
- Meridional rays: pass through the core axis ⇒ TE and TM modes
- Skew rays: follow a helical path through the fiber ⇒ hybrid modes (EH and HE)
- Acceptance angle:

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

Fiber	Δ	NA	θ_a
All-glass	0.0135	0.24	13.9°
PCS	0.041	0.41	24.2°
All-plastic	0.054	0.48	29°



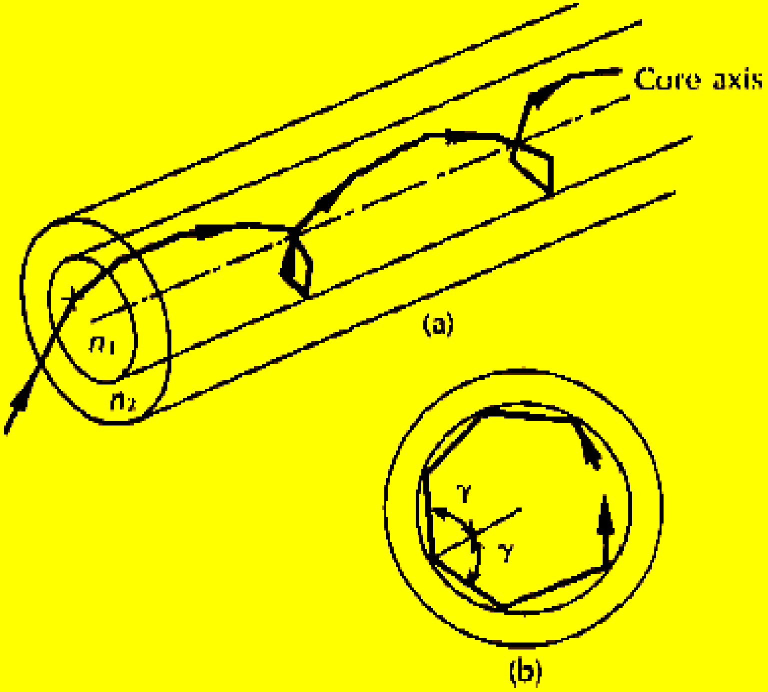




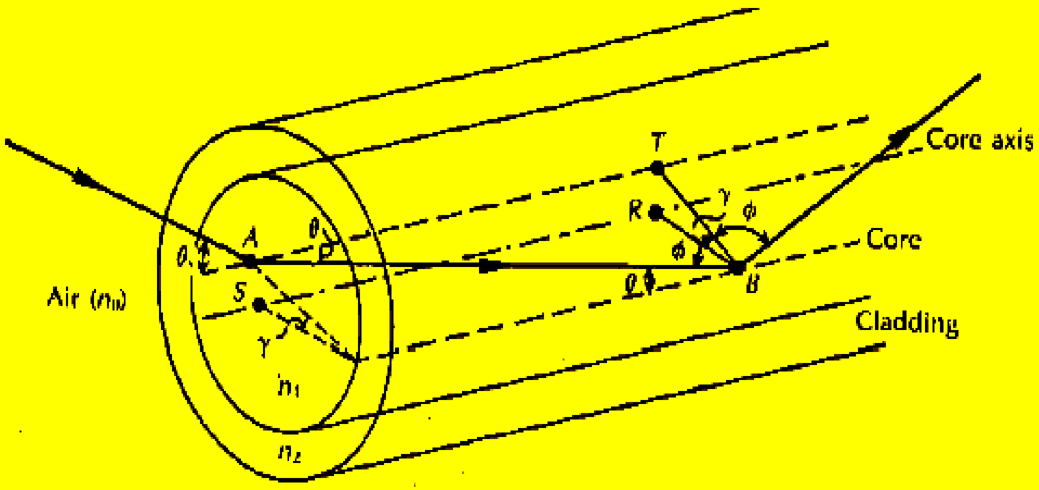
Skew Rays in Fiber

- Meridional rays are not the only type of ray which propagate in a fibre.
- Skew rays do not pass through the fibre centre axis.
- Skew rays greatly outnumber meridional rays.
- Skew rays follow a helical path within the fibre.

- Skew ray propagation is difficult to visualise, but looking at the fibre end on we see a 2d projection of the rays. Seen in this way reflection takes place with an angle γ to the radius
- With meridional rays at the fibre output the angle depends on the input angle. For skew rays this is not so, instead the output angle depends on the number of reflections undergone. Thus skew rays tend to make the light output from a fibre more uniform.



Acceptance angle for Skew Rays



- Analysis for skew rays is much more involved.
- Ray direction defined in two planes as shown.

Acceptance angle for skew rays $= \text{Sin}^{-1}\left[\dfrac{\sqrt{(n_1^{\,2} - n_2^{\,2})}}{\text{Cos}\ \gamma}\right]$

- γ is the angle of reflection for skew rays within the fibre, defined previously
- Since cos γ is < 1, acceptance angle is higher for skew rays.

Skew Ray Propagation

An optical fibre in air has an NA of 0.4. Compare the acceptance angle for meridional rays with that for skew rays, which change direction by 100 degrees at each reflection.

<u>**Solution**</u>

Acceptance angle for meridional rays = 23.6 degrees

Skew rays change direction by 100 degrees so γ is 50 degrees

Using the formula for the acceptance angle for skew rays gives:

Skew ray acceptance angle = 38.5 degrees

Notice that the acceptance angle for skew rays is higher than that for meridional rays

Modes in Fibre

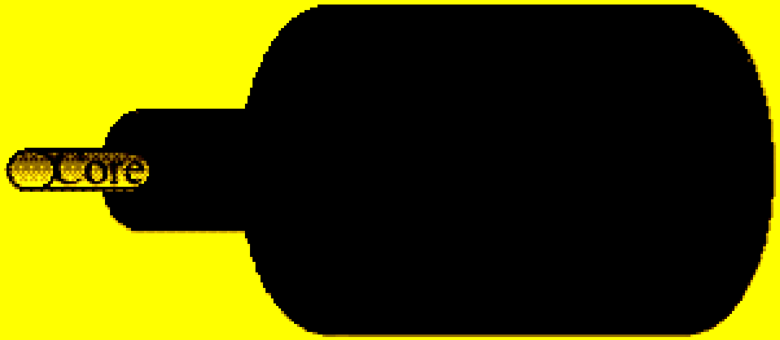
- A fiber can support:
  - many modes (multi-mode fibre).
  - a single mode (single mode fiber).
- The number of modes (V) supported in a fiber is determined by the indices, operating wavelength and the diameter of the core, given as.

$$V = \frac{2\pi}{\lambda} a \sqrt{n_c^2 - n_{cl}^2} \quad \text{or} \quad V = \frac{2\pi a}{\lambda} NA$$

- V<2.405 corresponds to a single mode fiber.
- By reducing the radius of the fiber, V goes down, and it becomes impossible to reach a point when only a single mode can be supported.

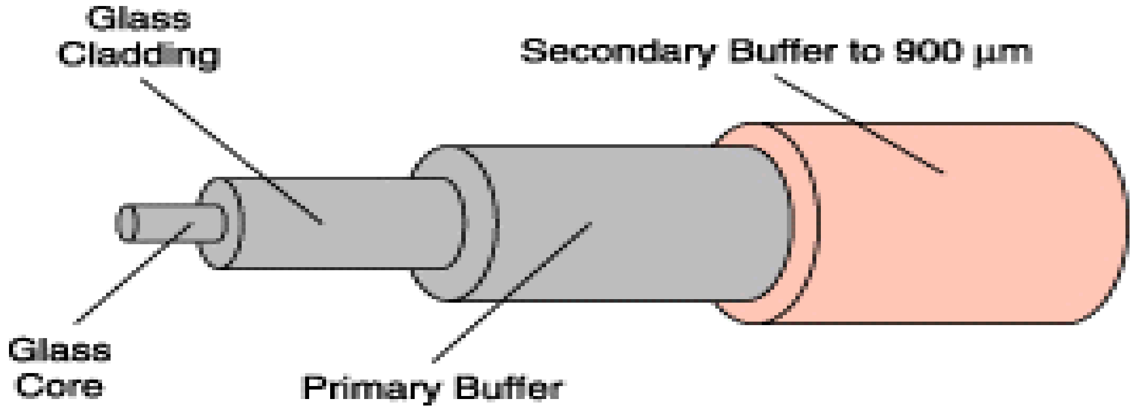
Basic Fibre Properties

- Cylindrical
- Dielectric
- Waveguide
- Low loss
- Usually fused silica
- Core refractive index > cladding refractive index
- Operation is based on total internal reflection



Fiber Structure

- A Core Carries most of the light, surrounded by
- A Cladding, Which bends the light and confines it to the core, covered by
- A primary buffer coating which provides mechanical protection, covered by
- A secondary buffer coating, which protects primary coating and the underlying fiber.



Some Refractive Indices

Medium	Air	Water	Glass	Diamon d
Refracti ve Index	1.003	1.33	1.52- 1.89	2.42

Types of Fibre

There are two main fibre types:

(1) Step index:
- **Multi-mode**
- **Single mode**

(2) Graded index multi-mode

Total number of guided modes M for multi-mode fibres:

Multi-mode SI $M = 0.5V^2$ Multi-mode GI $M \approx 0.25V^2$

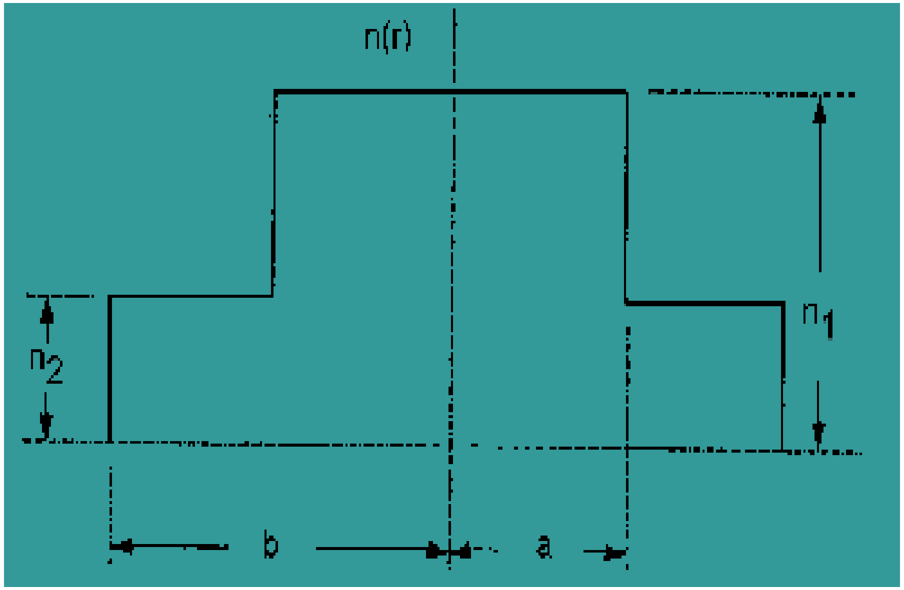
Multimode Step- Index Fibers

- As their name implies, multimode fibers propagate more than one mode. Multimode fibers can propagate over 100 modes. The number of modes propagated depends on the core size and numerical aperture (NA).
- As the core size and NA increases , the number of modes increases . Typical values of fiber core size and NA are 50 to 100 micrometer and 0.20 to 0.29, respectively.

A multimode step-index fiber has a core of radius (a) and a constant refractive index n_1. A cladding of slightly lower refractive index n_2 surrounds the core. Notice the step decrease in the value of refractive index at the core-cladding interface

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

$$NA \simeq n_1\sqrt{2\Delta}.$$



Dependence of Modes

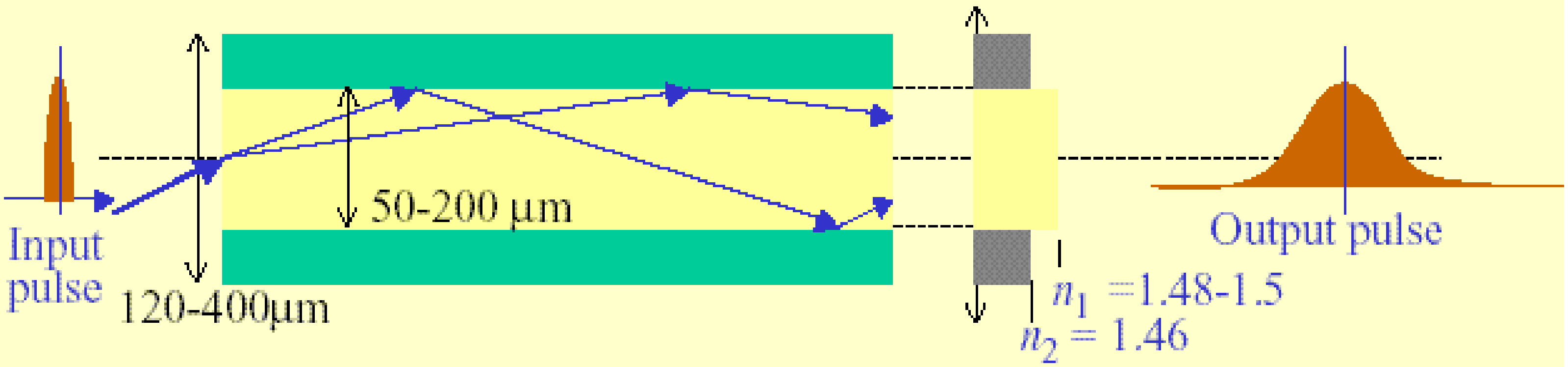
- The number of modes that multimode step-index fibers propagate depends on Delta and core radius (a) of the fiber.
The number of propagating modes also depend on the wavelength (λ) of the transmitted light.
In a typical multimode step-index fiber, there are hundreds of propagating modes.
Most modes in multimode step-index fibers propagate far from cutoff.

- Modes that are cut off cease to be bound to the core of the fiber. Modes that are farther away from the cutoff wavelength concentrate most of their light energy into the fiber core. Modes that propagate close to cutoff have a greater percentage of their light energy propagate in the cladding. Since most modes propagate far from cutoff, the majority of light propagates in the fiber core.
Therefore, in multimode step-index fibers, cladding properties, such as cladding diameter, have limited affect on mode (light) propagation.

Unfortunately, multimode step-index fibers have limited bandwidth capabilities.

Dispersion, mainly modal dispersion, limits the bandwidth or information-carrying capacity of the fiber. System designers consider each factor when selecting an appropriate fiber for each particular application.

Multimode step-index fiber selection depends on system application and design. Short-haul, limited bandwidth, low-cost applications typically use multimode step-index fibers.



Advantages:

- Allows the use of non-coherent optical light source, e.g. LED's
- Facilitates connecting together similar fibres
- Imposes lower tolerance requirements on fibre connectors.
- Cost effective

Disadvantages:

- Suffer from dispersion (i.e. low bandwidth (a few MHz)
- High power loss

- In a multimode step index fibre, a finite number of guided modes propagate. Number of modes is dependent on:
  - Wavelength λ, Core refractive index n_1
  - Relative refractive index difference Δ, Core radius a

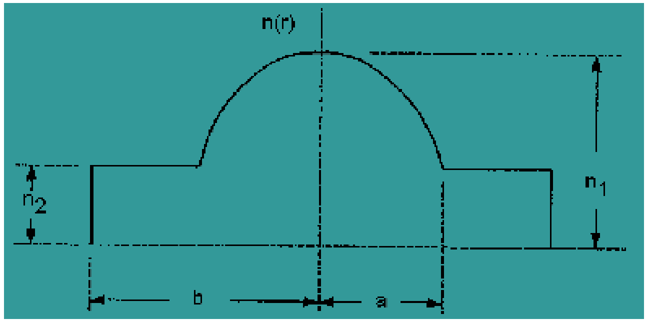
- Number of propagating modes (M) is normally expressed in terms of the normalised frequency V for the fibre:

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

Multi Mode Graded – Index Fibers

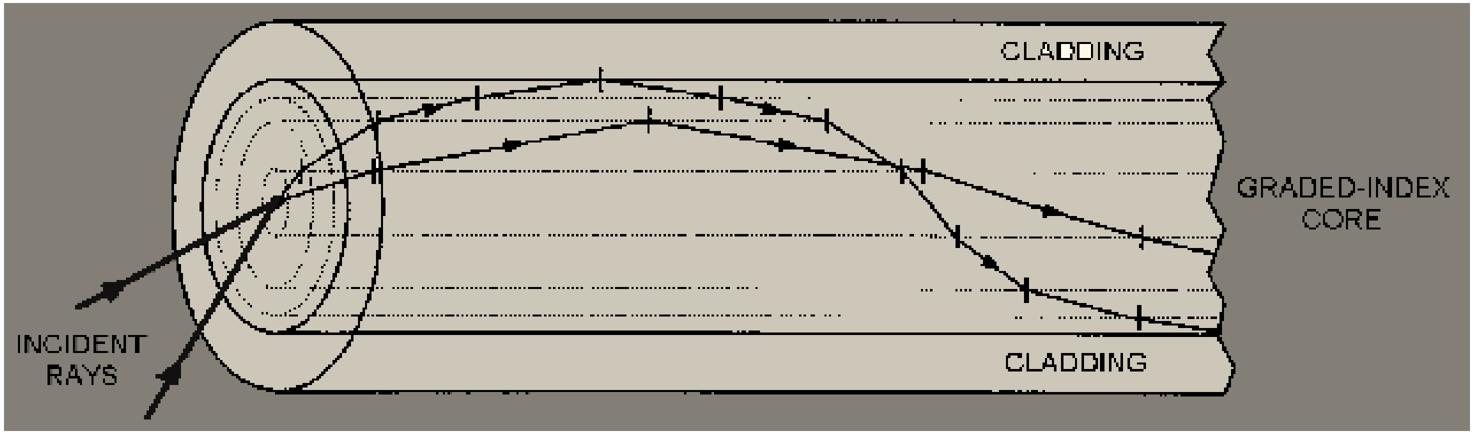
A multimode graded-index fiber has a core of radius (a). Unlike step-index fibers, the value of the refractive index of the core (n_1) varies according to the radial distance (r). The value of n_1 decreases as the distance (r) from the center of the fiber increases.

The value of n_1 decreases until it approaches the value of the refractive index of the cladding (n_2). The value of n_1 must be higher than the value of n_2 to allow for proper mode propagation. Like the step-index fiber, the value of n_2 is constant and has a slightly lower value than the maximum value of n_1. The relative refractive index difference (Delta;) is determined using the maximum value of n_1 and the value of n_2.



The NA of a multimode graded-index fiber is at its maximum value at the fiber axis. This NA is the axial numerical aperture [NA(0)]. NA(0) is approximately equal to

$$n_1\sqrt{2\Delta}\,.$$



- The gradual decrease in the core's refractive index from the center of the fiber causes propagating modes to be refracted many times.

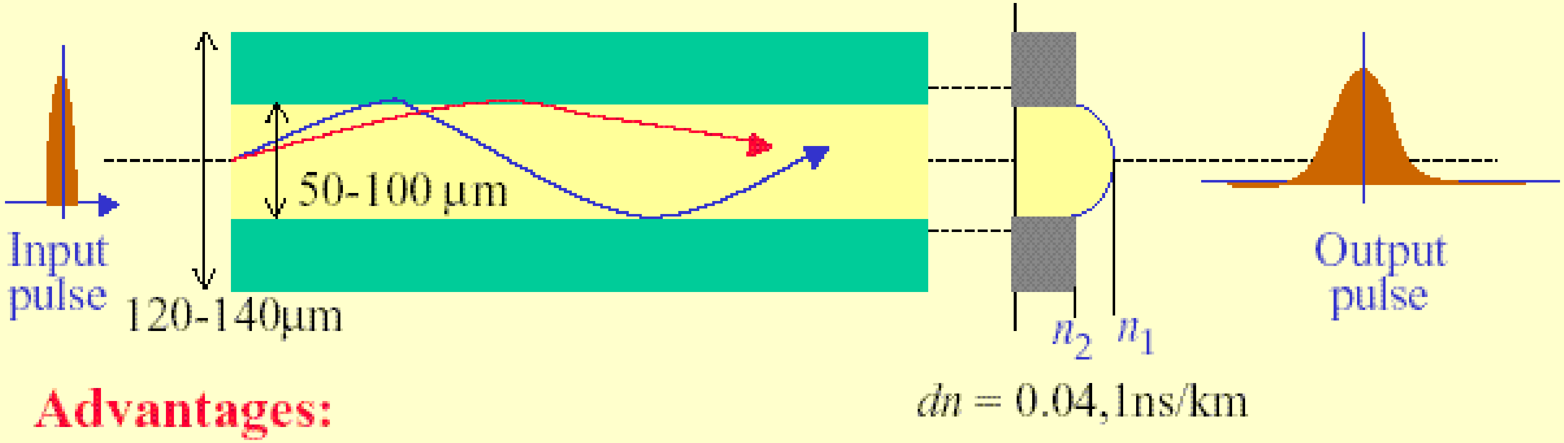
- Multimode graded-index fibers have less MODAL DISPERSION than multimode step-index fibers. Lower modal dispersion means that multimode graded-index fibers have higher bandwidth capabilities than multimode step-index fibers.

- SOURCE-TO-FIBER COUPLING EFFICIENCY and INSENSITIVITY TO MICROBENDING AND MACROBENDING LOSSES are distinguishing characteristics of multimode graded-index fibers. 62.5 micrometer fibers offer the best overall performance for multimode graded-index fibers.

- Coupled power increases with both core diameter and Delta while bending losses increase directly with core diameter and inversely with Delta. However, a smaller Delta improves fiber bandwidth.

In most applications, a multimode graded index fiber with a core and cladding size of 62.5/125 micrometer offers the best combination of the following properties:

- Relatively high source-to-fiber coupling efficiency
- Low loss
- Low sensitivity to microbending and macrobending
- High bandwidth
- Expansion capability



Advantages:

- Allows the use of non-coherent optical light source, e.g. LED's
- Facilitates connecting together similar fibres
- Imposes lower tolerance requirements on fibre connectors.
- Reduced dispersion compared with STMMF

Disadvantages:

- Lower bandwidth compared with STSMF
- High power loss compared with the STSMF

Calculating the number of modes in a graded index fibre is very involved

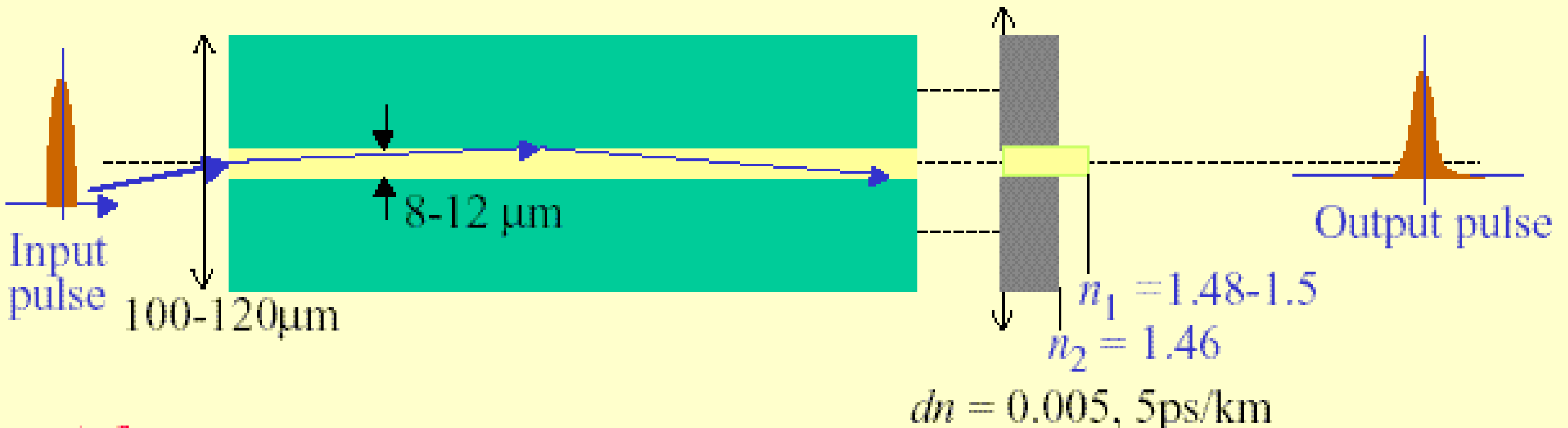
As an approximation it can be shown that the number of modes is dependent on the normalised frequency V and on the profile parameter α.

That is $$M = \left(\frac{\alpha}{\alpha + 2}\right)\frac{V^2}{2}$$

where Δ, is again given by: $$\Delta = \frac{n_1 - n_2}{n_1}$$ if Δ is << 1

Single Mode Fibers

- The core size of single mode fibers is small. The core size (diameter) is typically around 8 to 10 micrometers.
- A fiber core of this size allows only the fundamental or lowest order mode to propagate around a 1300 nanometer (nm) wavelength.
- Single mode fibers propagate only one mode, because the core size approaches the operational wavelength.
- The value of the normalized frequency parameter (V) relates core size with mode propagation.



Advantages:

- Only one mode is allowed due to diffraction/interference effects.
- Allows the use high power laser source
- Facilitates fusion splicing similar fibres
- **Low dispersion, therefore high bandwidth (a few GHz).**
- Low loss (0.1 dB/km)

Disadvantages:

- Cost

- In single mode fibers, V is less than or equal to 2.405. When V = 2.405, single mode fibers propagate the fundamental mode down the fiber core, while high-order modes are lost in the cladding.
- For low V values (<1.0), most of the power is propagated in the cladding material. Power transmitted by the cladding is easily lost at fiber bends. The value of V should remain near the 2.405 level.

Lecture 4
Physics of Optical Elements
Detectors

Optical Fiber Communication System

By Prof. Dr. Zainab Naser Jameel
Communication Engineering Department
Second Class Optical & Wireless Division
University of Technology-Iraq

6/April/2022

Photodetection

It converts the optical energy into an electrical current that is then processed by electronics to recover the information .

Photodiode :

An electronic device , whose vi-characteristics is sensitive to the intensity of an incident light wave.

All detectors for optical communications use optical absorption in a depletion region to convert photons into electron-hole pairs , and then sense the number of pairs .

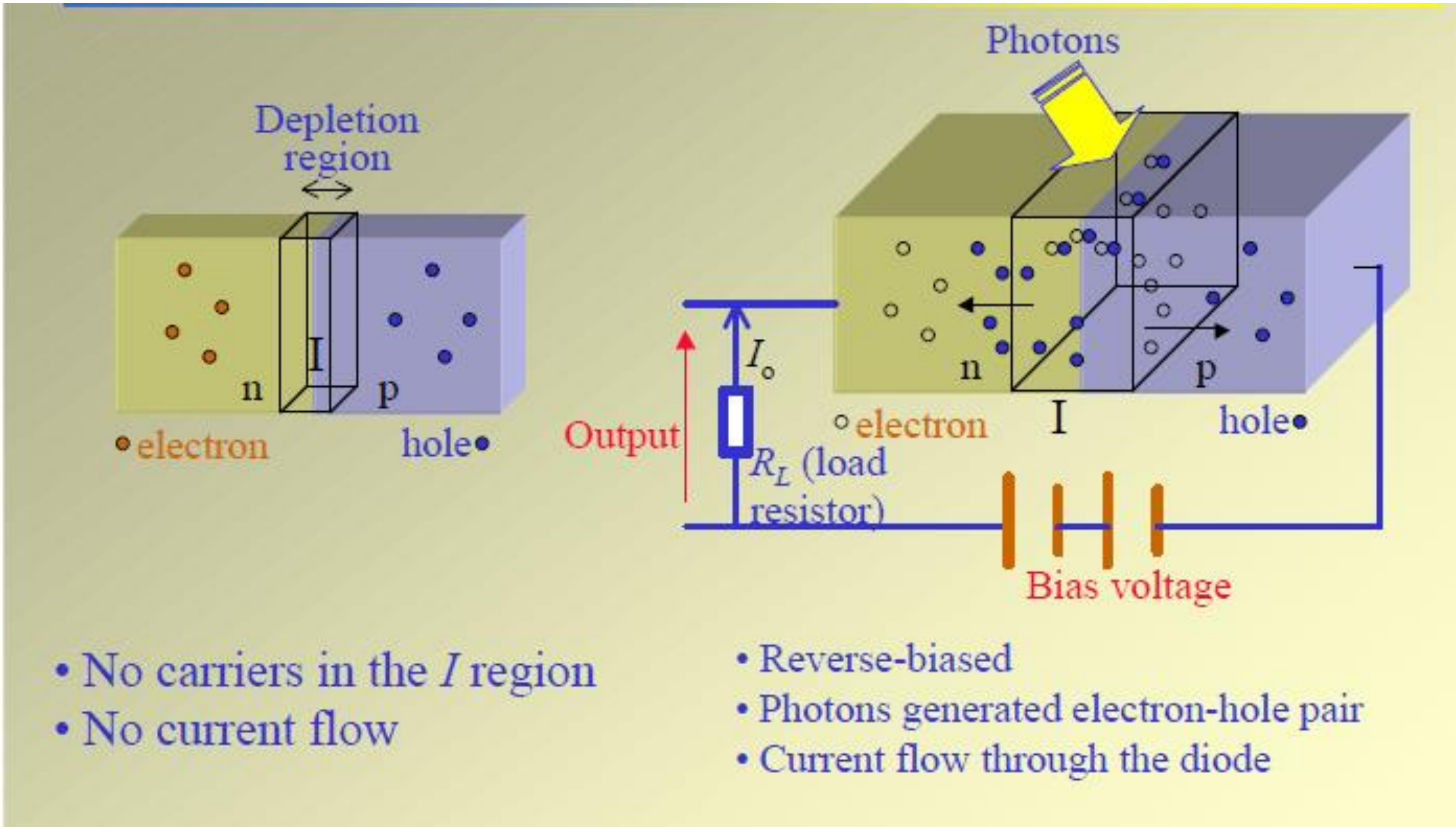
Because of the electric field in the depletion region, the electron-hole pairs give rise to a photocurrent , I_{ph} .

p-n Photodiode

- p-n junction has a space charge region at the interface of the two material types .
- This region is depleted of most carriers .
- A photon generates an electron-hole pair in this region that moves rapidly at the drift velocity by the electric field .
- Electron-hole pairs are created in the depletion region of a p-n junction in proportion to the optical power .
- Electrons and holes are swept out by the electric field , leading to a current .

- An electron-hole pair generated outside the depletion region move by diffusion at a much slower rate .
- Junction is typically reversed biased to increase the width of the depletion region .

p-n Photodiode Structure



Detector Responsivity

- Each absorbed photon generates an electron hole pair .

Photocurrent :

I_{ph} = (Number of absorbed photons) * (charge of electron)

Rate of incident photons depends on incident optical power P_{inc}

- Energy of the photon : $E_{ph} = hf$
- Generated current :

$$I_{ph} = \eta P_{inc} \frac{q}{h f}$$

where η is the quantum efficiency ,

η = average number of electron-hole pairs emitted r_e / average number of incident photons r_{ph} , and

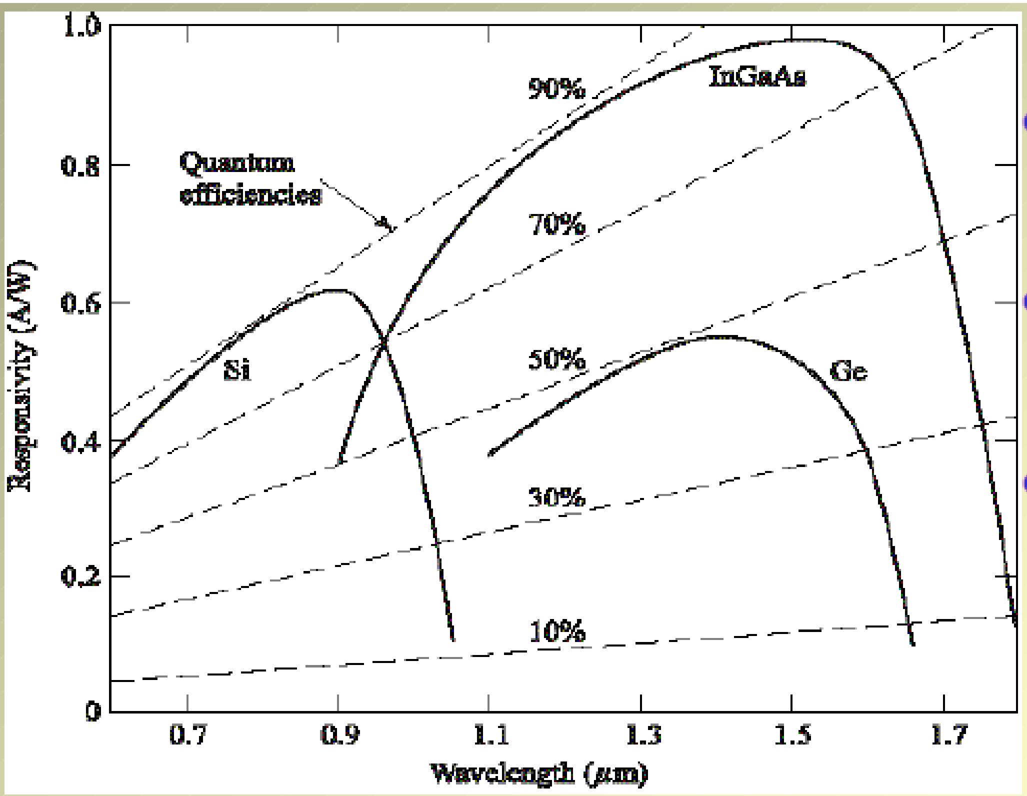
q = charge generated per photon .

Responsivity : It is defined as the ratio of the photocurrent I_{ph} to the incident (detected) optical power , P_{inc} :

$$R = \frac{I_{ph}}{P_{inc}} = \frac{\eta q}{hf} \qquad [A/W]$$

Responsivity depends on quantum efficiency η, and photon energy :

$$R = \eta \frac{q}{hf} = \eta \frac{\lambda}{1.24}$$



- Silicon (Si)
  - Least expensive
- Germanium (Ge)
  - "Classic" detector
- Indium gallium arsenide (InGaAs)
  - Highest speed

G Keiser , 2000

Detector Materials :

Band-gaps and emission wavelengths (at 300◦ K) of semiconductors used as detectors for optical communications :

Material	Bandgap, eV	Wavelength range (nm)	Wavelength of peak response (nm)	Responsivity (max) (A/W)
Si	1.17	300–1100	800	0.5
Ge	0.775	500–1800	1550	0.7
InGaAs	0.75–1.24	1000–1700	1700	1.1

Photodetector – Types

The most commonly used photodetectors in optical communications are:

- Positive – Intrinsic - Negative (PIN) .
- Avalanche Photo-Detector (APD) .

Semiconductor Positive – Intrinsic - Negative (PIN)

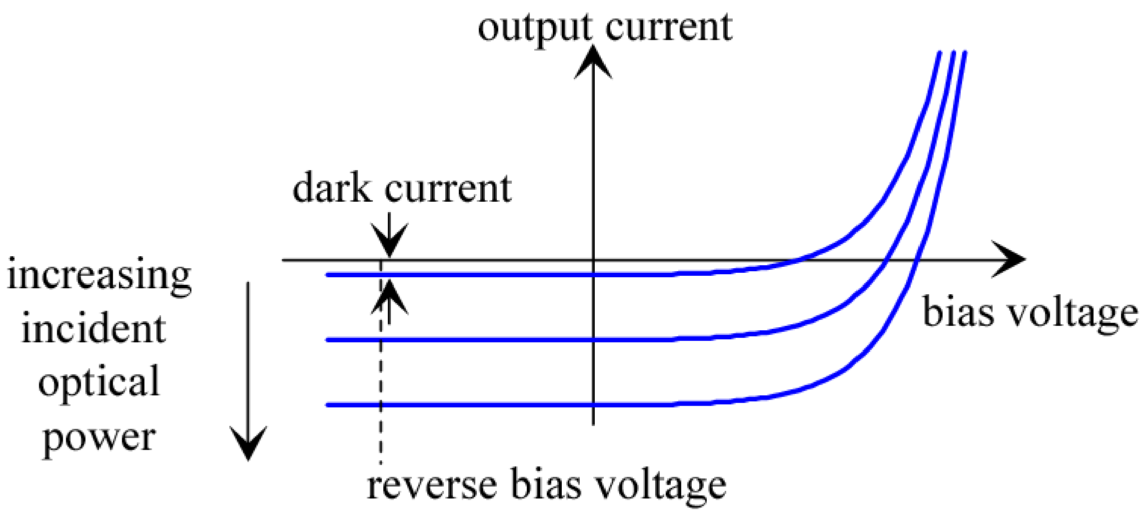
- Intrinsic layer is introduced
  - Increase the space charge region .
  - Minimize the diffusion current .

- Electric field is concentrated in a thin intrinsic (I) layer .
- No internal gain
- Low bias voltage
  [10-50 V @ λ = 850 nm, 5-15 V @ λ = 1300 –1550 nm].
- Highly linear .
- Low dark current .
- Most widely used .

I-V Characteristic of Reversed Biased pin

Photocurrent increases with incident optical power .

Dark current I_d: current with no incident optical power .



Avalanche Photo-Detector (APD)

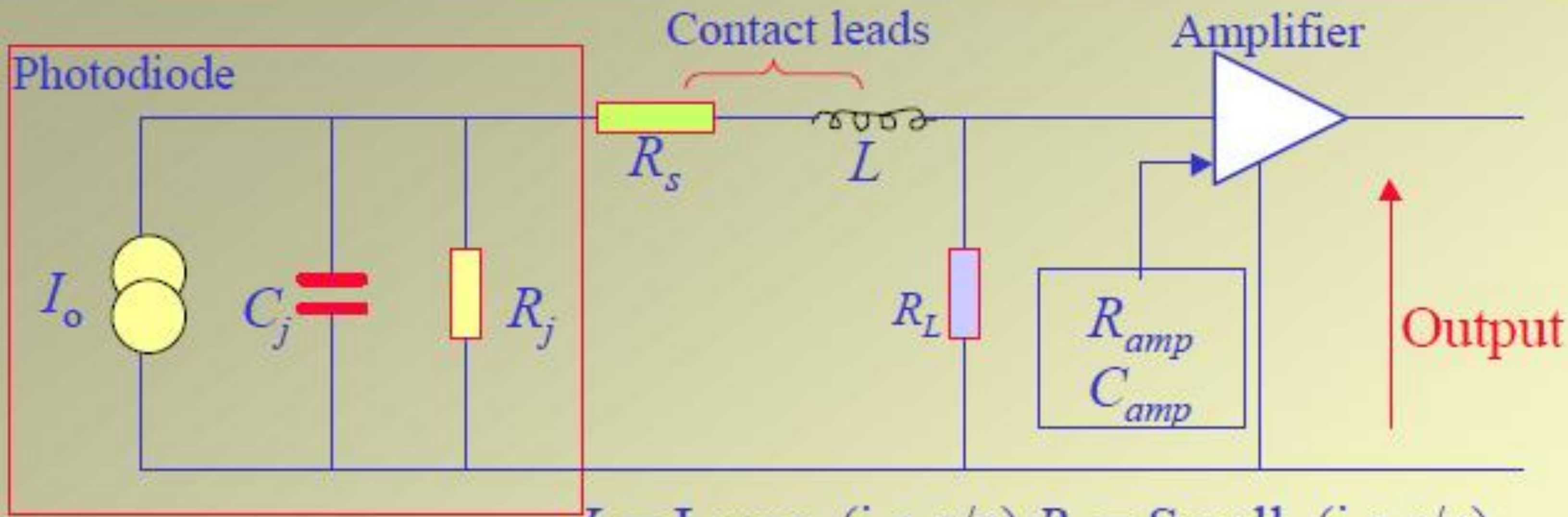
- Like p-i-n photodiodes, but have an additional layer in which an average of secondary electron-hole pairs are generated through impact ionization for each primary pair .
- Internal gain (increased sensitivity) .

$$R_{APD} = GR = G\frac{I_{ph}}{P_{inc}} = G\frac{\eta q}{hf}$$

where , G = APD gain .

- Best for high speed and highly sensitive receivers .
- Strong temperature dependence .
- High bias voltage[250 V @ λ = 850 nm, 20-30 V @λ= 1300 –1550 nm] .
- Costly .

Photodiode - Equivalent Circuit



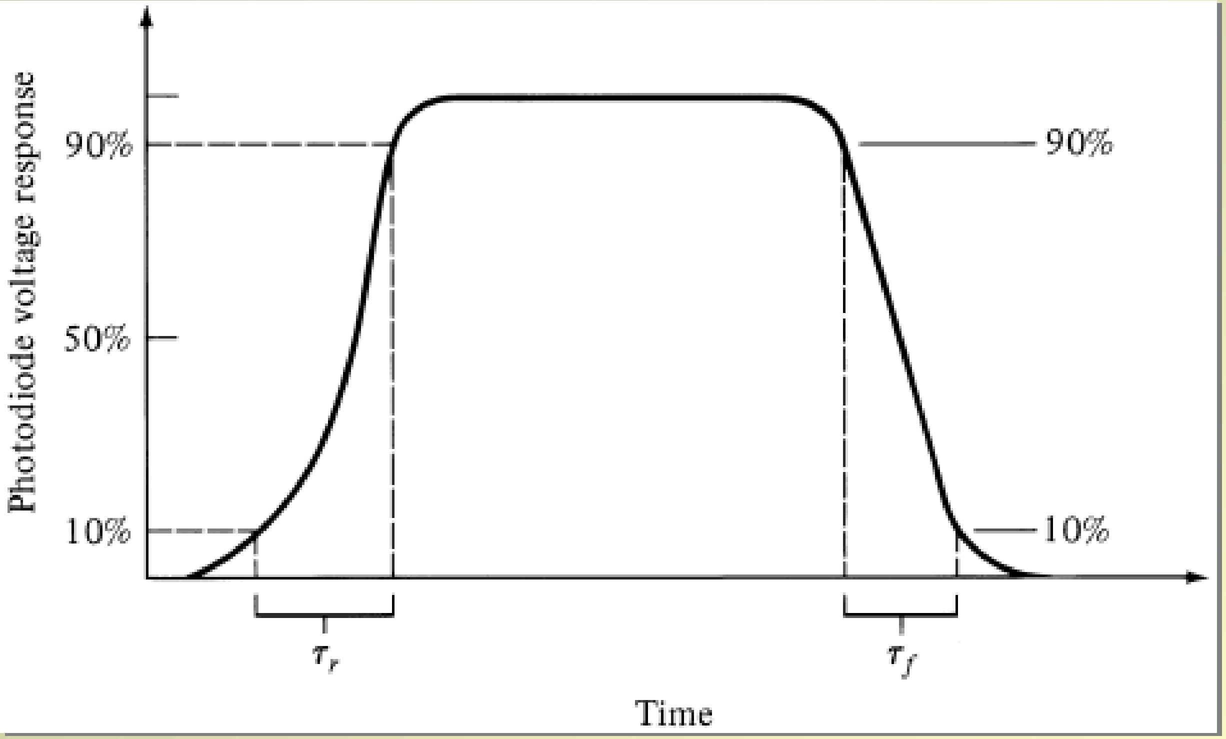
L = Large, (i.e o/c) R_s = Small, (i.e s/c)

$$C_T = C_j + C_{amp} \qquad R_T = R_j \,||\, R_L \,||\, R_{amp}$$

The detector behaves approximately like a first order RC low-pas filter with a bandwidth of:

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

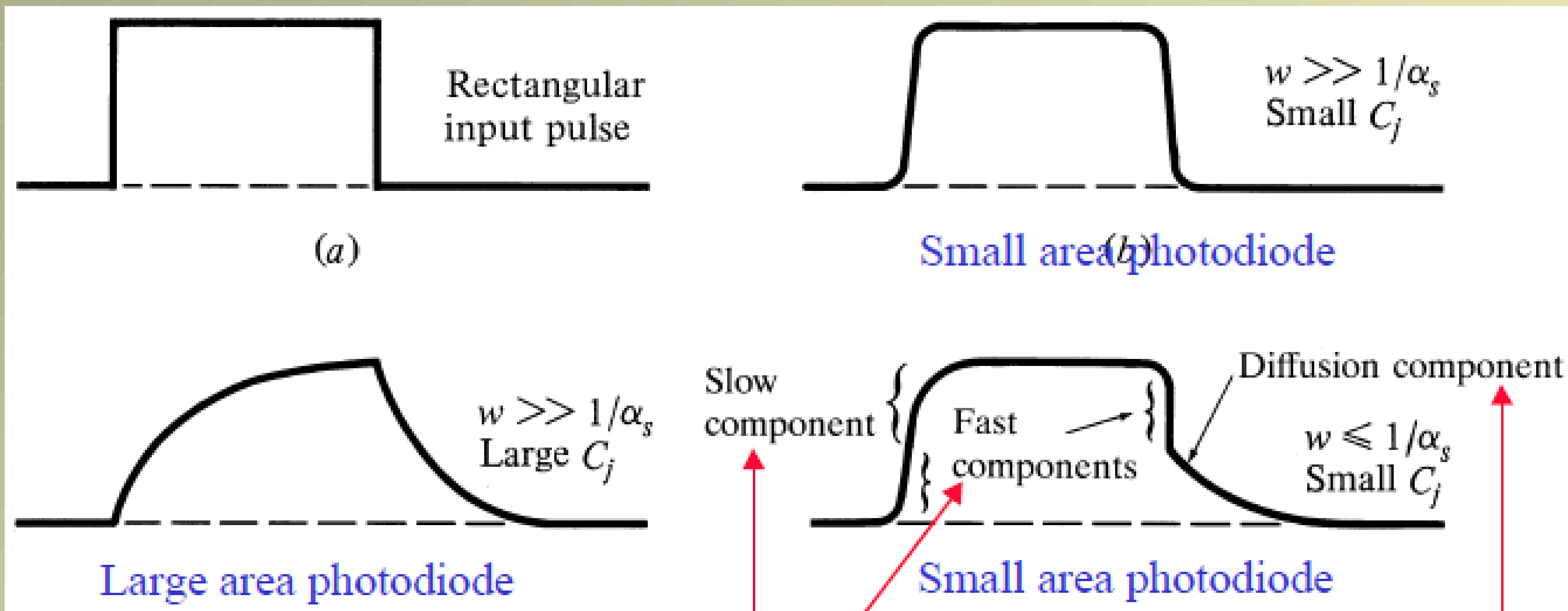
Photodiode Pulse Responses



- At low bias levels rise and fall times are different. Since photo collection time becomes significant contributor to the rise time.

G Keiser , 2000

Photodiode Pulse Responses



w = depletion layer

α_s = absorption coefficient

Due to carrier generated in w

Due to diffusion of carrier from the edge of w

G Keiser , 2000

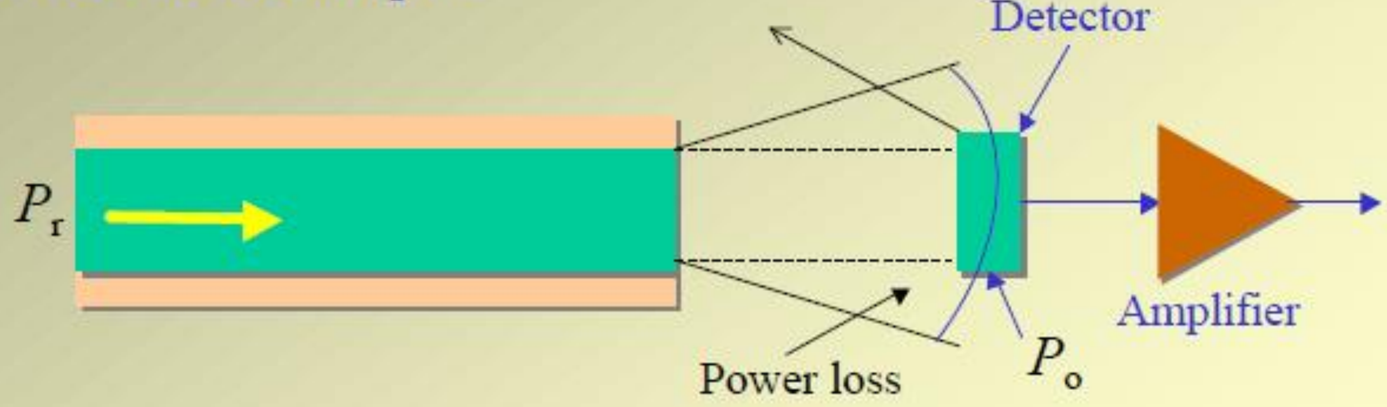
Photodiodes – Typical Characteristics

Parameters	Si PIN	Si APD	Ge PIN	Ge APD	InGaAS PIN	InGaAS APD
Wavelength range Peak (nm)	400-1100		800-1800		900-1700	
	900	830	1550	1300	1300 (1550)	1300 (1550)
Responsivity (A/W)	0.35-0.55	50-120	0.5-0.65	2.5-25	0.5-0.7	-
Quantum Efficiency (%)	65-90	77	50-55	55-75	60-70	60-70
Bias voltage (-V)	45-100	220	6-10	20-35	5	<30
Dark current (nA)	1-10	0.1-1	50-500	10-500	-	1-5
Rise time (ns)	0.5-1	0.1-2	0.1-0.5	0.5-0.8	0.06-0.5	0.1-0.5
Capacitance (pF)	1.2-3	1.3-2	2-5	2-5	0.5-2	0.1-0.5

Minimum Received Power

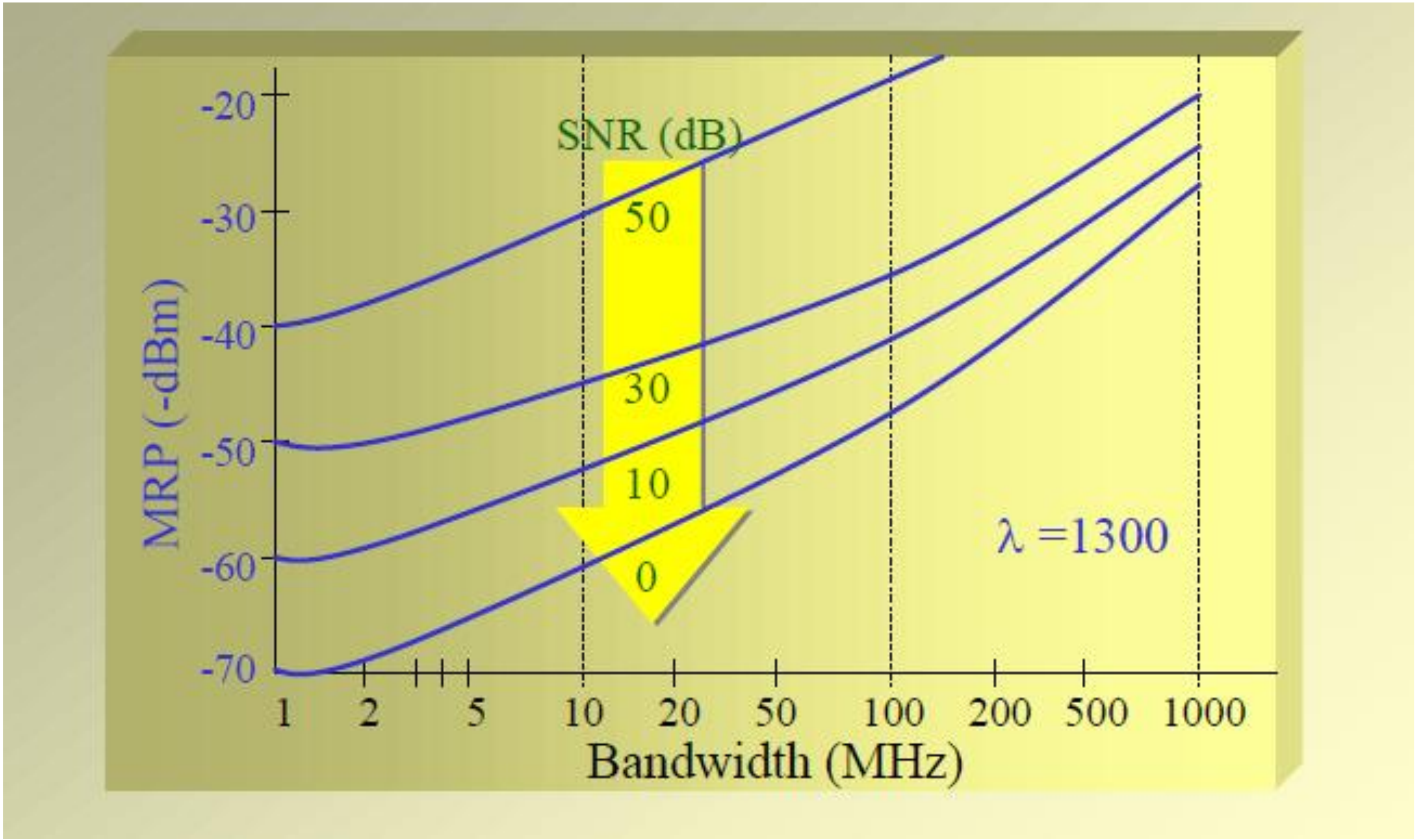
- Is a measure of receiver sensitivity defined for a specific:
  - Signal-to-noise ratio (SNR),
  - Bit error Rate (BER),
  - Bandwidth (bit rate),

at the receiver output.

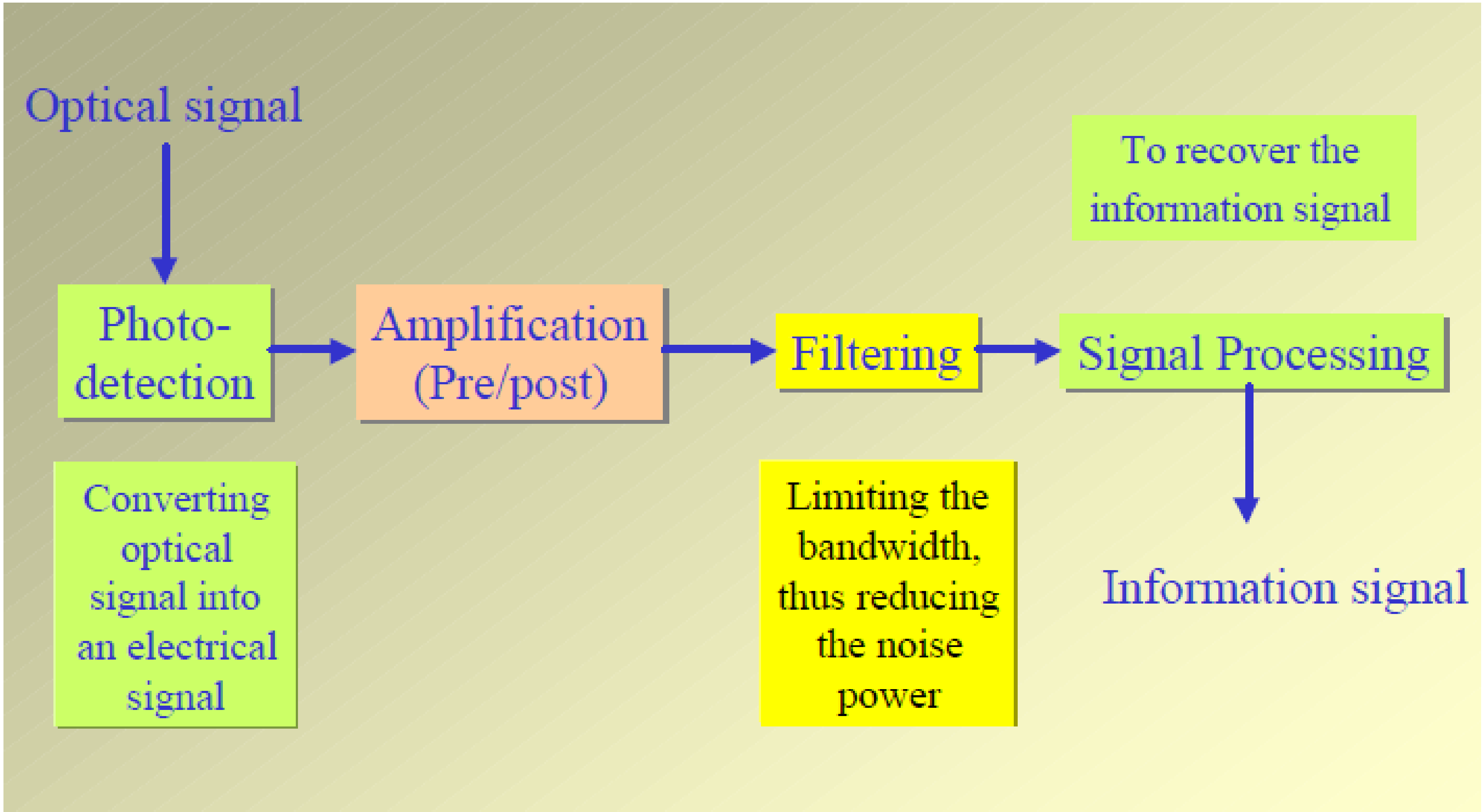


MRP = Minimum Detected Power (MDP) – Coupling Loss

MRP Vs. Bandwidth



Optical Receiver



Selection Criteria and Task Optical

Optical

- Optical Sensitivity for a given BER and SNR
- Operating wavelength
- Dynamic range
- Simplicity
- Reliability and stability

Electrical

- Data rate
- Bit error rate (digital)
- Maximum Bandwidth (analogue)
- Signal-to-noise ratio (analogue)

Task:

- To extract the optical signal (low level) from various noise disturbances
- To reconstruct the original information correctly

Receivers: Basics

- The most important and complex section of an optical fibre system
- It sensitivity is design dependent, particularly the first stage or front-end
- Main source of major noise sources:
  - Shot noise current
  - Thermal noise: Due to biasing/amplifier input impedance
  - Amplifier noise:
    - Current
    - Voltage
  - Transimpedance noise

Receiver - Bandwidth

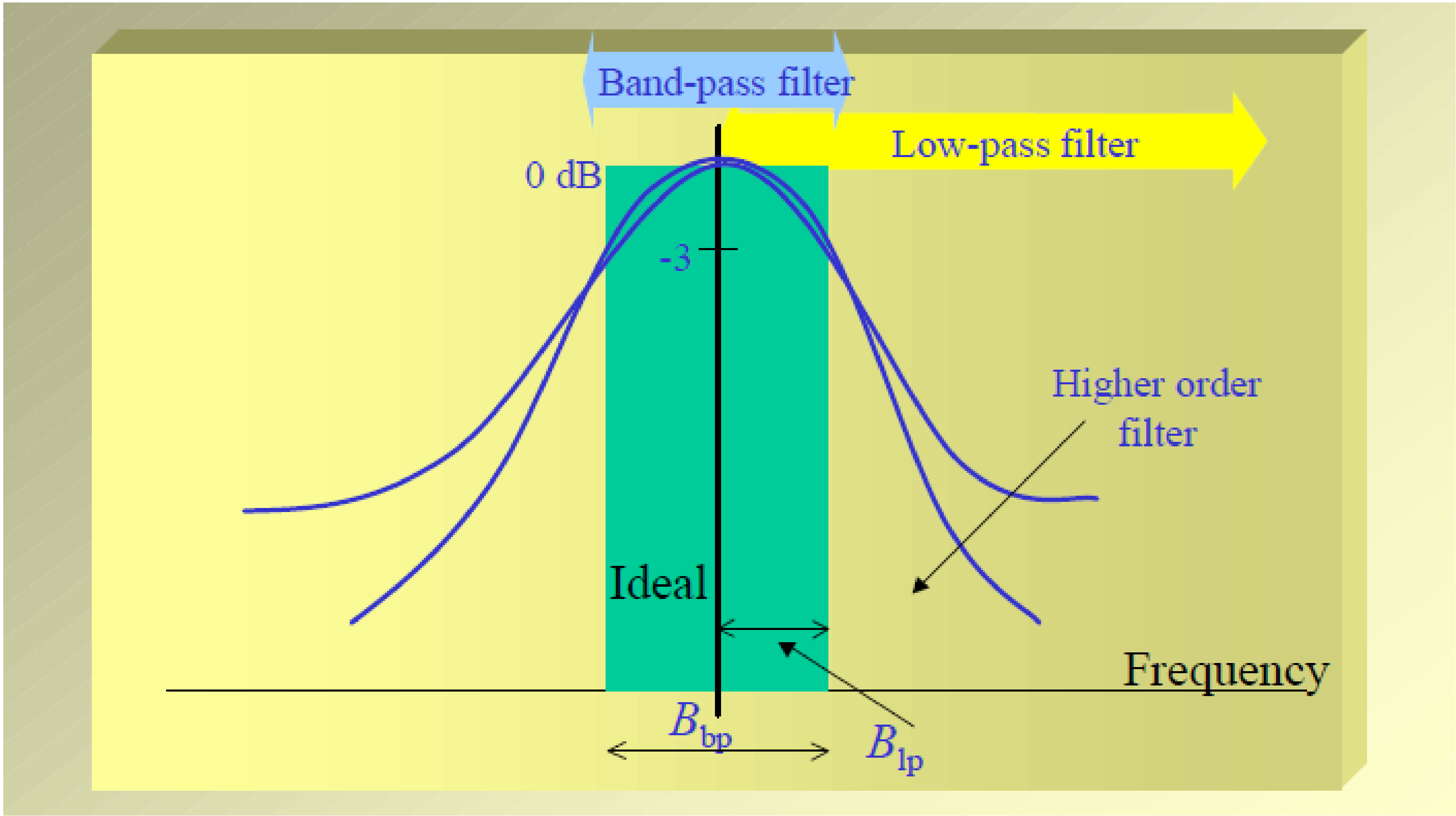
A range of frequencies that can be defined in terms of:

- Spectral profile of a signal
- Response of filter networks
- Equivalent bandwidth: Defines the amount of noise in a system

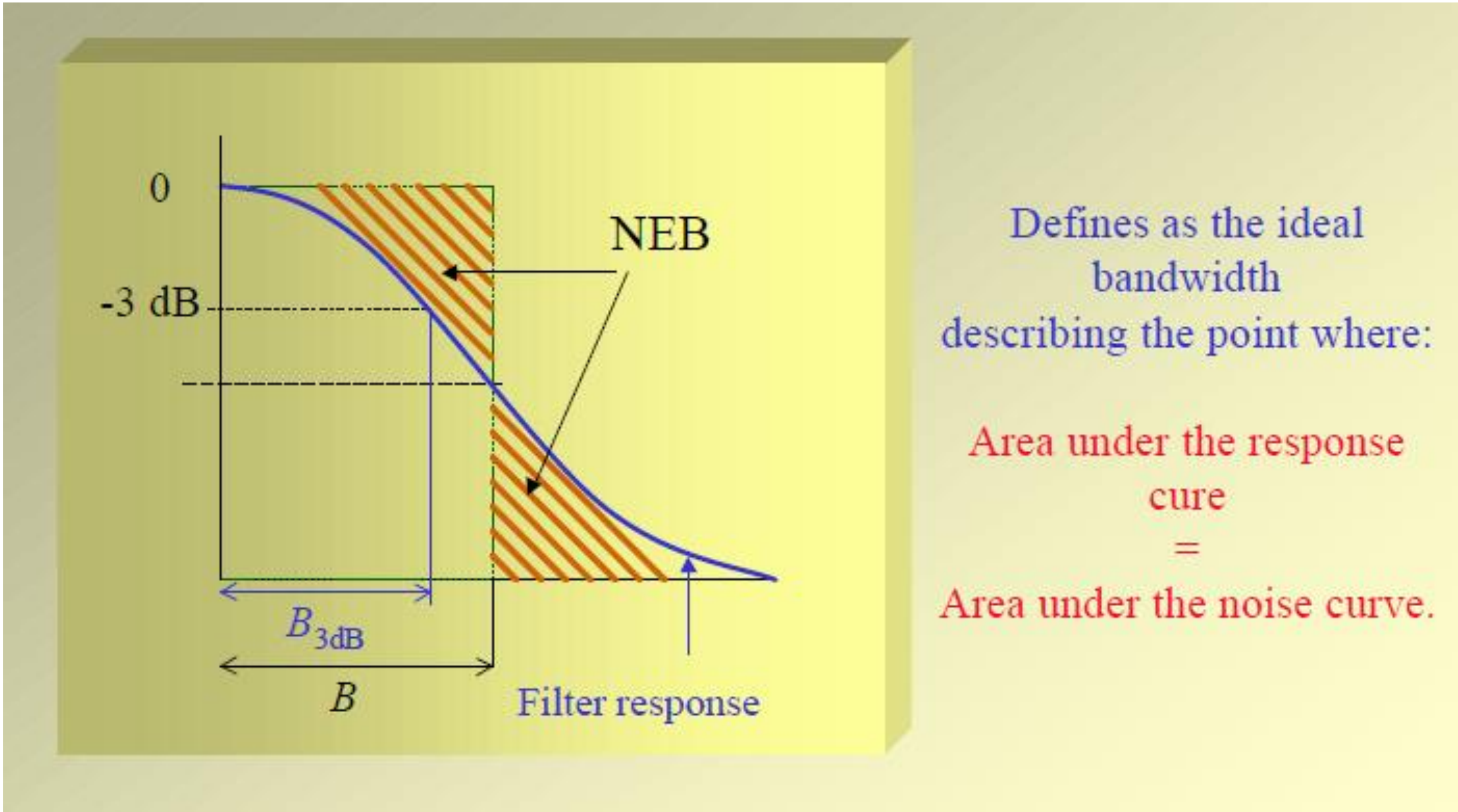
Types of Bandwidth

- Ideal
- Baseband
- Passband
- Intermediate-Channel
- Transmission
- **Noise**

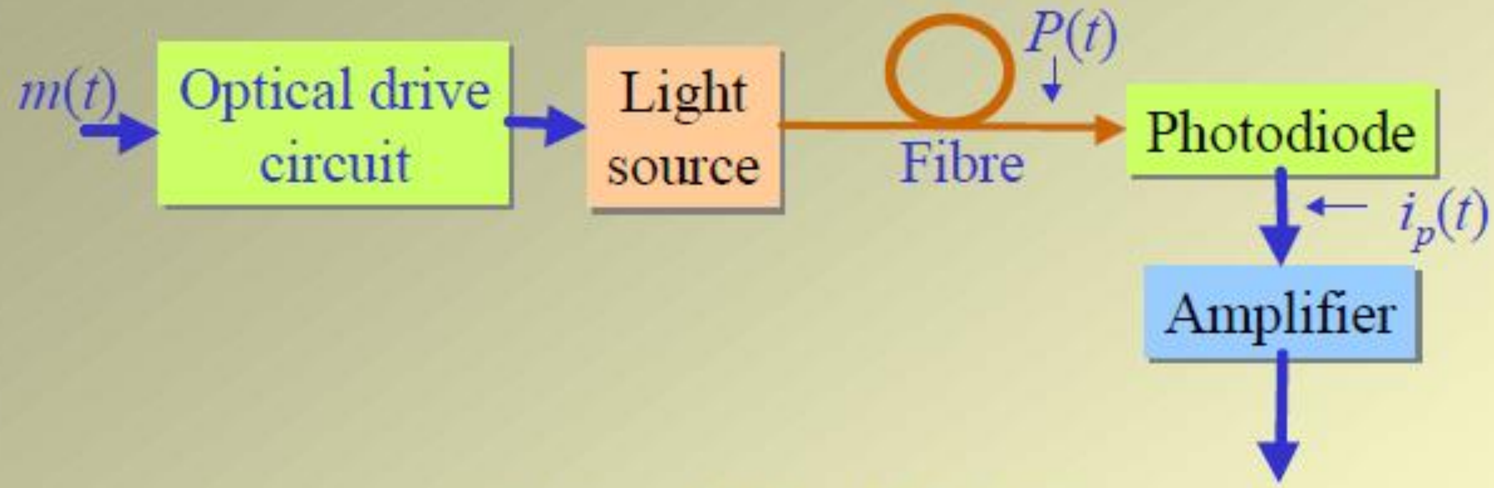
Ideal, Low-pass and Band-pass Filters



Noise Equivalent Bandwidth (NEB) *B*



Optical System



$$P(t) = P_t(1 + Mm(t))$$

Photocurrent $i_p(t) = R \cdot P(t) = R \cdot P_t(1 + Mm(t))$

Photocurrent = Average photocurrent (DC current) I_o + Signal current $i_o(t)$

For $m(t) = \sin \omega t$

The mean square signal current is

$$\overline{i_s^{\,2}} = \overline{i_o^{\,2}(t)} \qquad \textit{for PIN}$$

$$\overline{i_s^{\,2}} = \overline{i_o^{\,2}(t)}\; G^2 \qquad \textit{for APD}$$

Optical System - Noise Sources

- Source Noise
- Modal noise
  - Due to interaction of (constructive & destructive) multiple coherent modes, resulting in intensity modulation.
- Photodetector Noise ✓
- Preamplifier (receiver) Noise ✓
- Distortion due to Non-linearity
- Crosstalk and Reflection in the Couplers

- LED: Due to:
  - In-coherent intensity fluctuation
  - Beat frequencies between modes
- LD: Due to:
  - Non-linearities
  - Quantum noise: In the photon generation
  - Mode hopping: Within the cavity
  - Reflection from the fibre back into the cavity, which reduces coherence
  - Difficult to measure, to isolate and to quantify
  - Most problematic with multimode LD and multimode fibre

Lecture 5
Physics of Optical Elements

Transmission Characteristics of Optical Fibers

By Prof. Dr. Zainab Naser Jameel
Communication Engineering Department
Second Class Optical & Wireless Division
University of Technology-Iraq

13/April/2022

Transmission Characteristics of Optical Fibers

- The transmission characteristics of most interest: **attenuation (*loss*)** and **bandwidth**.

- Now, *silica-based* glass fibers have losses about 0.2 dB/km (i.e. 95% launched power remains after 1 km of fiber transmission). This is essentially the *fundamental lower limit* for attenuation in silica-based glass fibers.

- **Fiber bandwidth** is limited by the *signal dispersion* within the fiber. Bandwidth determines the number of bits of information transmitted in a given time period. Now, fiber bandwidth has reached many 10's Gbit/s over many km's per wavelength channel.

Attenuation

- Signal attenuation within optical fibers is usually expressed in the logarithmic unit of the decibel.

The decibel, which is used for comparing two *power* levels, may be defined for a particular optical wavelength as the *ratio* of the output optical power P_o from the fiber to the input optical power P_i.

$$\text{Loss (dB)} = -10 \log_{10} (P_o/P_i) = 10 \log_{10} (P_i/P_o)$$

$$(P_o \leq P_i)$$

*The logarithmic unit has the advantage that the operations of *multiplication* (*and division*) reduce to *addition* (*and subtraction*).

In numerical values: $P_o/P_i = 10^{[-Loss(dB)/10]}$

The attenuation is usually expressed in decibels per unit length (i.e. dB/km):

$$\gamma L = -10 \log_{10} (P_o/P_i)$$

γ (dB/km): signal attenuation per unit length in decibels

L (km): fiber length

dBm

- dBm is a specific unit of power in decibels when the reference power is 1 mW:

$$dBm = 10 \log_{10} (Power/1\ mW)$$

e.g. 1 mW = 0 dBm; 10 mW = 10 dBm; 100 μW = - 10 dBm

=> Loss (dB) = input power (dBm) - output power (dBm)

e.g. Input power = 1 mW (0 dBm), output power = 100 μW (-10 dBm)

$$\Rightarrow loss = -10 \log_{10} (100\ \mu W/1\ mW) = 10\ dB$$

OR 0 dBm – (-10 dBm) = 10 dB

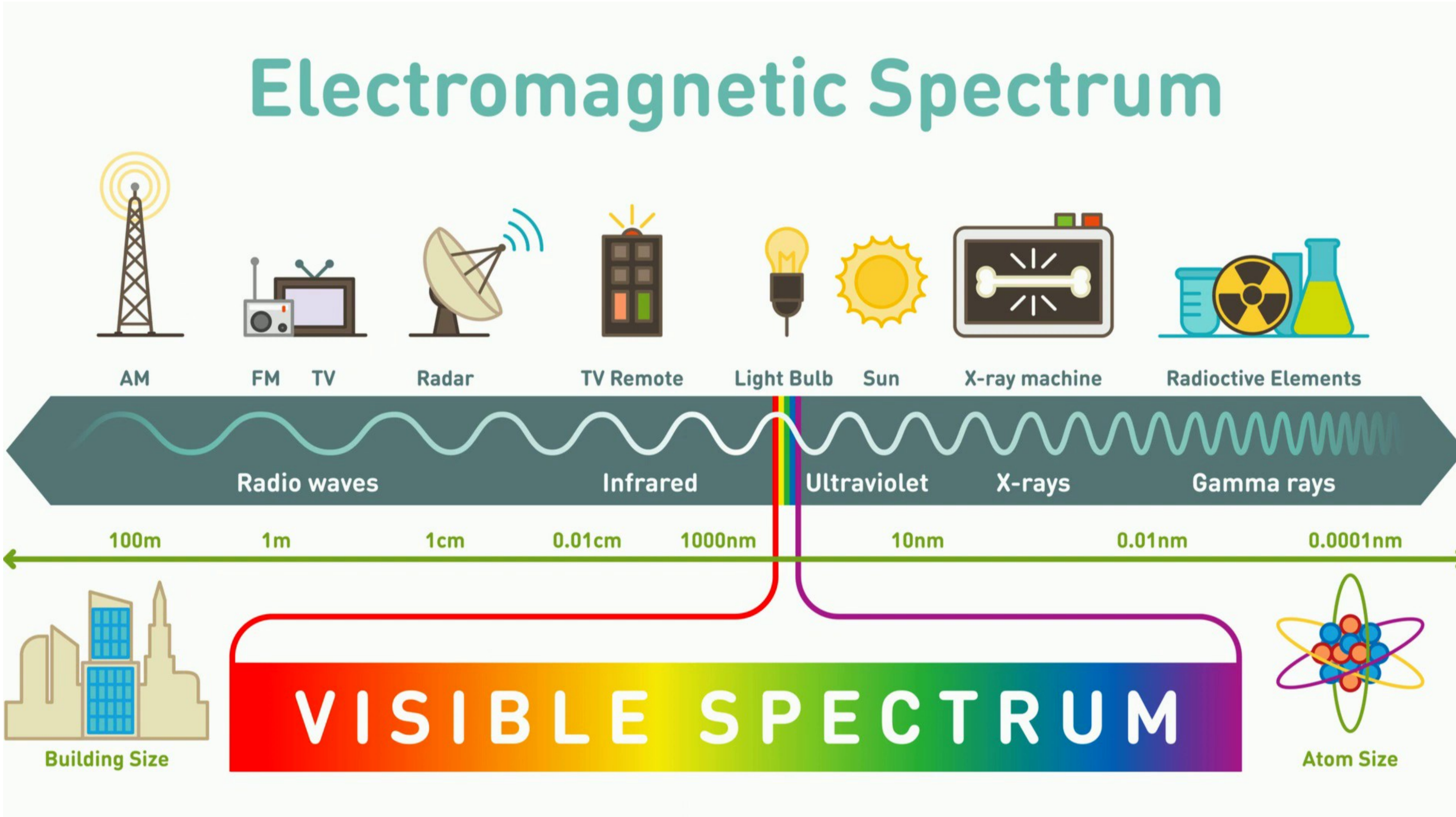
Fiber attenuation mechanisms:

1. Material absorption losses in silica glass fibers .
2. Scattering loss
3. Bending loss
4. Radiation loss (due to mode coupling)
5. Leaky modes

1. Material absorption losses in silica glass fibers

- Material absorption is a loss mechanism related to both *the material composition* and the *fabrication process* for the fiber. The optical power is lost as *heat* in the fiber.

- The light absorption can be *intrinsic* (due to the material components of the glass) or *extrinsic* (due to impurities introduced into the glass during fabrication).



Electromagnetic Spectrum
AM
FM
TV
Radar
TV Remote
Light Bulb
Sun
X-ray machine
Radioctive Elements
Radio waves
Infrared
Ultraviolet
X-rays
Gamma rays
100m
1m
1cm
0.01cm
1000nm
10nm
0.01nm
0.0001nm
Building Size
VISIBLE SPECTRUM
Atom Size

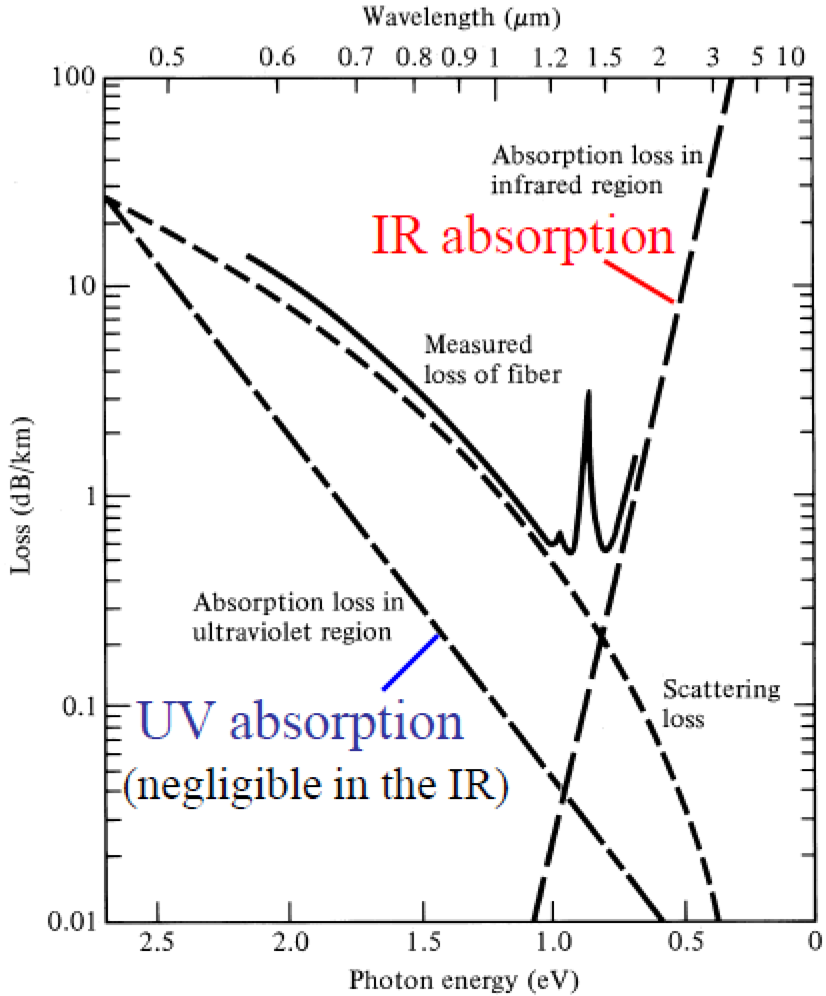
Intrinsic absorption

- Pure silica-based glass has *two* major intrinsic absorption mechanisms at optical wavelengths:

(1) a *fundamental UV absorption* edge, the peaks are centered in the *ultraviolet wavelength region*. This is due to the *electron transitions* within the glass molecules. The tail of this peak may extend into the shorter wavelengths of the fiber transmission spectral window.

(2) A fundamental *infrared and far-infrared absorption edge*, due to *molecular vibrations* (such as Si-O). The tail of these absorption peaks may extend into the longer wavelengths of the fiber transmission spectral window.

Fundamental fiber attenuation characteristics



Extrinsic absorption

Extrinsic absorption is much more significant than intrinsic .

- Caused by impurities introduced into the fiber material during manufacture – iron, nickel, and chromium .
- Caused by transition of metal ions to a higher energy level .
- Modern fabrication techniques can reduce impurity levels below 1 part in 10^{10}.

• For some of the more common metallic impurities in silica fiber the table shows the peak attenuation wavelength and the attenuation caused by an impurity concentration of 1 in 10^9

	Peak wavelength (nm)	One part in 10^9 (dB km^{-1})
Cr^{3+}	625	1.6
C^{2+}	685	0.1
Cu^{2+}	850	1.1
Fe^{2+}	1100	0.68
Fe^{3+}	400	0.15
Ni^{2+}	650	0.1
Mn^{3+}	460	0.2
V^{4+}	725	2.7

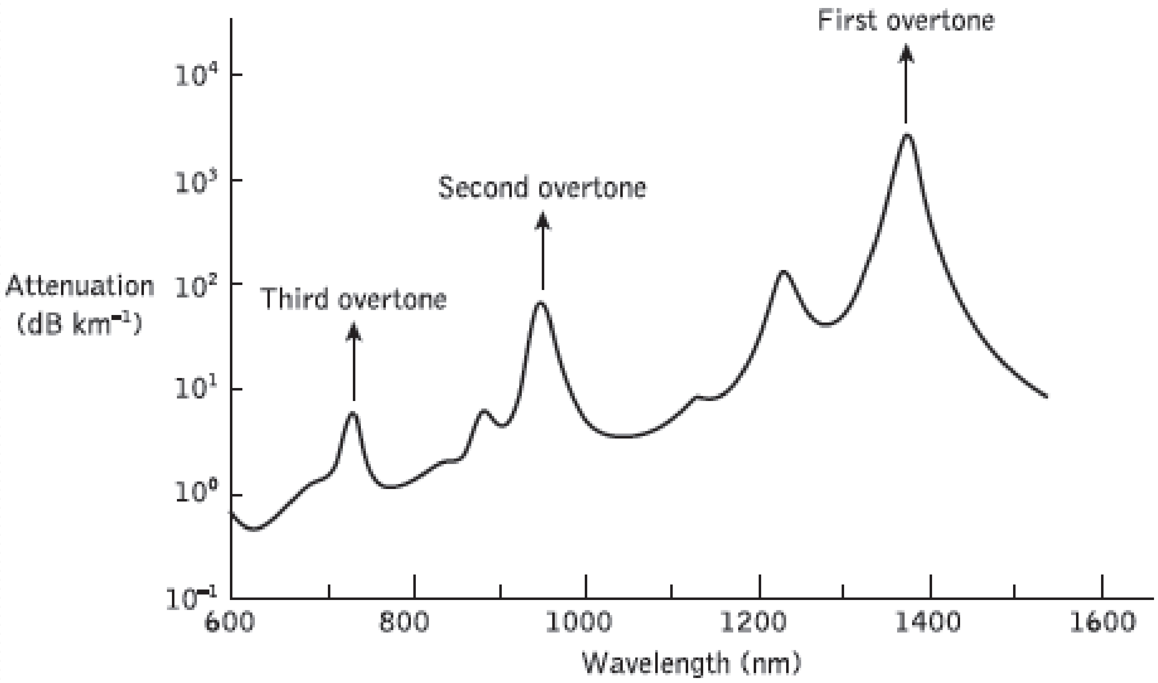
Another major extrinsic loss mechanism is caused by absorption due to water (as the hydroxyl or OH ion) dissolved in the glass.

- These OH^- ions are bonded into the glass structure and have absorption peaks (due to *molecular vibrations*) at 1.38 μm.

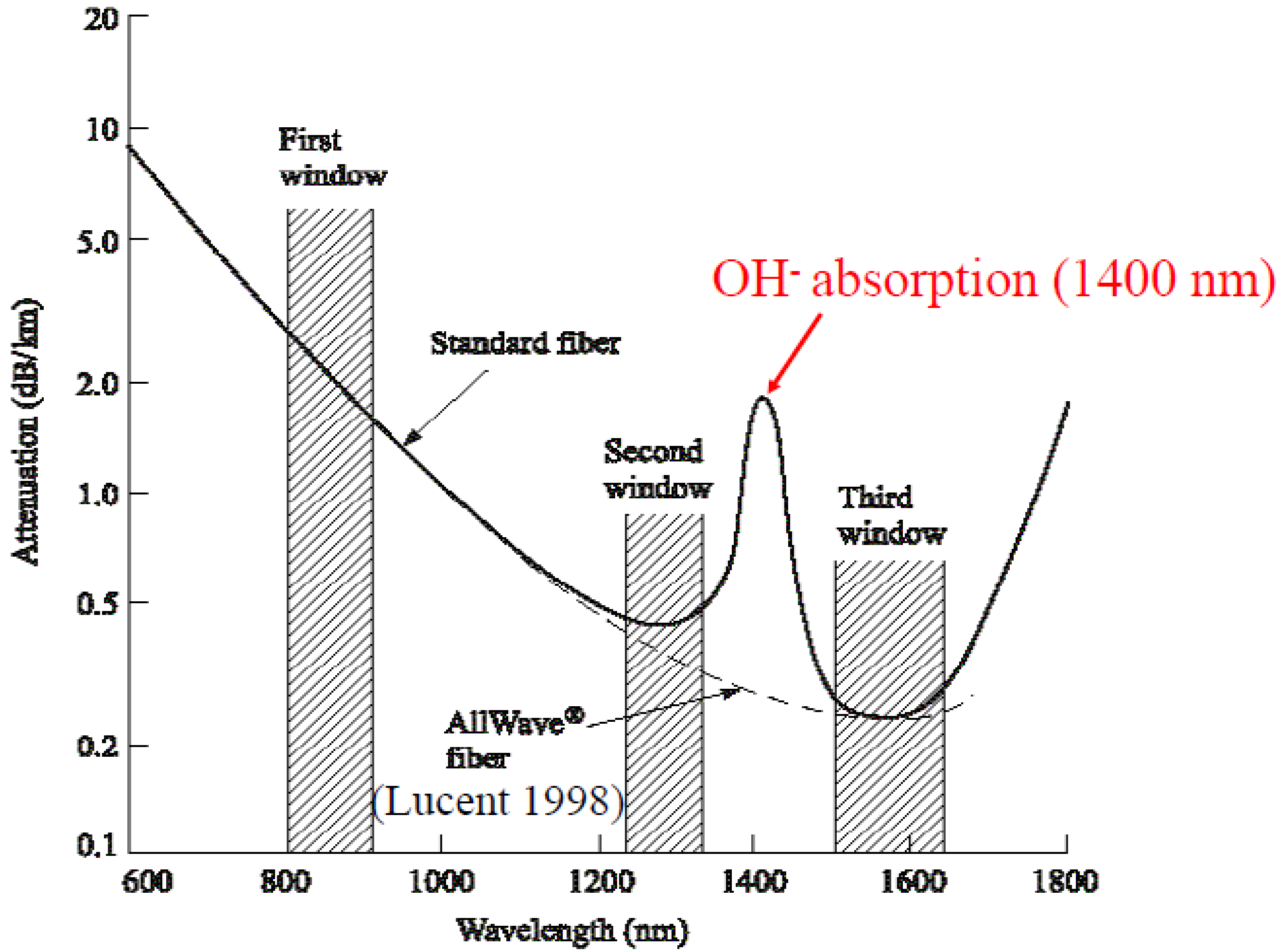
- Since these OH^- absorption peaks are sharply peaked, narrow spectral windows exist around 1.3 μm and 1.55 μm which are essentially unaffected by OH^- absorption.

- The lowest attenuation for typical silica-based fibers occur at wavelength 1.55 μm at about 0.2 dB/km, approaching the *minimum possible attenuation* at this wavelength.

The absorption spectrum for the hydroxyl (OH) group in silica



1400 nm OH^- absorption peak and spectral windows



OFS AllWave fiber: example of a "low-water-peak" or "full spectrum" fiber.
Prior to 2000 the fiber transmission bands were referred to as "windows."

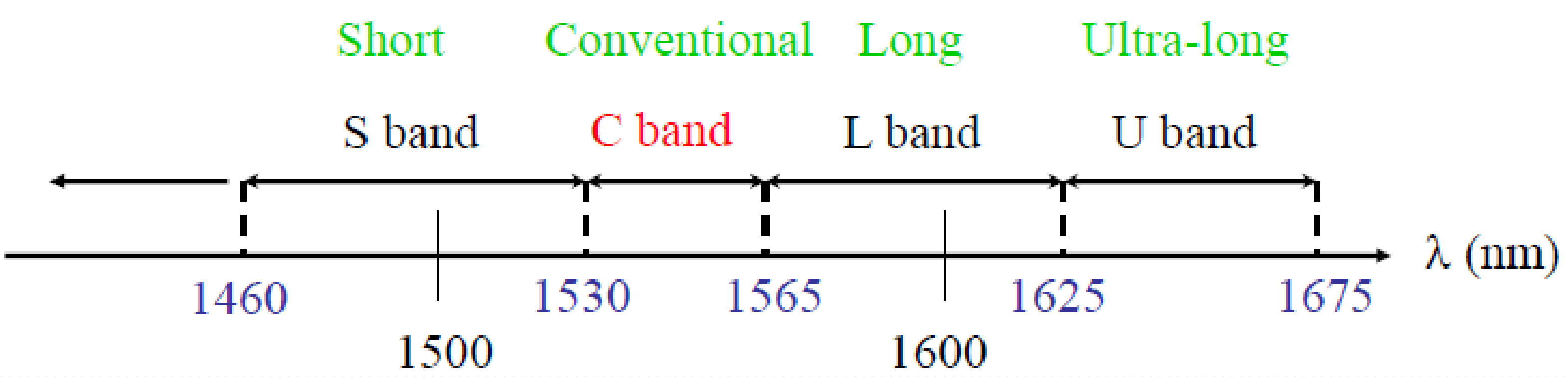
Three major spectral windows where fiber attenuation is low

The 1st window: 850 nm, attenuation 2 dB/km

The 2nd window: 1300 nm, attenuation 0.5 dB/km

The 3rd window: 1550 nm, attenuation 0.3 dB/km

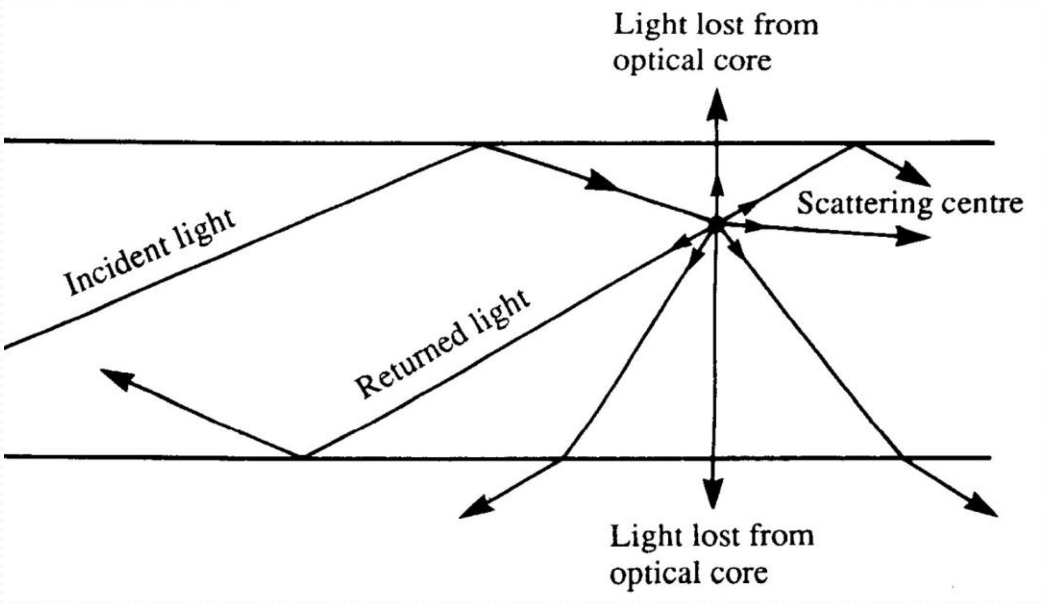
1550 nm window is today's standard **long-haul** communication wavelengths.



3-Scattering Losses in Fiber

Scattering is a process whereby all or some of the optical power in a mode is transferred into another mode.

- **Frequently causes attenuation, since the transfer is often to a mode which does not propagate well. (also called a leaky or radiation mode).**



Types of Scattering Loss in Fiber

Two basic types of scattering exist :

1- Linear scattering :

(a) Rayleigh .

(b) Mie .

2-Non-linear scattering:

(a) Stimulated Brillouin .

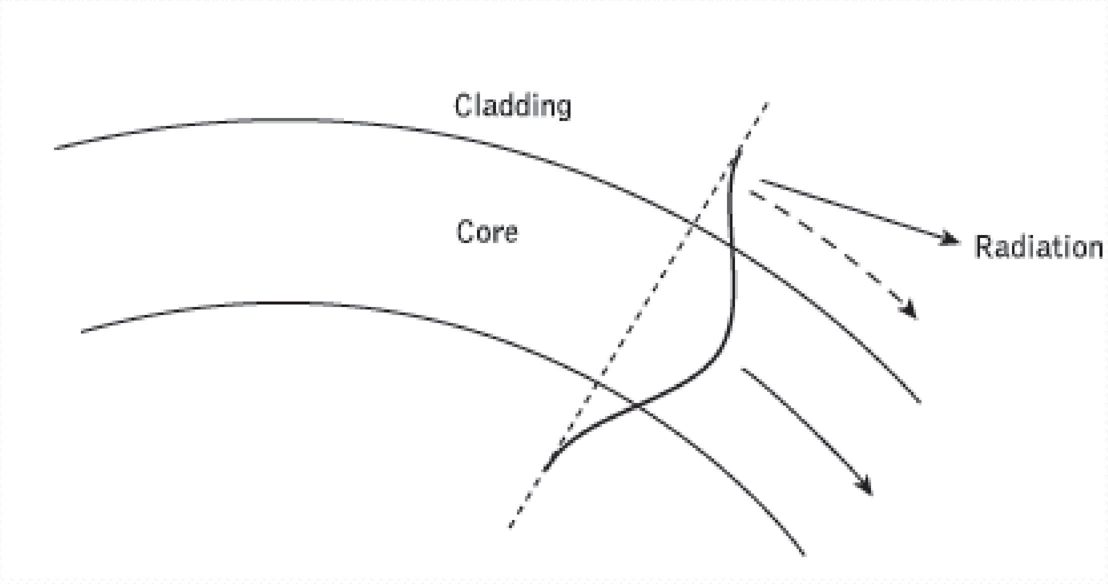
(b) Stimulated Raman.

Rayleigh is the dominant loss mechanism in the low loss silica window between 800 nm and 1700 nm.

Raman scattering is an important issue in Dense WDM systems .

3 - Fiber bend loss

Optical fibers suffer radiation losses at bends or curves on their paths. This is due to the energy in the evanescent field at the bend exceeding the velocity of light in the cladding and hence the guidance mechanism is inhibited, which causes light energy to be radiated from the fiber.



Macrobending Loss

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

$$R_c \simeq \frac{3n_1^2\lambda}{4\pi(n_1^2 - n_2^2)^{\frac{3}{2}}}$$

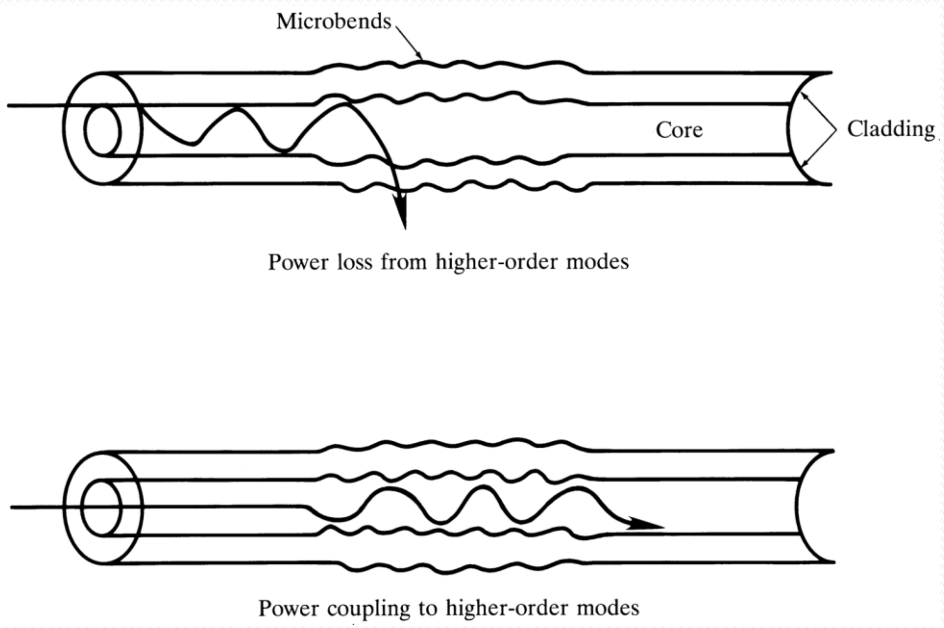
Potential macro-bending losses may be reduced by:

(a) designing fibers with large relative refractive index differences;

(b) operating at the shortest wavelength possible.

Micro-bending Loss

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



Lecture 6
Physics of Optical Elements

Problems for Lecture 1, 2, Sources Lect. and Detectors Lect.

By Assistant Prof. Dr. Zainab Naser Jameel

Communication Engineering Department

Second Class Optical & Wireless Division

University of Technology-Iraq

20/April/2022

Example 2.1

A silica optical fiber with a core diameter large enough to be considered by ray theory analysis has a core refractive index of 1.50 and a cladding refractive index of 1.47.

Determine: (a) the critical angle at the core–cladding interface; (b) the *NA* for the fiber; (c) the acceptance angle in air for the fiber.

Solution: (a) The critical angle ϕ_c at the core–cladding interface is given by Eq. (2.2) where:

$$\phi_c = \sin^{-1}\frac{n_2}{n_1} = \sin^{-1}\frac{1.47}{1.50}$$

$$= 78.5°$$

(b) From Eq. (2.8) the *NA* is:

$$NA = (n_1^2 - n_2^2)^{\frac{1}{2}} = (1.50^2 - 1.47^2)^{\frac{1}{2}}$$
$$= (2.25 - 2.16)^{\frac{1}{2}}$$
$$= 0.30$$

(c) Considering Eq. (2.8) the acceptance angle in air θ_a is given by:

$$\theta_a = \sin^{-1} NA = \sin^{-1} 0.30$$
$$= 17.4°$$

Example 2.2

A typical relative refractive index difference for an optical fiber designed for long-distance transmission is 1%. Estimate the NA and the solid acceptance angle in air for the fiber when the core index is 1.46. Further, calculate the critical angle at the core–cladding interface within the fiber. It may be assumed that the concepts of geometric optics hold for the fiber.

Solution: Using Eq. (2.10) with $\Delta = 0.01$ gives the NA as:

$$NA = n_1(2\Delta)^{\frac{1}{2}} = 1.46(0.02)^{\frac{1}{2}}$$
$$= 0.21$$

For small angles the solid acceptance angle in air ζ is given by:

$$\zeta \simeq \pi\theta_a^2 = \pi \sin^2 \theta_a$$

Hence from Eq. (2.8):

$$\zeta \simeq \pi(NA)^2 = \pi \times 0.04$$
$$= 0.13 \text{ rad}$$

Using Eq. (2.9) for the relative refractive index difference Δ gives:

$$\Delta \simeq \frac{n_1 - n_2}{n_1} = 1 - \frac{n_2}{n_1}$$

Hence

$$\frac{n_2}{n_1} = 1 - \Delta = 1 - 0.01$$
$$= 0.99$$

From Eq. (2.2) the critical angle at the core–cladding interface is:

$$\phi_c = \sin^{-1}\frac{n_2}{n_1} = \sin^{-1} 0.99$$
$$= 81.9°$$

Example 2.4

A multimode step index fiber with a core diameter of 80 μm and a relative index difference of 1.5% is operating at a wavelength of 0.85 μm. If the core refractive index is 1.48, estimate: (a) the normalized frequency for the fiber; (b) the number of guided modes.

Solution: (a) The normalized frequency may be obtained from Eq. (2.70) where:

$$V \simeq \frac{2\pi}{\lambda} a n_1 (2\Delta)^{\frac{1}{2}} = \frac{2\pi \times 40 \times 10^{-6} \times 1.48}{0.85 \times 10^{-6}} (2 \times 0.015)^{\frac{1}{2}} = 75.8$$

(b) The total number of guided modes is given by Eq. (2.74) as:

$$M_s \simeq \frac{V^2}{2} = \frac{5745.6}{2}$$

$$= 2873$$

Hence this fiber has a V number of approximately 76, giving nearly 3000 guided modes.

Example 2.5

A graded index fiber has a core with a parabolic refractive index profile which has a diameter of 50 μm. The fiber has a numerical aperture of 0.2. Estimate the total number of guided modes propagating in the fiber when it is operating at a wavelength of 1 μm.

Solution: Using Eq. (2.69), the normalized frequency for the fiber is:

$$V = \frac{2\pi}{\lambda} a(NA) = \frac{2\pi \times 25 \times 10^{-6} \times 0.2}{1 \times 10^{-6}}$$

$$= 31.4$$

The mode volume may be obtained from Eq. (2.95) where for a parabolic profile:

$$M_g \simeq \frac{V^2}{4} = \frac{986}{4} = 247$$

Hence the fiber supports approximately 247 guided modes.

Estimate the maximum core diameter for an optical fiber with the same relative refractive index difference (1.5%) and core refractive index (1.48) as the fiber given in Example 2.4 in order that it may be suitable for single-mode operation. It may be assumed that the fiber is operating at the same wavelength (0.85 μm). Further, estimate the new maximum core diameter for single-mode operation when the relative refractive index difference is reduced by a factor of 10.

Solution: Considering the relationship given in Eq. (2.96), the maximum V value for a fiber which gives single-mode operation is 2.4. Hence, from Eq. (2.70) the core radius a is:

$$a = \frac{V\lambda}{2\pi n_1(2\Delta)^{\frac{1}{2}}} = \frac{2.4 \times 0.85 \times 10^{-6}}{2\pi \times 1.48 \times (0.03)^{\frac{1}{2}}}$$

$$= 1.3\ \mu\text{m}$$

Therefore the maximum core diameter for single-mode operation is approximately 2.6 μm.

Reducing the relative refractive index difference by a factor of 10 and again using Eq. (2.70) gives:

$$a = \frac{2.4 \times 0.85 \times 10^{-6}}{2\pi \times 1.48 \times (0.003)^{\frac{1}{2}}} = 4.0\ \mu\text{m}$$

Hence the maximum core diameter for single-mode operation is now approximately 8 μm.

Example 2.8

Determine the cutoff wavelength for a step index fiber to exhibit single-mode operation when the core refractive index and radius are 1.46 and 4.5 μm, respectively, with the relative index difference being 0.25%.

Solution: Using Eq. (2.98) with $V_c = 2.405$ gives:

$$\lambda_c = \frac{2\pi a n_1 (2\Delta)^{\frac{1}{2}}}{2.405} = \frac{2\pi 4.5 \times 1.46 (0.005)^{\frac{1}{2}}}{2.405} \, \mu\text{m}$$

$$= 1.214 \, \mu\text{m}$$

$$= 1214 \text{ nm}$$

Hence the fiber is single-moded to a wavelength of 1214 nm.

$$\frac{\text{Stimulated emission rate}}{\text{Spontaneous emission rate}} = \frac{B_{21}\rho_f}{A_{21}} = \frac{1}{\exp(hf/KT) - 1} \tag{6.11}$$

Example 6.1

Calculate the ratio of the stimulated emission rate to the spontaneous emission rate for an incandescent lamp operating at a temperature of 1000 K. It may be assumed that the average operating wavelength is 0.5 μm.

Solution: The average operating frequency is given by:

$$f = \frac{c}{\lambda} = \frac{2.998 \times 10^{8}}{0.5 \times 10^{-6}} \simeq 6.0 \times 10^{14}\ \text{Hz}$$

Using Eq. (6.11) the ratio is:

$$\frac{\text{Stimulated emission rate}}{\text{Spontaneous emission rate}} = \frac{1}{\exp\left(\frac{6.626 \times 10^{-34} \times 6 \times 10^{14}}{1.381 \times 10^{-23} \times 1000}\right)}$$

$$= \exp(-28.8)$$

$$= 3.1 \times 10^{-13}$$

Example 6.5

A GaAs injection laser has an optical cavity of length 250 μm and width 100 μm. At normal operating temperature the gain factor $\bar{\beta}$ is 21×10^{-3} A cm^{-3} and the loss coefficient $\bar{\alpha}$ per cm is 10. Determine the threshold current density and hence the threshold current for the device. It may be assumed that the cleaved mirrors are uncoated and that the current is restricted to the optical cavity. The refractive index of GaAs may be taken as 3.6.

Solution: The reflectivity for normal incidence of a plane wave on the GaAs–air interface may be obtained from Eq. (5.1) where:

$$r_1 = r_2 = r = \left(\frac{n-1}{n+1}\right)^2$$

$$= \left(\frac{3.6-1}{3.6+1}\right)^2 \simeq 0.32$$

$$J_{th} = \frac{1}{\bar{\beta}}\left[\bar{\alpha} + \frac{1}{2L}\ln\frac{1}{r_1 r_2}\right]$$

The threshold current density may be obtained from Eq. (6.34) where:

$$J_{th} = \frac{1}{\bar{\beta}}\left[\bar{\alpha}\frac{1}{L}\ln\frac{1}{r}\right]$$

$$= \frac{1}{21 \times 10^{-3}}\left[10 + \frac{1}{250 \times 10^{-4}}\ln\frac{1}{0.32}\right]$$

$$= 2.65 \times 10^3 \text{ A cm}^{-2}$$

The threshold current I_{th} is given by:

$$I_{th} = J_{th} \times \text{area of the optical cavity}$$
$$= 2.65 \times 10^3 \times 250 \times 100 \times 10^{-8}$$
$$\simeq 663 \text{ mA}$$

Therefore the threshold current for this device is 663 mA if the current flow is restricted to the optical cavity.

$$\eta_{ep} = \eta_T \left(\frac{E_g}{V} \right) \times 100\% \tag{6.42}$$

Example 6.6

The total efficiency of an injection laser with a GaAs active region is 18%. The voltage applied to the device is 2.5 V and the bandgap energy for GaAs is 1.43 eV. Calculate the external power efficiency of the device.

Solution: Using Eq. (6.42), the external power efficiency is given by:

$$\eta_{ep} = 0.18 \left(\frac{1.43}{2.5} \right) \times 100 \simeq 10\%$$

This result indicates the possibility of achieving high overall power efficiencies from semiconductor lasers which are much larger than for other laser types.

$$\bar{g}_{th} = \bar{\alpha} + \frac{1}{2L} \ln \frac{1}{r_1 r_2} \tag{6.20}$$

The second term on the right hand side of Eq. (6.20) represents the transmission loss through the mirrors.*

For laser action to be easily achieved it is clear that a high threshold gain per unit length is required in order to balance the losses from the cavity. However, it must be noted that the parameters displayed in Eq. (6.20) are totally dependent on the laser type.

Example 6.3

An injection laser has an active cavity with losses of 30 cm^{-1} and the reflectivity of the each cleaved laser facet is 30%. Determine the laser gain coefficient for the cavity when it has a length of 600 μm.

Solution: The threshold gain per unit length where $r_1 = r_2 = r$ is given by Eq. (6.20) as:

$$\bar{g}_{th} = \bar{\alpha} + \frac{1}{L} \ln \frac{1}{r}$$

$$= 30 + \frac{1}{0.06} + \ln \frac{1}{0.3}$$

$$= 50 \text{ cm}^{-1}$$

The threshold gain per unit length is equivalent to the laser gain coefficient for the active cavity, which is 50 cm^{-1}.

Example 6.2

A ruby laser contains a crystal of length 4 cm with a refractive index of 1.78. The peak emission wavelength from the device is 0.55 μm. Determine the number of longitudinal modes and their frequency separation.

Solution: The number of longitudinal modes supported within the structure may be obtained from Eq. (6.12) where:

$$q = \frac{2nL}{\lambda} = \frac{2 \times 1.78 \times 0.04}{0.55 \times 10^{-6}} = 2.6 \times 10^{5}$$

Using Eq. (6.14) the frequency separation of the modes is:

$$\delta f = \frac{c}{2nL}$$

$$\delta f = \frac{2.998 \times 10^{8}}{2 \times 1.78 \times 0.04} = 2.1 \text{ GHz}$$

Example 6.4

Compare the approximate radiative minority carrier lifetimes in gallium arsenide and silicon when the minority carriers are electrons injected into the p-type region which has a hole concentration of 10^{18} cm^{-3}. The injected electron density is small compared with the majority carrier density.

Solution: Equation (6.24) gives the radiative minority carrier lifetime τ_r as:

$$\tau_r \simeq [B_r(N+P)]^{-1}$$

$$\tau_r = [B_r(N+P)]^{-1}$$

In the p-type region the hole concentration determines the radiative carrier lifetime as $P \gg N$. Hence:

$$\tau_r \simeq [B_r N]^{-1}$$

Semiconductor material	*Energy bandgap (eV)*	*Recombination coefficient B_r (cm^3 s^{-1})*
GaAs	Direct: 1.43	7.21×10^{-10}
CaSb	Direct: 0.73	2.39×10^{-10}
InAs	Direct: 0.35	8.5×10^{-11}
InSb	Direct: 0.18	4.58×10^{-11}
Si	Indirect: 1.12	1.79×10^{-15}
Ge	Indirect: 0.67	5.25×10^{-14}
GaP	Indirect: 2.26	5.37×10^{-14}

Thus for gallium arsenide:

$$\tau_r \simeq [7.21 \times 10^{-10} \times 10^{18}]^{-1}$$
$$= 1.39 \times 10^{-9}$$
$$= 1.39 \text{ ns}$$

For silicon:

$$\tau_r \simeq [1.79 \times 10^{-15} \times 10^{18}]^{-1}$$
$$= 5.58 \times 10^{-4}$$
$$= 0.56 \text{ ms}$$

Thus the direct bandgap gallium arsenide has a radiative carrier lifetime factor of around 2.5×10^{-6} less than the indirect bandgap silicon.

Example 8.1

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.

Solution: From Eq. (8.2):

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

$$= \frac{1.2 \times 10^{11}}{3 \times 10^{11}}$$

$$= 0.4$$

The quantum efficiency of the photodiode at 0.85 μm is 40%.

From Eq. (8.11):

$$\text{Responsivity } R = \frac{\eta e \lambda}{hc}$$

$$= \frac{0.4 \times 1.602 \times 10^{-19} \times 0.85 \times 10^{-6}}{6.626 \times 10^{-34} \times 2.998 \times 10^{8}}$$

$$= 0.274 \text{ A W}^{-1}$$

The responsivity of the photodiode at 0.85 μm is 0.27 A W^{-1}.

Example 8.2

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.

Solution: (a) From Eq. (6.1), the photon energy $E = hf = hc/\lambda$. Therefore:

$$\lambda = \frac{hc}{E} = \frac{6.626 \times 10^{-34} \times 2.998 \times 10^{8}}{1.5 \times 10^{-19}}$$

$$= 1.32\ \mu\text{m}$$

The photodiode is operating at a wavelength of 1.32 μm.

(b) From Eq. (8.9):

$$\text{Responsivity } R = \frac{\eta e}{hf} = \frac{0.65 \times 1.602 \times 10^{-19}}{1.5 \times 10^{-19}}$$

$$= 0.694 \text{ A W}^{-1}$$

Also from Eq. (8.4):

$$R = \frac{I_p}{P_o}$$

Therefore:

$$P_o = \frac{25 \times 10^{-6}}{0.694} = 3.60 \ \mu\text{W}$$

The incident optical power required is 3.60 μW.

Example 8.3

GaAs has a bandgap energy of 1.43 eV at 300 K. Determine the wavelength above which an intrinsic photodetector fabricated from this material will cease to operate.

Solution: From Eq. (8.14), the long wavelength cutoff:

$$\lambda_c = \frac{hc}{E_g} = \frac{6.626 \times 10^{-34} \times 2.998 \times 10^{8}}{1.43 \times 1.602 \times 10^{-19}}$$

$$= 0.867\ \mu m$$

The GaAs photodetector will cease to operate above 0.87 µm.

Example 8.4

A silicon *p–i–n* photodiode has an intrinsic region with a width of 20 μm and a diameter of 500 μm in which the drift velocity of electrons is 10^5 m s^{-1}. When the permittivity of the device material is 10.5×10^{-13} F cm^{-1}, calculate: (a) the drift time of the carriers across the depletion region; (b) the junction capacitance of the photodiode.

Solution: (a) The drift time for the carriers across the depletion region for the photodiode can be obtained using Eq. (8.15) as:

$$t_{\text{drift}} = \frac{w}{\upsilon_{\text{d}}}$$

$$= \frac{20 \times 10^{-6}}{1 \times 10^{5}}$$

$$= 2 \times 10^{-10}\ \text{s}$$

The drift time for the carriers across the depletion region is therefore 200 ps.

(b) The junction capacitance is given by Eq. (8.17) as:

$$C_{\text{j}} = \frac{\varepsilon_{\text{s}} A}{w}$$

where the area $A = \pi \times r^2 = 3.14 \times (500 \times 10^{-6})^2 = 0.79 \times 10^{-6}\ \text{m}^2$. Therefore:

$$C_{\text{j}} = \frac{10.5 \times 10^{-13} \times 0.79 \times 10^{-6}}{20 \times 10^{-6}}$$

$$= 0.41 \times 10^{-13}$$

The photodiode has a junction capacitance of 4 pF.

Example 8.5

The carrier velocity in a silicon *p–i–n* photodiode with a 25 μm depletion layer width is 3×10^4 m s^{-1}. Determine the maximum response time for the device.

Solution: The maximum 3 dB bandwidth for the photodiode may be obtained from Eq. (8.18) where:

$$B_m = \frac{\upsilon_d}{2\pi w} = \frac{3 \times 10^4}{2\pi \times 25 \times 10^{-6}} = 1.91 \times 10^8 \text{ Hz}$$

The maximum response time for the device is therefore:

$$\text{Max. response time} = \frac{1}{B_m} = 5.2 \text{ ns}$$

It must be noted, however, that the above response time takes no account of the diffusion of carriers in the photodiode or the capacitance associated with the device junction and the external connections.

Example 8.6

A germanium *p–i–n* photodiode with active dimensions of 100 × 50 μm has a quantum efficiency of 55% when operating at a wavelength of 1.3 μm. The measured dark current at this wavelength is 8 nA. Calculate the noise equivalent power and specific detectivity for the device. It may be assumed that dark current is the dominant noise source.

Solution: The noise equivalent power is given by Eq. (8.26) as:

$$NEP \simeq \frac{hc(2eI_{\mathrm{d}})^{\frac{1}{2}}}{\eta e\lambda}$$

$$= \frac{6.626\times10^{-34}\times2.998\times10^{8}(2\times1.602\times10^{-19}\times8\times10^{-9})^{\frac{1}{2}}}{0.55\times1.602\times10^{-19}\times1.3\times10^{-6}}$$

$$= 8.78\times10^{-14}\ \mathrm{W}$$

Substituting for the detectivity D in Eq. (8.29) from Eq. (8.27) allows the specific detectivity to be written as:

$$D^{*} = \frac{A^{\frac{1}{2}}}{NEP} = \frac{(100\times10^{-6}\times50\times10^{-6})^{\frac{1}{2}}}{8.78\times10^{-14}}$$

$$= 8.1\times10^{8}\ \mathrm{m\ Hz^{\frac{1}{2}}\ W^{-1}}$$

Example 8.7

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.

Solution: From Eq. (8.11), the responsivity:

$$R = \frac{\eta e \lambda}{hc} = \frac{0.8 \times 1.602 \times 10^{-19} \times 0.9 \times 10^{-6}}{6.626 \times 10^{-34} \times 2.998 \times 10^{8}}$$

$$= 0.581 \text{ A W}^{-1}$$

Also, from Eq. (8.4), the photocurrent:

$$\begin{aligned} I_\mathrm{p} &= P_\mathrm{o} R \\ &= 0.5 \times 10^{-6} \times 0.581 \\ &= 0.291\ \mu\text{A} \end{aligned}$$

Finally, using Eq. (8. 30):

$$M = \frac{I}{I_\mathrm{p}} = \frac{11 \times 10^{-6}}{0.291 \times 10^{-6}}$$

$$= 37.8$$

The multiplication factor of the photodiode is approximately 38.

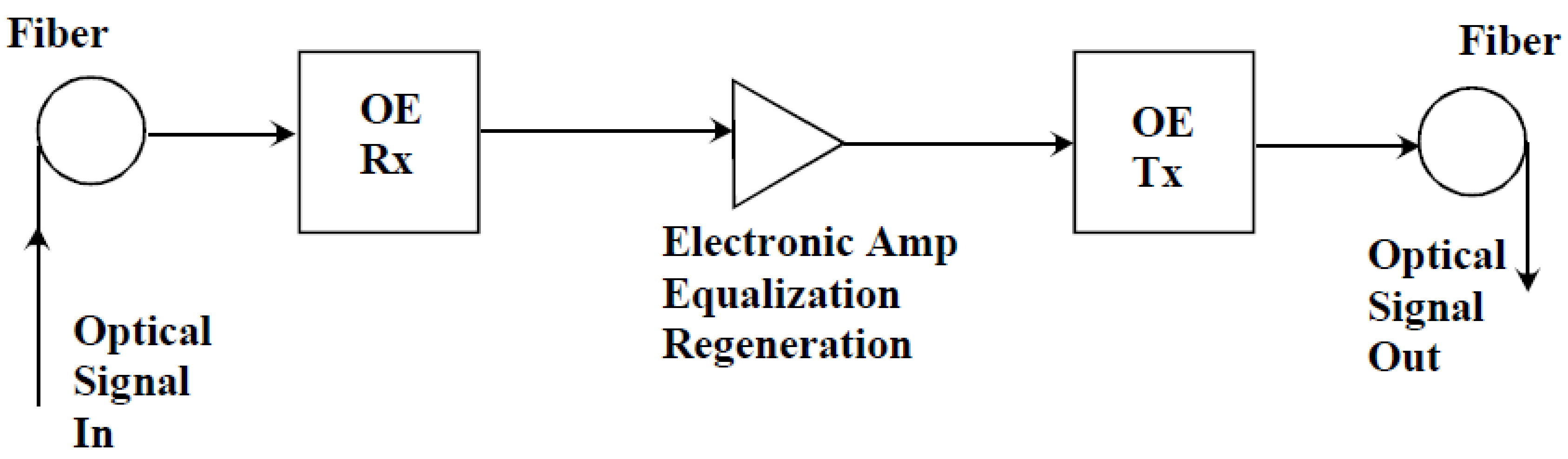
Lecture 7
Physics of Optical Elements
Optical Amplifier

By Prof. Dr. Zainab Naser Jameel
Communication Engineering Department
Second Class Optical & Wireless Division
University of Technology-Iraq
14/May/2022

In order to transmit signals over long distances (>100 km) it is necessary to compensate for attenuation losses within the fiber.

Initially this was accomplished with an optoelectronic module consisting of an optical receiver, a regeneration and equalization system, and an optical transmitter to send the data.

Although functional this arrangement is limited by the optical to electrical and electrical to optical conversions



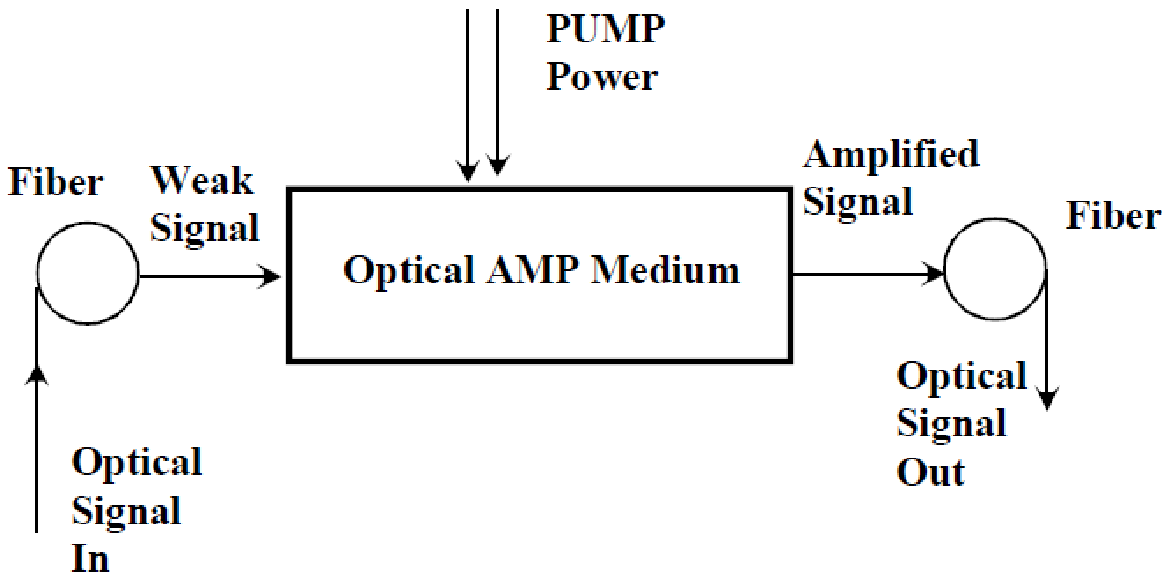
Several types of optical amplifiers have since been demonstrated to replace the OE – electronic regeneration systems.

These systems eliminate the need for E-O and O-E conversions.

This is one of the main reasons for the success of today's optical communications systems.

OPTICAL AMPLIFIERS

The general form of an optical amplifier:



Some types of OAs that have been demonstrated include:

Semiconductor optical amplifiers (SOAs)

Fiber Raman and Brillouin amplifiers

Rare earth doped fiber amplifiers (erbium – EDFA 1500 nm, praseodymium – PDFA 1300 nm)

The most practical optical amplifiers to date include the SOA and EDFA types. New pumping methods and materials are also improving the performance of Raman amplifiers.

Characteristics of SOA types:

Polarization dependent – require polarization maintaining fiber

Relatively high gain ~20 dB

Output saturation power 5-10 dBm

Large BW

Can operate at 800, 1300, and 1500 nm wavelength regions.

Compact and easily integrated with other devices

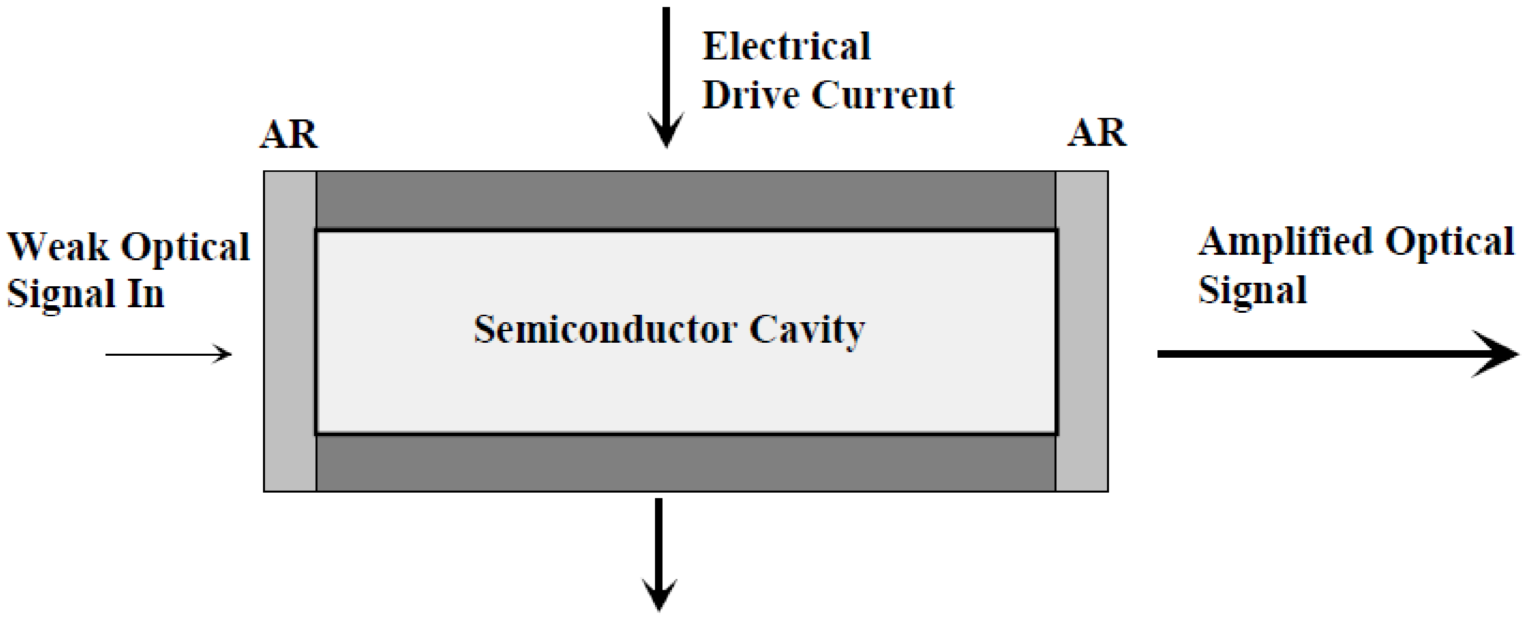
Can be integrated into arrays

High noise figure and cross-talk levels due to nonlinear phenomenon such as 4-wave mixing.

This last feature restricts the use of SOAs.

Semiconductor Optical Amplifier (SOA) – similar to a laser cavity. Used as a discrete amplifiers. They can be integrated into arrays of amplifying switching and gating devices. Finding application in all optical 3R-regeneration systems.

Limited in operation below 10 Gb/s. (Higher rates are possible with lower gain.)



Rare Earth Doped Fiber Amplifier Characteristics:

Rare earth doped fiber amplifiers are finding increasing importance in optical communications systems. Perhaps the most important version is erbium doped fiber amplifiers (EDFAs) due to their ability to amplify signals at the low loss 1.55 m wavelength range.

Characteristics of EDFAs (advantages):

High power transfer efficiency from pump to signal power (> 50%).

Wide spectral band amplification with relative flat gain (>20 dB) – useful for WDM applications.

Saturation output > 1 mW (10 to 25 dBm).

Gain-time constant long (>100 msec) to overcome patterning effects and inter-modulation distortions (low noise).

Large dynamic range.

Low noise figure.

Polarization independent.

Suitable for long-haul applications.

Disadvantages of EDFAs:

Relatively large devices (km lengths of fiber) – not easily integrated with other devices.

ASE – amplified spontaneous emission. There is always some output even with no signal input due to some excitation of ions in the fiber – spontaneous noise.

Cross-talk effects.

Gain saturation effects.

Pumping is primarily done optically with the primary pump wavelengths at 1.48 m and 0.98 m. As indicated atoms pumped to the 4I (11/2) 0.98 m band decays to the primary emission transition band. Pumping with 1.48 m light is directly to the upper transition levels of the emission band.

Semiconductor lasers have been developed for both pump wavelengths.

10-20 mW of absorbed pump power at these wavelengths can produce 30-40 dB of amplifier gain.

Pump Efficiencies of 11 dB/mW achieved at 980 nm.

Pumping can also be performed at 820 and 670 nm with GaAlAs laser diodes. Pump efficiencies are lower but these lasers can be made with high output power.

Since the gain spectrum of erbium resembles a 3-level atom it is possible to model the gain properties using this approach.

Several different wavelength bands have been designated for wavelength division multiplexing and EDFAs have been designed to operate in these bands.

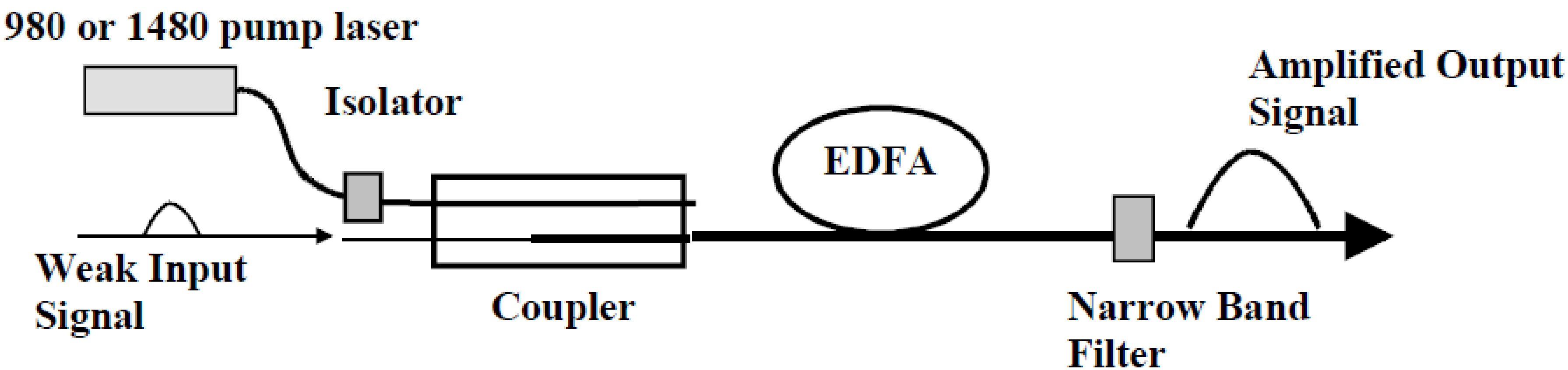
The divisions have been designated as*:

S-Band 1480-1520 nm

C-Band 1521-1560 nm

L-Band 1561-1620 nm

General EDFA Amplifier Configuration:



Basic Amplifier Characteristics

Optical Gain

Rare earth doped optical amplifiers work much like a laser.

The primary difference is that they do not have a resonator.

Amplification occurs primarily through the stimulated emission process.

The medium is pumped until a population inversion state is achieved. Pump powers are typically several 20-250 mW. An isolator is used to reduce reflections at the input to the amplifier. A narrow band optical filter is used to reduce transmission of amplified spontaneous emission frequency components.

The resultant optical gain depends both on the optical frequency and the local beam intensity within the amplifier section.
For basic discussion consider a two-level homogeneously broadened medium.

The gain coefficient can be expressed as:

$$g(\omega) = \frac{g_o}{1 + (\omega - \omega_o)^2 T_2^2 + P / P_s},$$

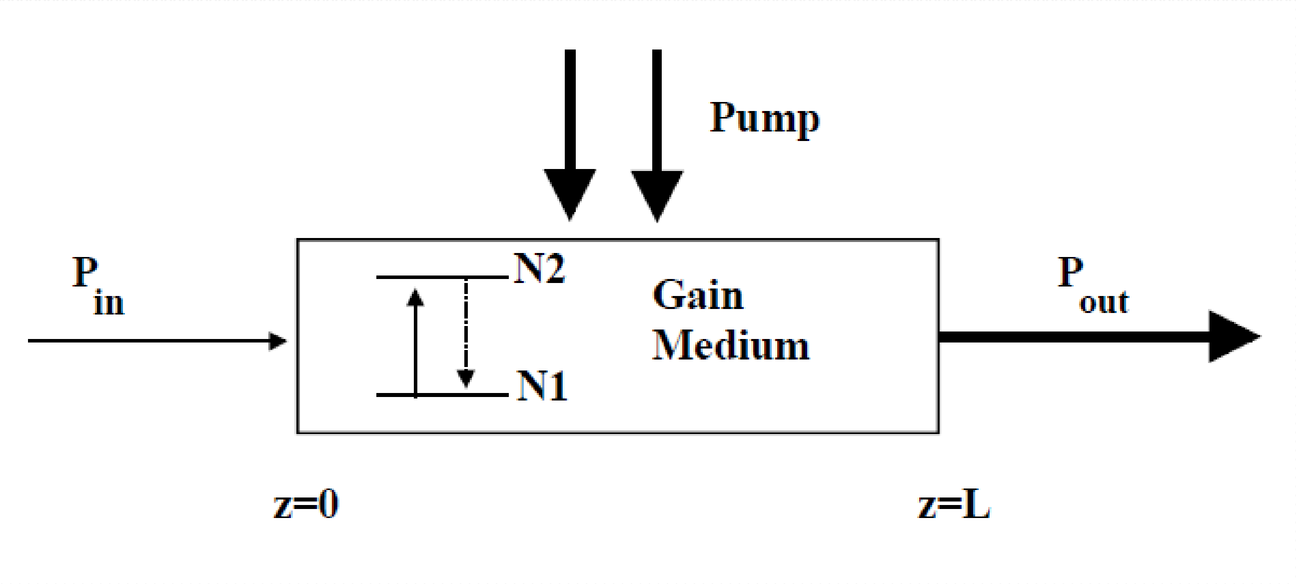
g_o is the peak gain, ω is the optical frequency of the incident signal,
ω_o is the transition frequency, P is the optical power of the incident signal,
T_2 is the dipole relaxation time, and P_s is the saturation power.
Typically T_2 is small < 1 ps, and the saturation power P_s depends on gain medium parameters such as the fluorescence time and the transition cross section.

Amplification factor:

Define as:

$$G = P^{out}/P^{in}$$

P^{out} is the amplifier output power and P^{in} the input power of a CW input signal.



From the previous discussion of the laser the gain in optical power per length of gain medium (z) with gain g is

$$\frac{dP}{dz} = gP \, .$$

Integrating over a length z of amplifier medium gives the resultant optical power

$$P(z) = P(0)\exp(gz) \, .$$

The amplification factor after a length L of OAM (optical amplifier medium) is

$$G(\omega) = \exp[g(\omega)L]$$

Both g(ω) and G(ω) are a maximum when the frequency is at resonance $\omega = \omega_o$ and decrease when the frequency is detuned from resonance.

However the *amplifier factor(G)* decreases much faster than the *gain coefficient(g).*

- The *amplifier BW* $\Delta\nu_A$ is defined as the *FWHM of G(ω)*

$$\Delta\nu_A = \Delta\nu_g\left(\frac{\ln 2}{\ln(G_o/2)}\right)^{0.5}$$

where $\Delta\nu_g$ is the gain BW, and $G_o = \exp(g_o L)$.

- The *amplifier BW* is smaller than the *gain BW*. The difference depends on the *amplifier gain* characteristics.

$$\text{If } G_o = 10,\ \Delta\nu_A = 0.656\Delta\nu_g$$

Amplifier Noise:

- *Spontaneous emission* in the amplifier will *degrade the SNR* by adding to the noise during the amplification process.

- SNR degradation is quantified through the *amplifier noise figure F_n*

$$F_n = \frac{(SNR)_{in}}{(SNR)_{out}}$$

where the SNR is based on the electrical power after converting the optical signal to an electrical current. Therefore F_n is referenced to the detection process and depends on parameters such as detector bandwidth (B_e) and thermal and shot noise.

- Consider a simple case with an ideal detector with performance limited by *shot noise.*

- The amplifier has an *amplification factor G* ($P_{out} = G\ P_{in}$).

- SNR of the input signal:

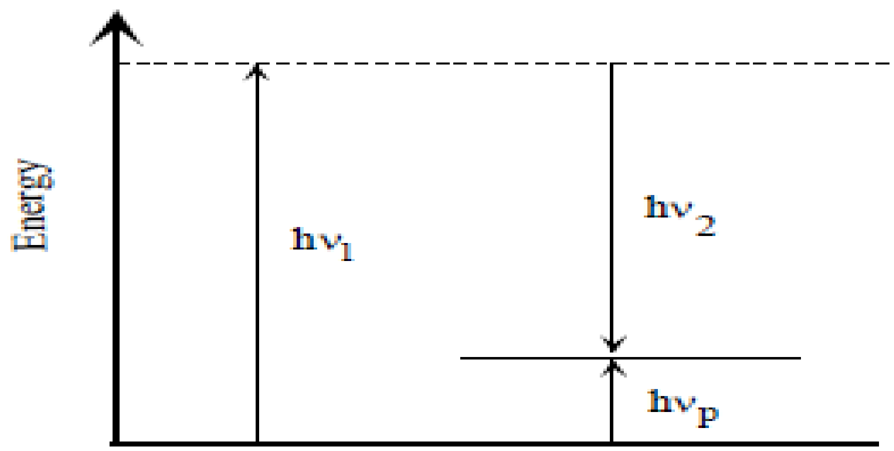
$$SNR_{in} = \frac{\langle I \rangle^2}{\sigma_s^2} = \frac{(RP_{in})^2}{2q(RP_{in})B_e} = \frac{P_{in}}{2h\nu B_e},$$

$$\sigma_s^2 = 2q(RP_{in})B_e .$$

Raman Scattering, Stimulated Raman Scattering, and Raman Amplifiers:

- Raman scattering is an *elastic scattering mechanism*. Does not require a population inversion.
- A photon with energy $h\nu_1$ traveling through a material can excite a *vibrational transition* of the material forming an *optical phonon* with energy $h\nu_p$ and a photon with slightly reduced energy $h\nu_2$ given by

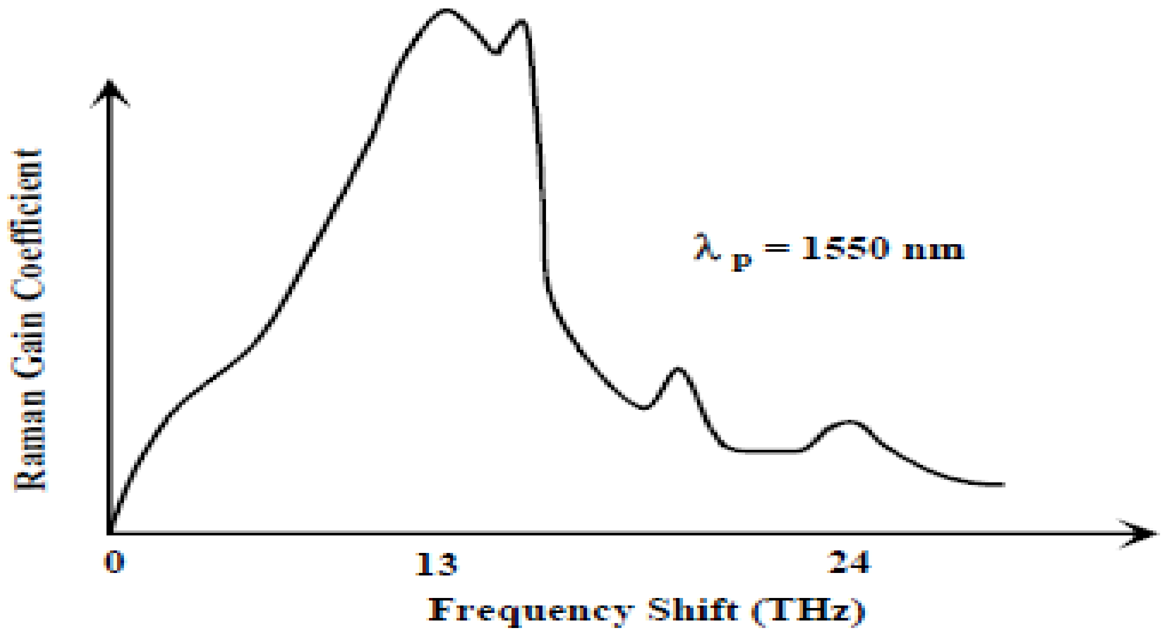
$$\nu_2 = \nu_1 - \nu_p$$



- Molecule is raised to a new *vibrational state* and the energy of the photon is reduced.
- There is a large difference between the photon and phonon energies.
- Raman scattering is *weak effect*. It occurs through a slight modulation of the refractive index through molecular vibrations of the material.
- Can derive the effect through a discussion of polarizability of a material.

Properties of Raman Amplifiers:

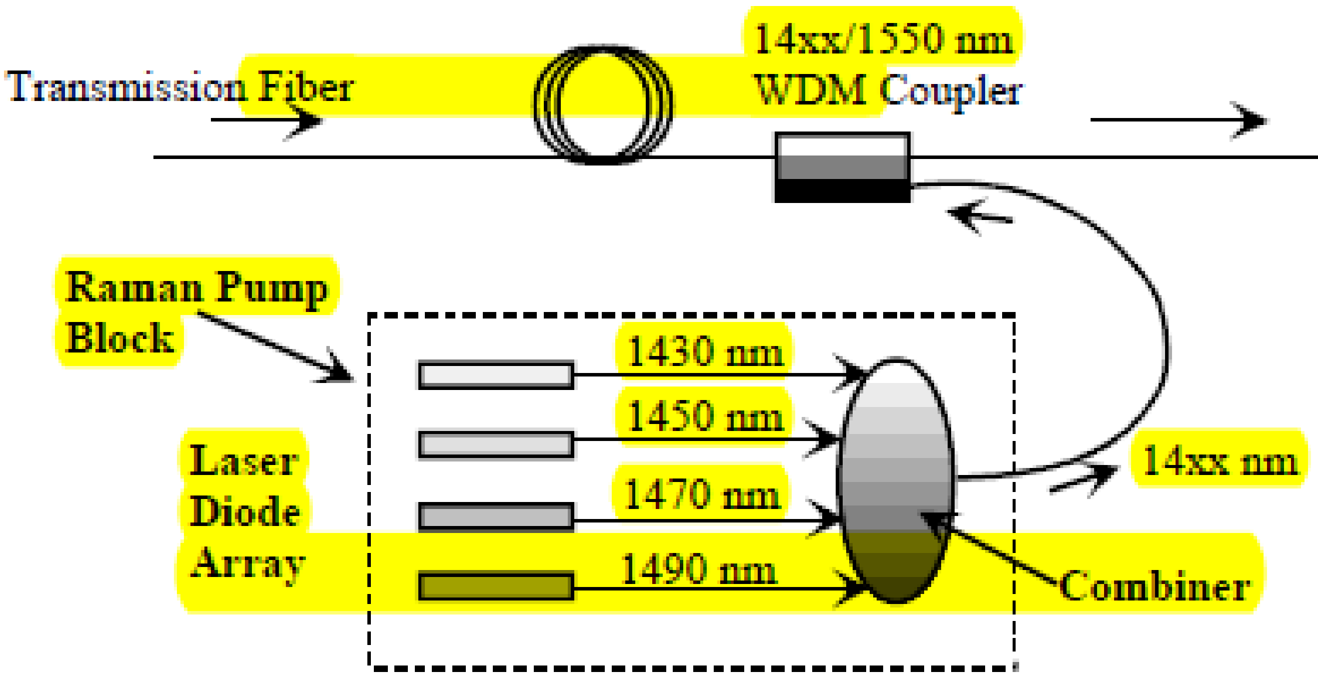
- The peak resonance in silica fibers occurs about 13 THz from the pump wavelength. At 1550 nm this corresponds to a shift of about 100 nm.



- As indicated power is transferred from shorter wavelengths to longer wavelengths.
- Coupling with the pump wavelength can be accomplished either in the forward or counter propagating direction.
- Power is coupled from the pump only if the signal channel is sending a 1 bit.

Pump Arrangement to Extend the Range for Stimulated Raman Amplification:

- An array of laser diodes can be used to provide the Raman pump. The beams are combined and then coupled to the transmission fiber. The pump beams can counter propagate to the direction of the signal beams.



Difficulties with Raman Amplifiers:

- The Pump and amplified signals are at *different wavelengths*. Therefore the signal and the pump pulses will separate due to dispersion *(waveguide dispersion)* after a certain propagation distance. The difference in *propagation time* is given by:

$$\delta\tau = (L/c)\lambda^2 d^2 n/d\lambda^2 (\delta\nu/\nu)$$

L is the fiber length.

- A 1 psec pump pulse at 600 nm separates from a 1 psec Stokes pulse in ~ 30 cm.
- A *second problem* is that the *pump power decreases* along the fiber length due to linear absorption and scattering – Raman gain is greater at the input end.
- A final problem results from *amplifying spontaneous Raman photons*. This occurs when the pump power is increased to offset attenuation losses and spontaneous Raman photons are coupled into the guided mode all along the length of the fiber. This increases noise.
- Upper limit on the power into a communications signal from SRS amplification can be defined as the *point at which the Stokes power P_r equals the signal power P_{sig}.*

$$P = \frac{16\pi w_o^2}{G_r L_{eff}}$$

$$L_{eff} = \frac{1-e^{-\alpha L}}{\alpha}$$