Key Elements of Fiber Optic Communication

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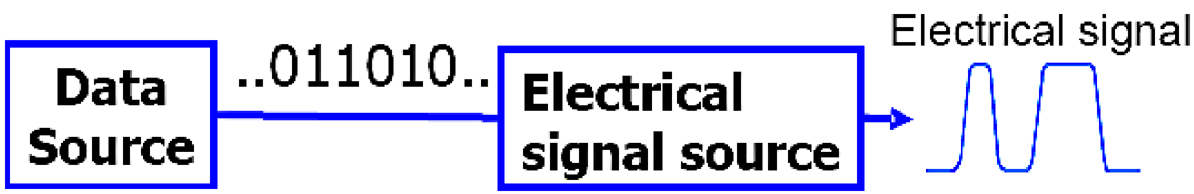
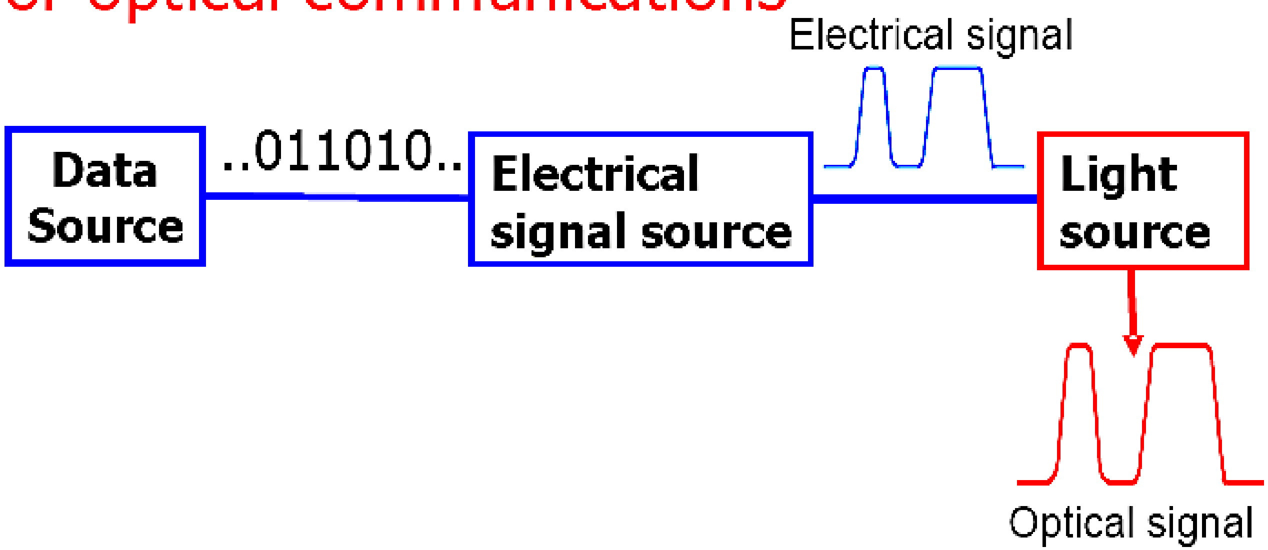
VIT

Communication by Light Signals

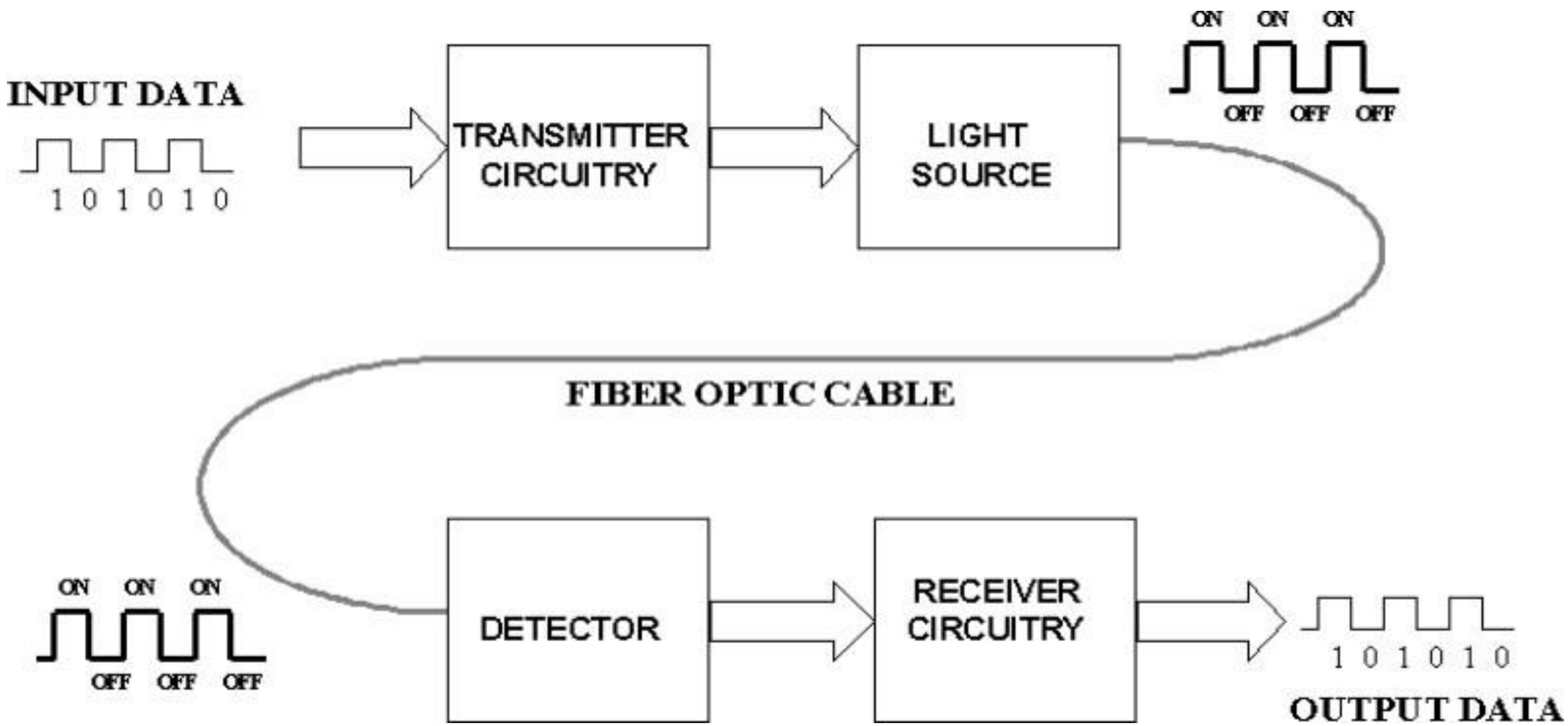
- ❑ Electrical communications

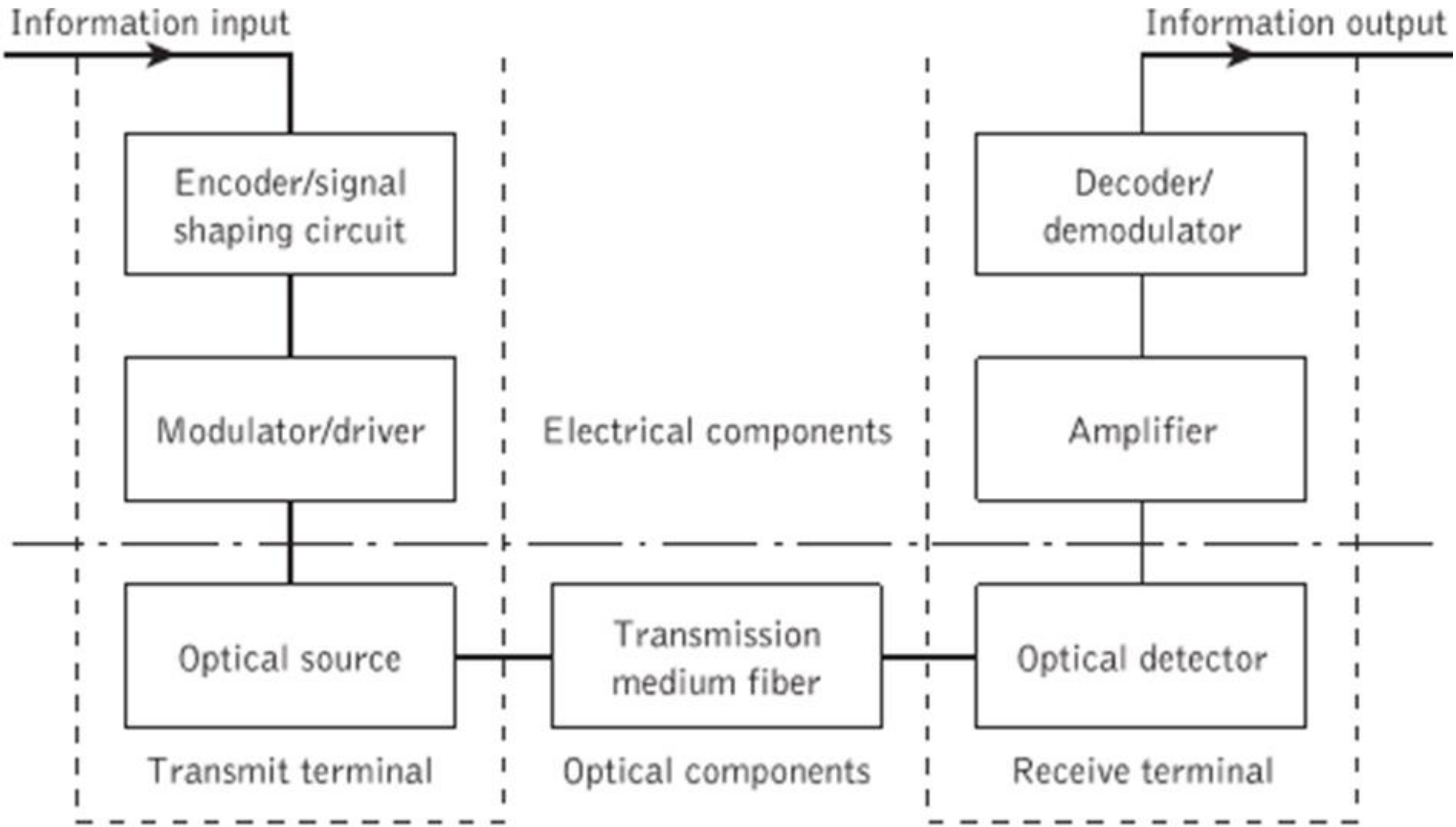


- ❑ Light or optical communications



BASIC FIBER OPTIC COMMUNICATION SYSTEM





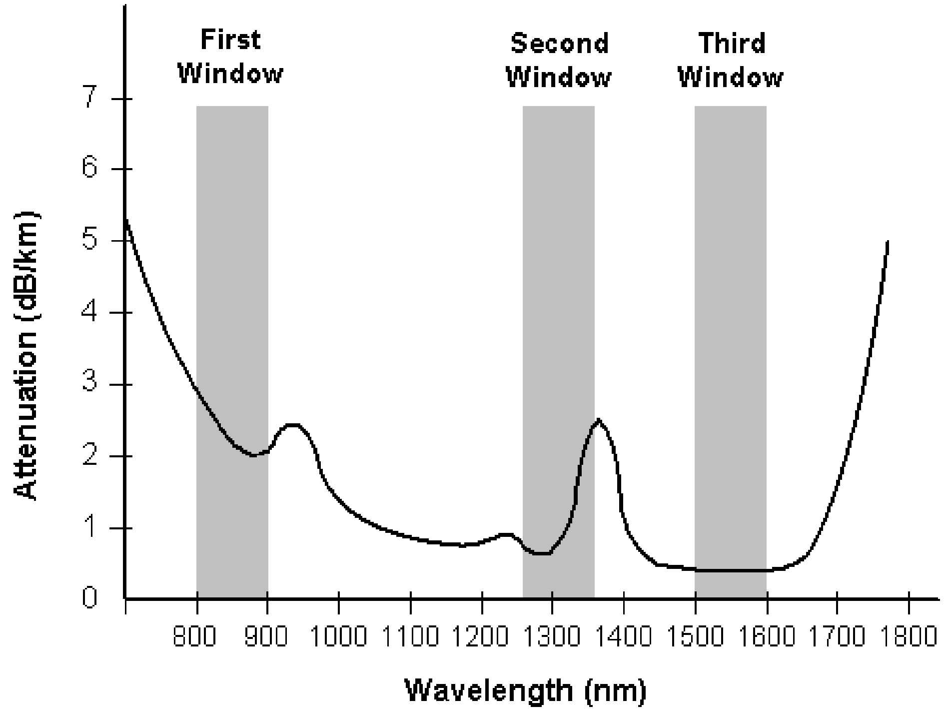
The principal components of an optical fiber communication system

OC System

- Tx
  - Sources
    - Laser
    - LED
  - Modulators
    - DM
    - EM
- OF
  - Non-dispersion shifted
  - Dispersion shifted
  - Non-Zero dispersion shifted
- Rx
  - PD → PIN, APD

Fiber Optic Transmission Windows

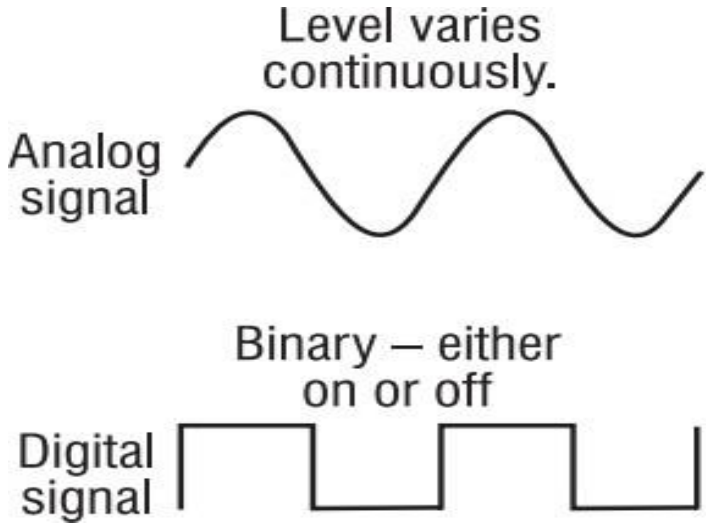
- Lasers → 1310- or 1550-nm single-mode applications
- LEDs → 850- or 1300-nm multimode applications



Fiber Optic Transmission Windows

Window	Operating Wavelength
800 – 900 nm	850 nm
1250 – 1350 nm	1310 nm
1500 – 1600 nm	1550 nm

ANALOG VERSUS DIGITAL SIGNALS



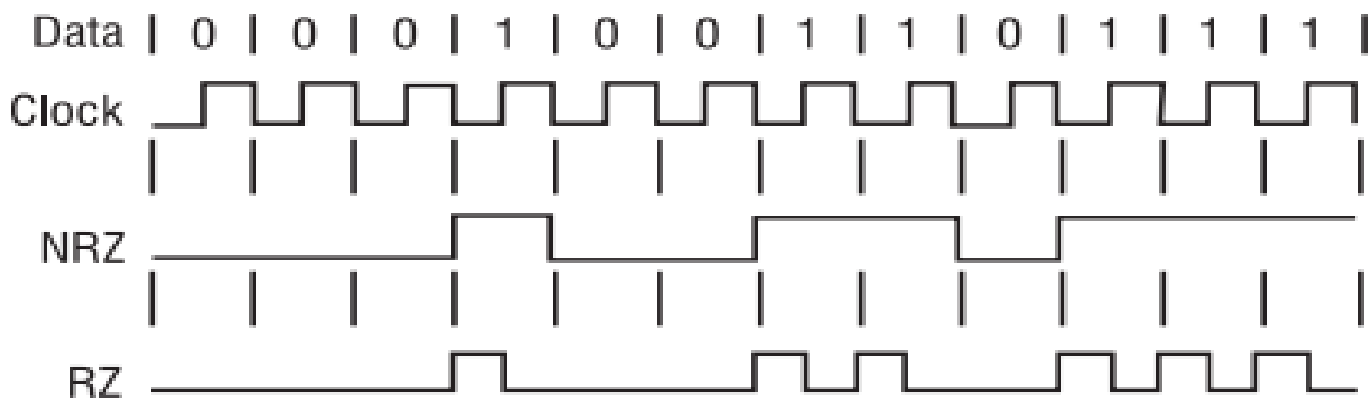
Analog Versus Digital Signals

- Easier to process
- No conversion is necessary
- Less susceptible to noise
- Harder to corrupt
- Robust to noise
- Easy to recover

DIGITAL ENCODING SCHEMES

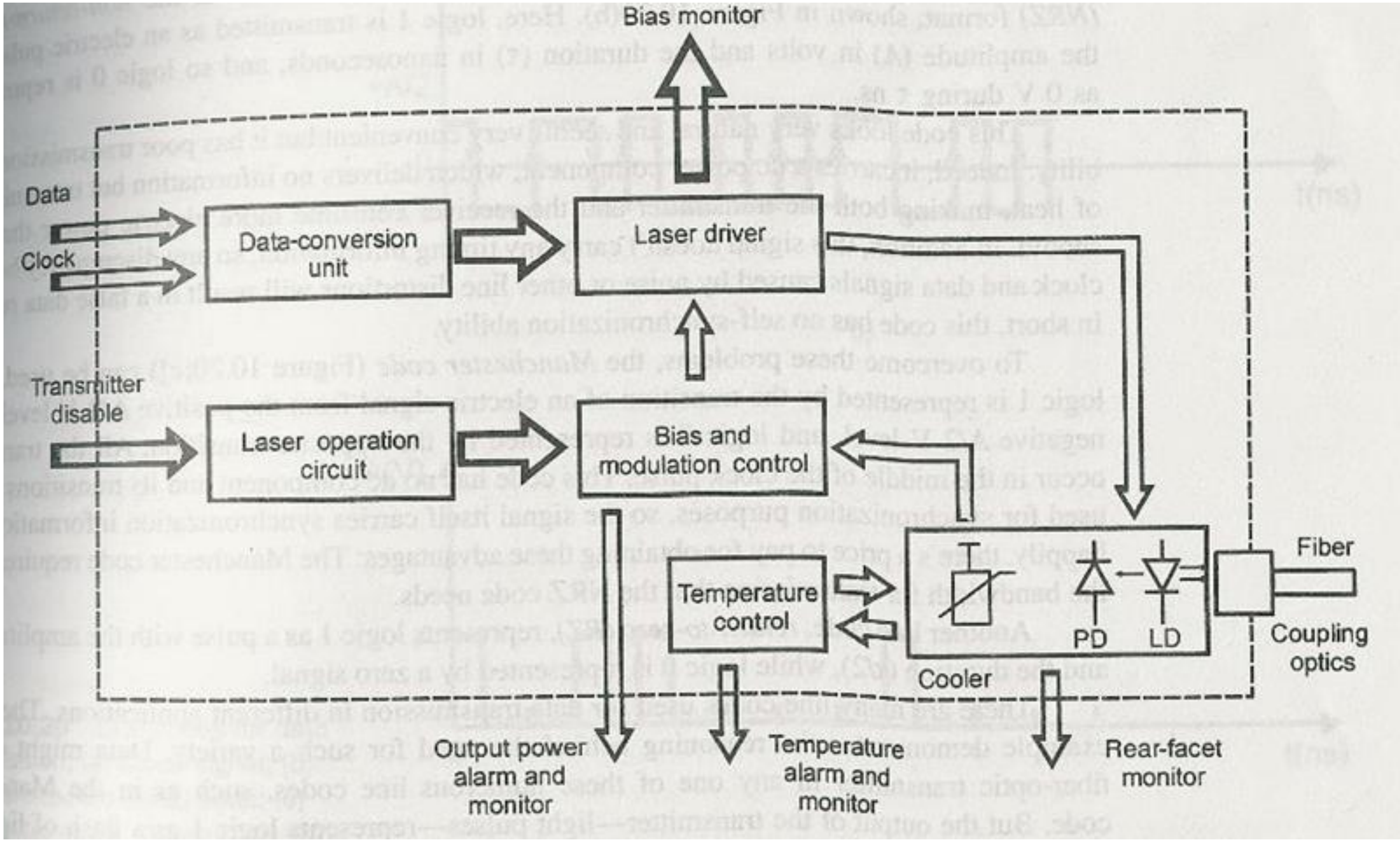
- Signal format is an important consideration in evaluating the performance of a fiber optic system.
- The signal format directly affects the detection of the transmitted signals.
- Many coding schemes are used in digital communication systems, each with its own benefits and drawbacks.
- The most common encoding schemes are the return-to-zero (RZ) and non-return-to-zero (NRZ).
- The NRZ encoding scheme, for example, requires only one transition per symbol, whereas RZ format requires two transitions for each data bit.
- This implies that the required bandwidth for RZ must be twice that of NRZ.

DIGITAL ENCODING SCHEMES



Format	Symbols per Bit	Self-Clocking	Duty Factor Range (%)
NRZ	1	No	0-100
RZ	2	No	0-50

TRANSMITTER

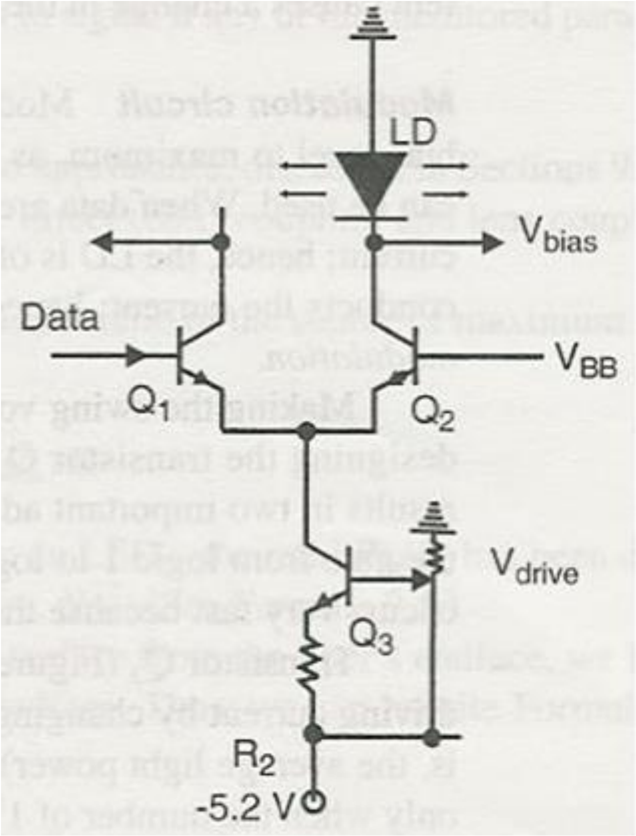


MODULATION CIRCUIT

✓Modulation is controlled by simply changing the driving current from the bias level to maximum.

✓When Data voltage > V_{BB}, transistor Q1 conducts the current.

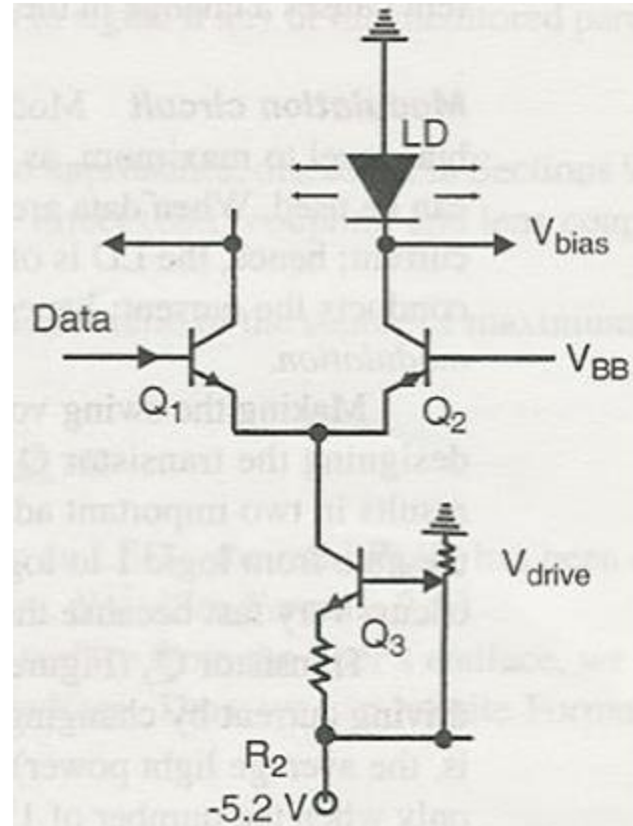
✓When Data voltage < V_{BB}, transistor Q2 conducts the current, hence LD is on.



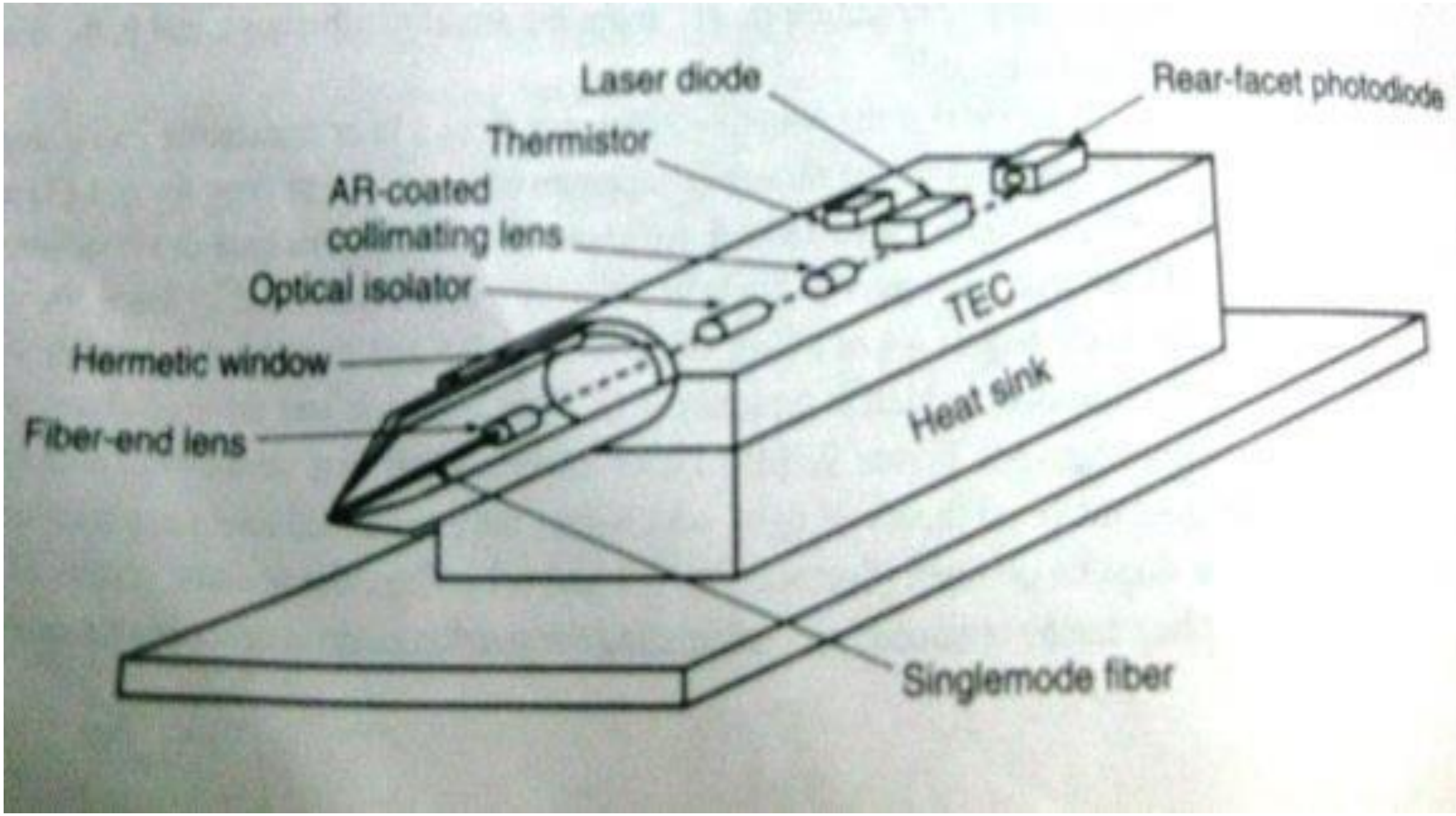
Modulation Circuit

✓ **Results in intensity modulation (optical power output of a source is varied in accordance with some characteristic of the modulating signal)**

✓ **Making the swing voltage V_{BB} small, and properly designing the transistor Q3, we can keep transistors Q1 and Q2 from saturating(switching between the transistors Q1 and Q2 occurs fast).**



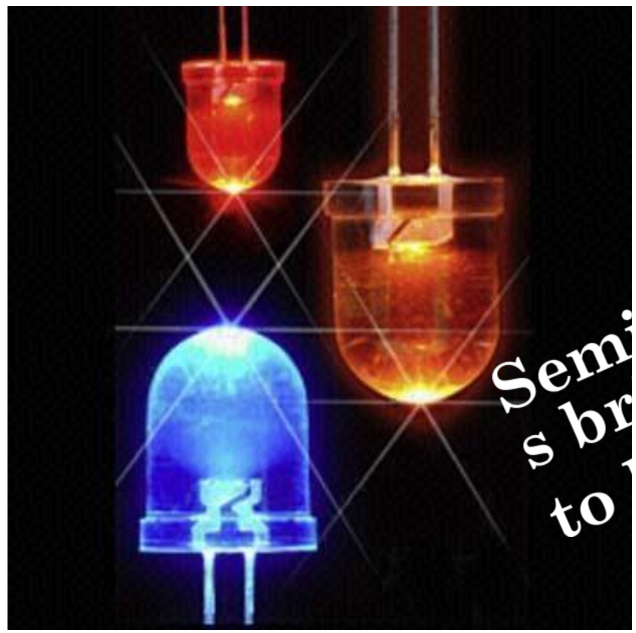
PACKAGING


Laser diode
Rear-facet photodiode
Thermistor
AR-coated
collimating lens
Optical isolator
Hermetic window
Fiber-end lens
TEC
Heat sink
Singlemode fiber

Optical Sources

- LED
  - Semiconductor device
  - Medium modulation speed
  - Incoherent output light
  - Mainly used for short range FSO systems (shorter than 1 km)
- Laser
  - Highly directional beam profile
  - Used for long range FSO systems
  - High modulation speed
  - Coherent output light
- Lamp
  - Lower efficiency compared to LED and laser
  - Lower cost
  - Low modulation speed
  - Incoherent output light
  - Provides higher power

What is LED?



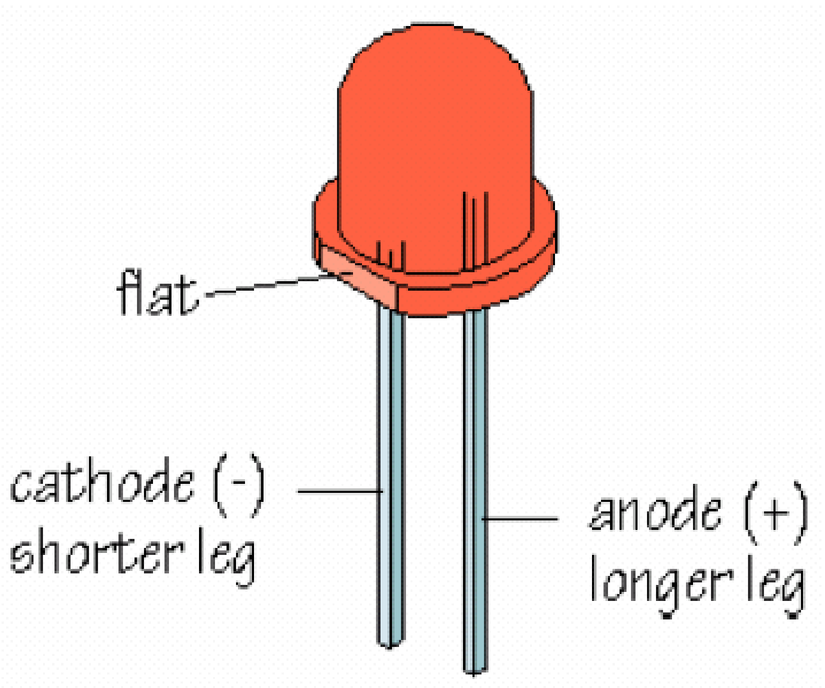
LED are semiconductor p-n junctions that under forward bias conditions can emit radiation by electroluminescence in the UV, visible or infrared regions of the electromagnetic spectrum. The qaunta of light energy released is approximately proportional to the band gap of the semiconductor.

ELECTROLUMINESCENCE

- Electroluminescence (EL) is an optical phenomenon and electrical phenomenon in which a material emits light in response to the passage of an electric current or to a strong electric field

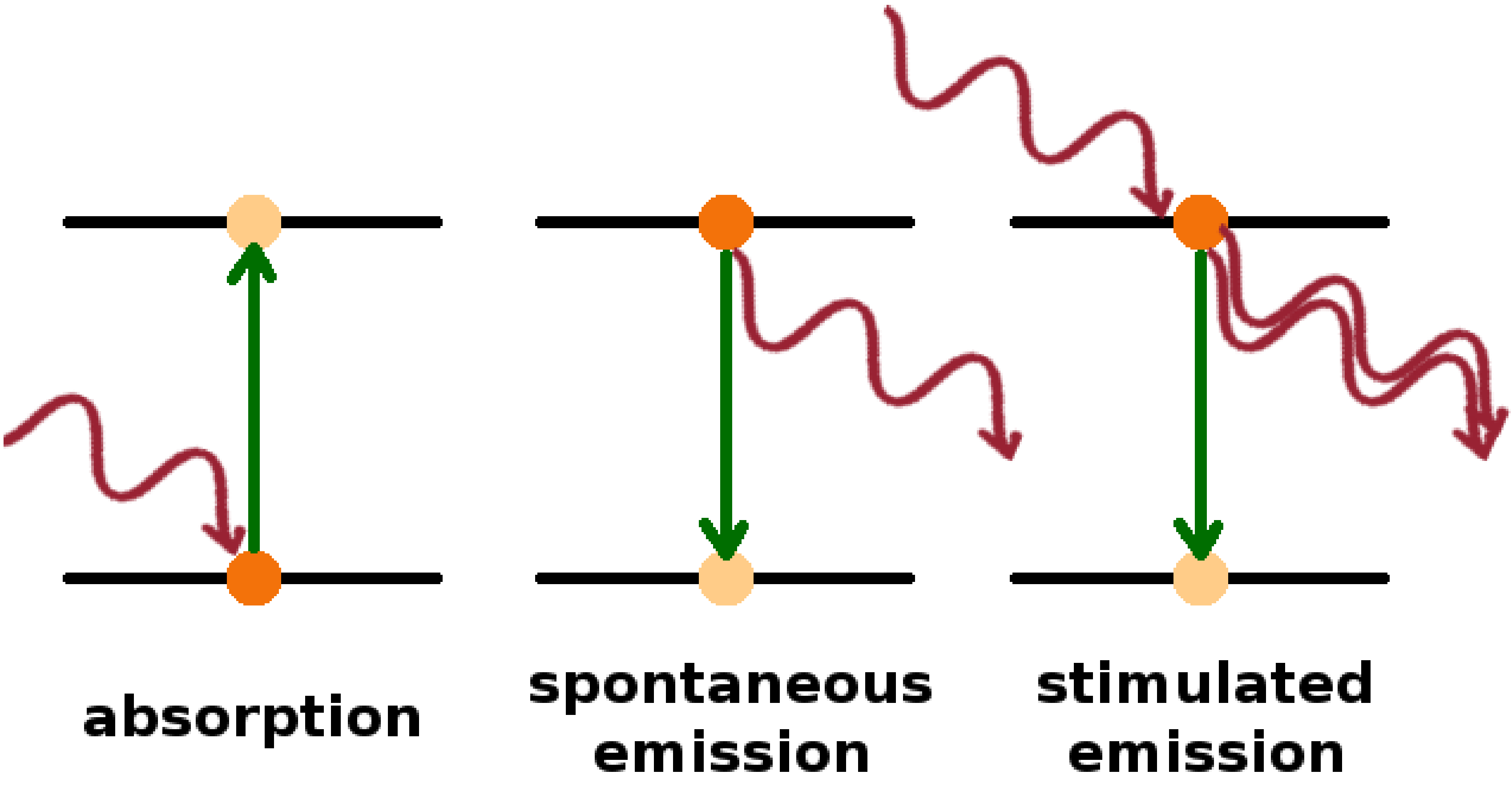
What is an LED?

- Light-emitting diode
- Semiconductor
- Has polarity

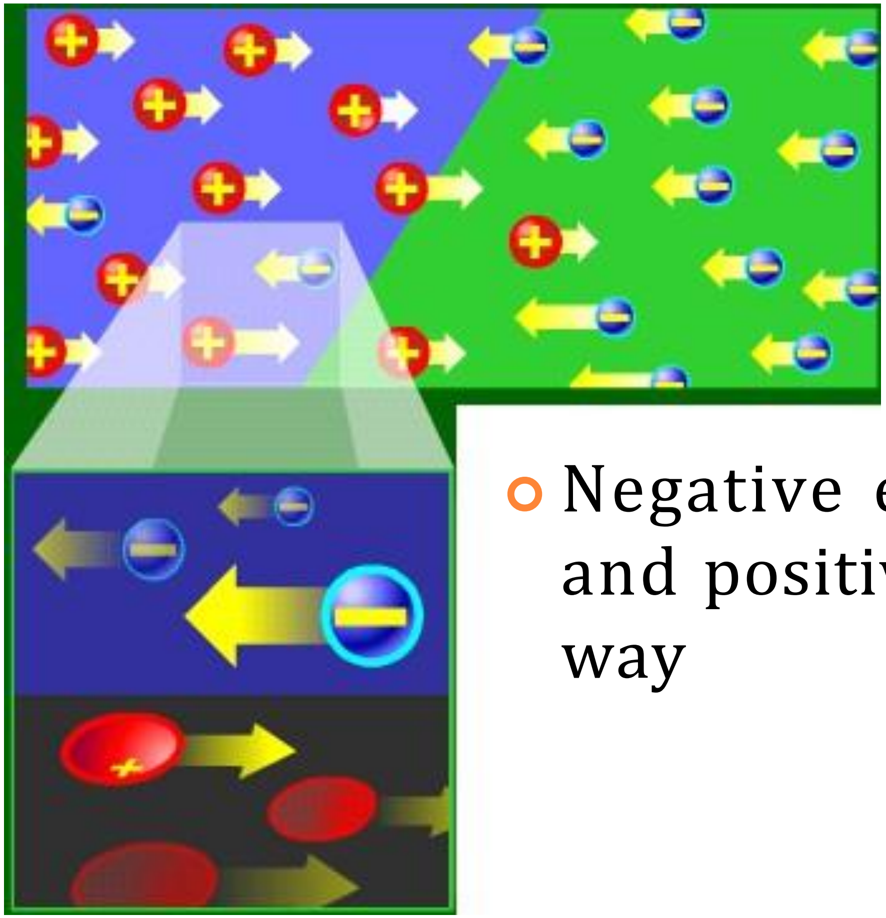


WORKING PRINCIPLE

- Spontaneous emission

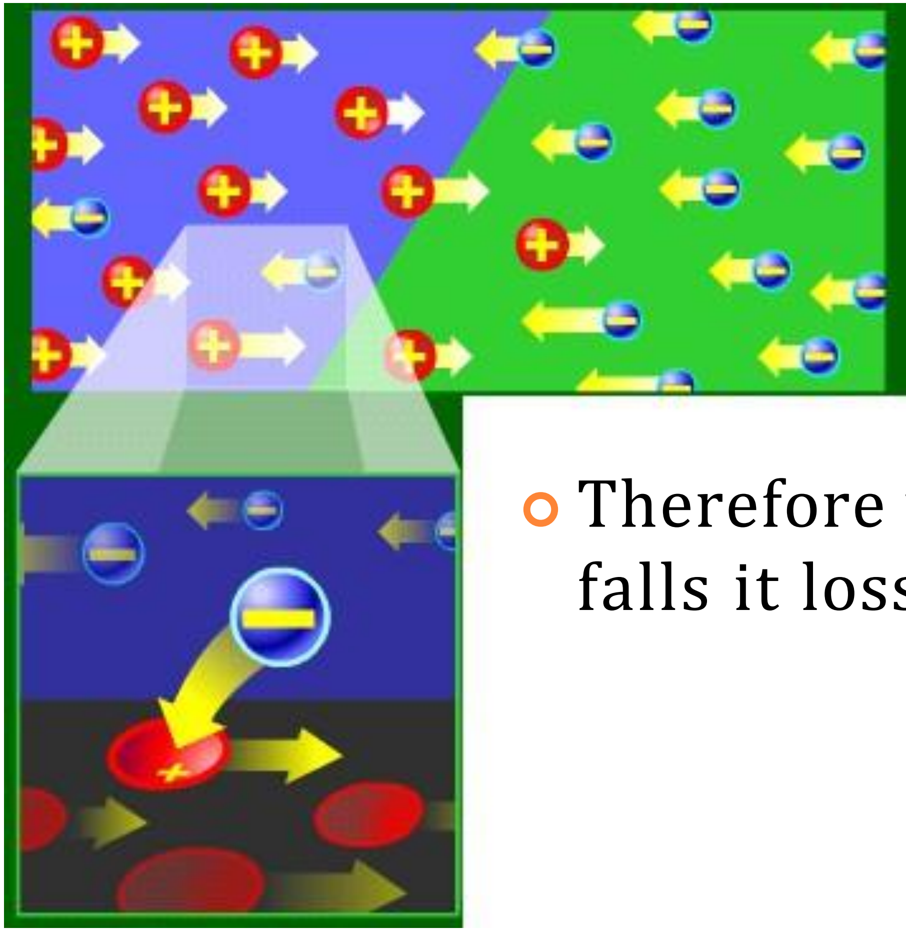


LED: How It Works



- When current flows across a diode
- Negative electrons move one way and positive holes move the other way

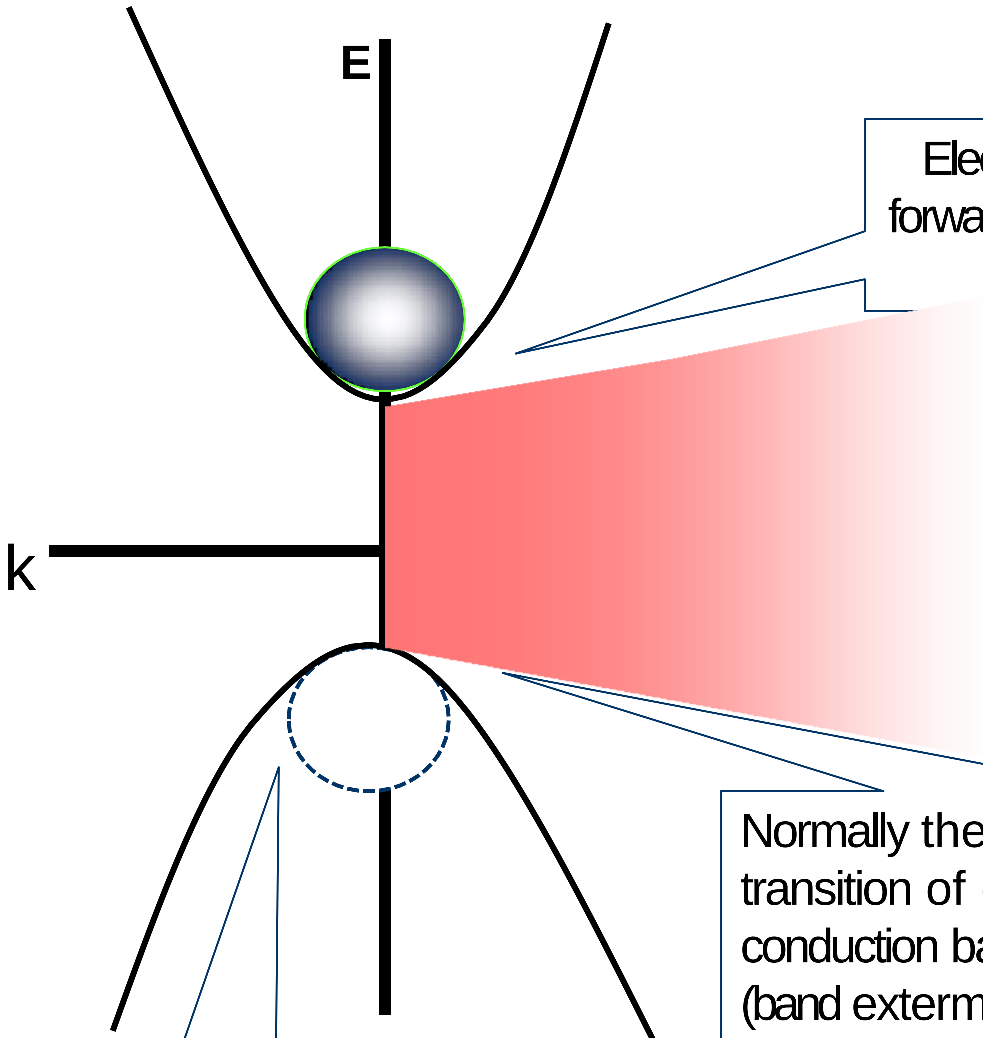
LED: How It Works



- The holes exist at a lower energy level than the free electrons

- Therefore when a free electrons falls it losses energy

Excitation



Electron (excited by the biased forward voltage) is in the conduction band

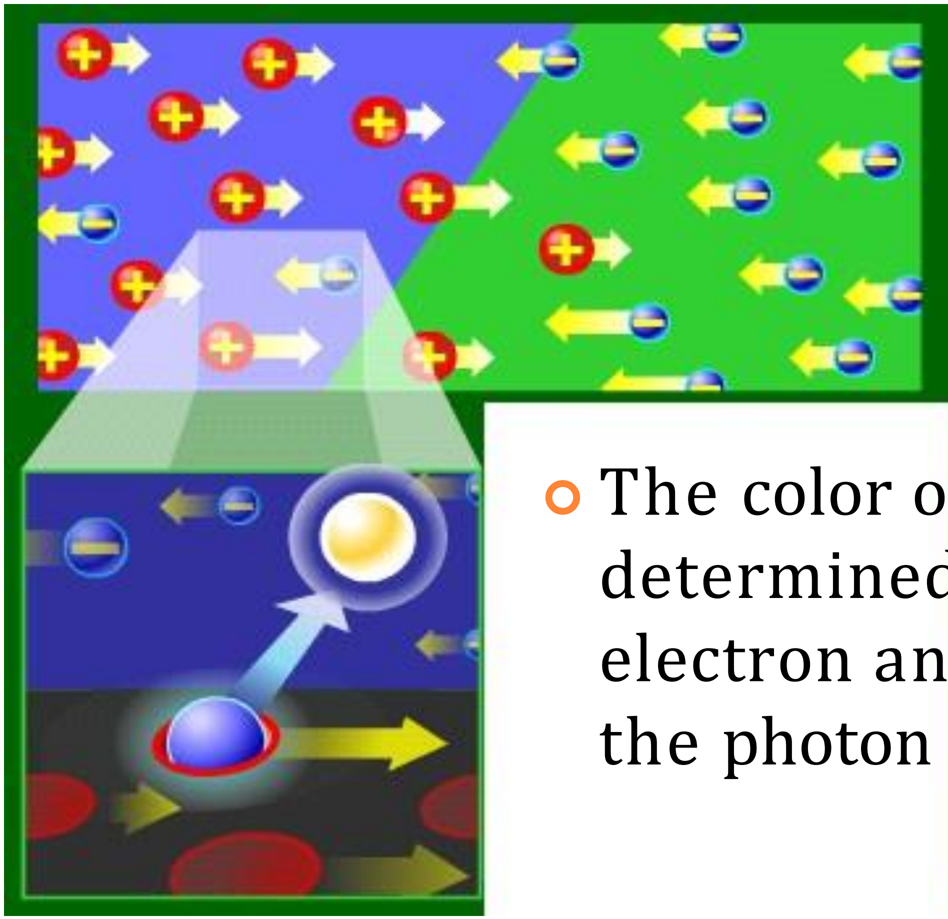
Hole is in valance band

Normally the recombination takes place between transition of electrons between the bottom of the conduction band and the top of the valance band (band exterma).

The emission of light is therefore;

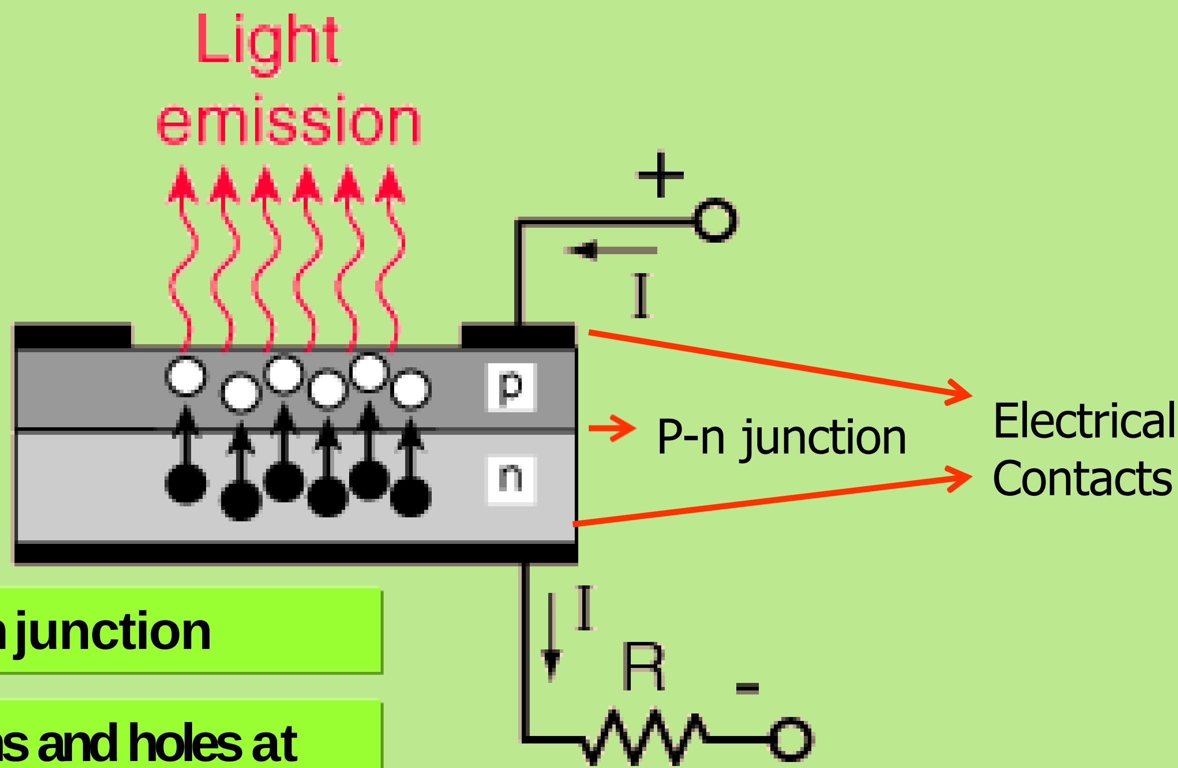
$hc/\lambda = E_c - E_v = E_g$ (only direct band gap allows radiative transition)

LED: How It Works



- This energy is emitted in a form of a photon, which causes light
- The color of the light is determined by the fall of the electron and hence energy level of the photon

How does it work?



A typical LED needs a p-n junction

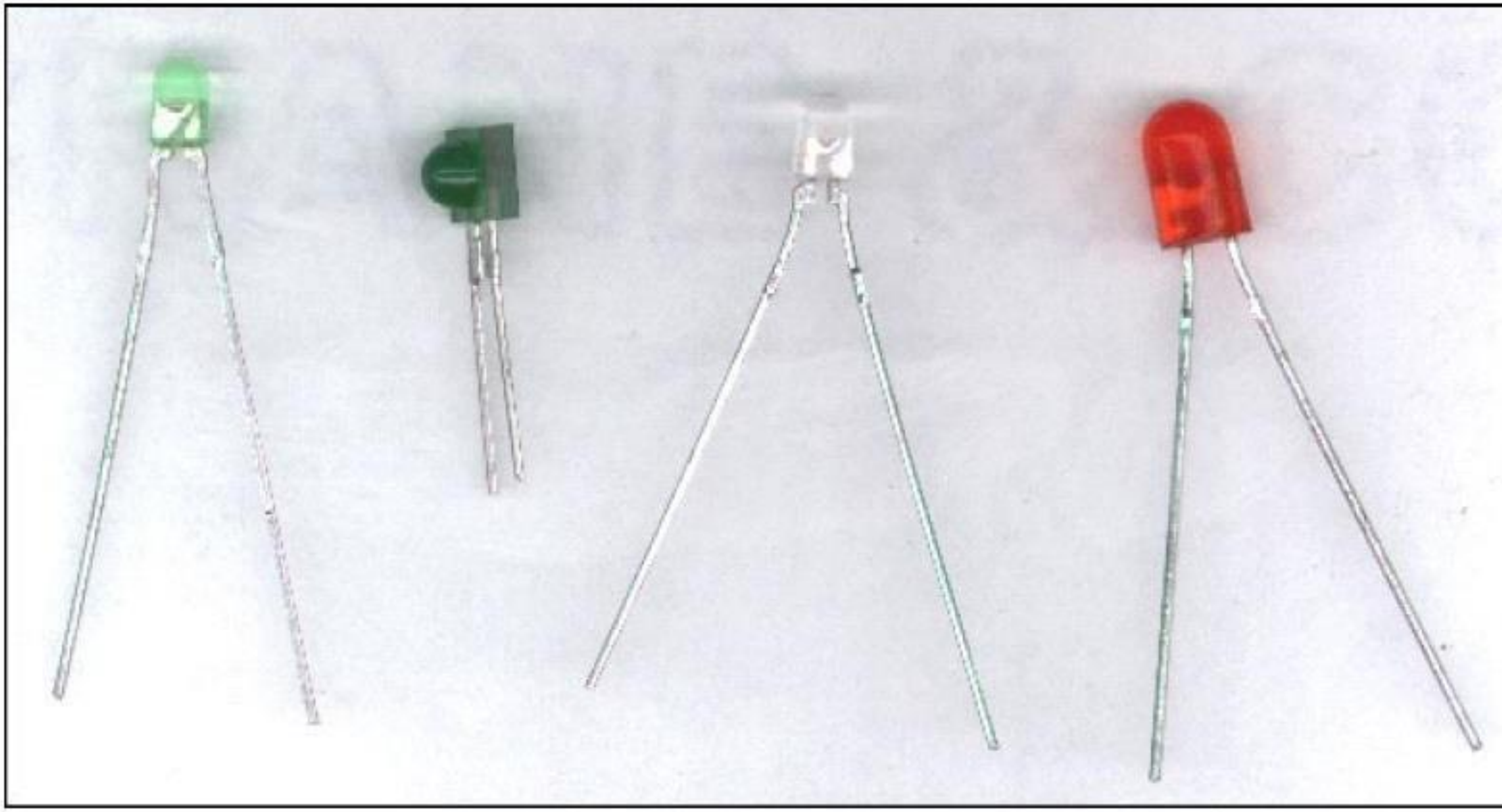
There are a lot of electrons and holes at the junction due to excitations

Electrons from n need to be injected to p to promote recombination

Junction is biased to produce even more e-h and to inject electrons from n to p for recombination to happen

Recombination produces light!!

KINDS OF LEDs



Definition:

LED which could emit visible light, the band gap of the materials that we use must be in the region of visible wavelength = 390- 770nm.   This coincides with the energy value of 3.18eV- 1.61eV which corresponds to colours as stated below:

Colour of an LED should emits

Colour	The band gap, E_g that the semiconductor must posses to emit each light
Violet	**~ 3.17eV**
Blue	**~ 2.73eV**
Green	**~ 2.52eV**
Yellow	**~ 2.15eV**
Orange	**~ 2.08eV**
Red	**~ 1.62eV**

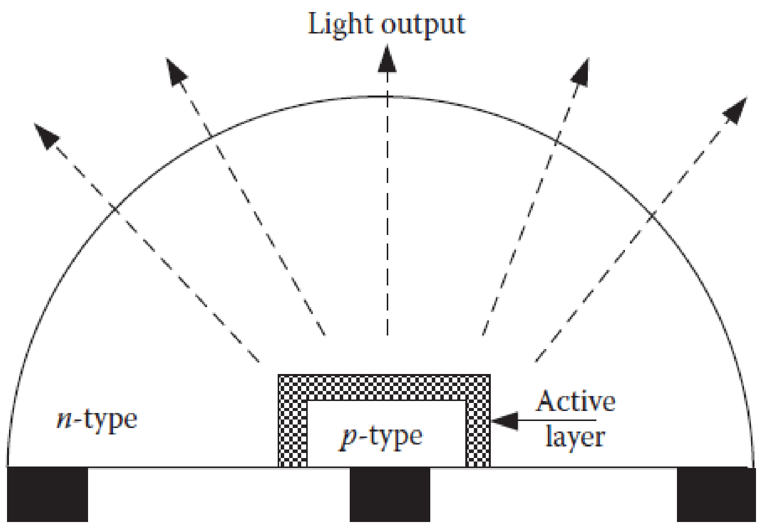
APPLICATIONS

- Displays
- Automobiles
- Home appliances

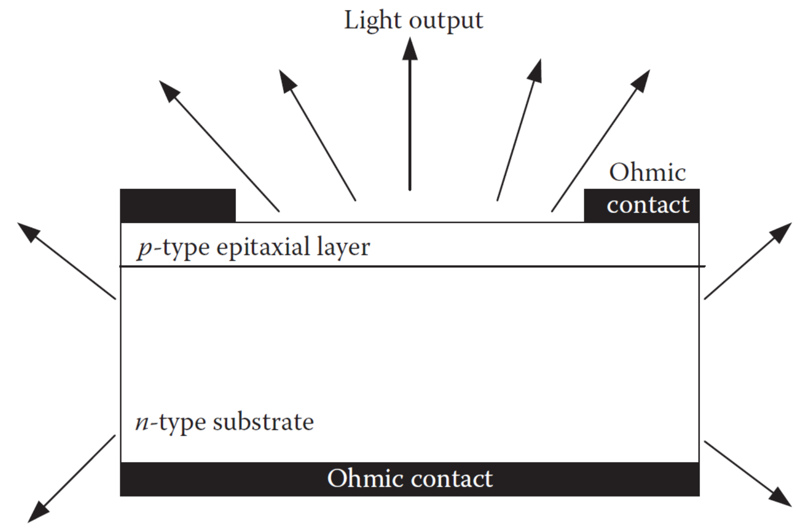
- **OLED**

LED - Types

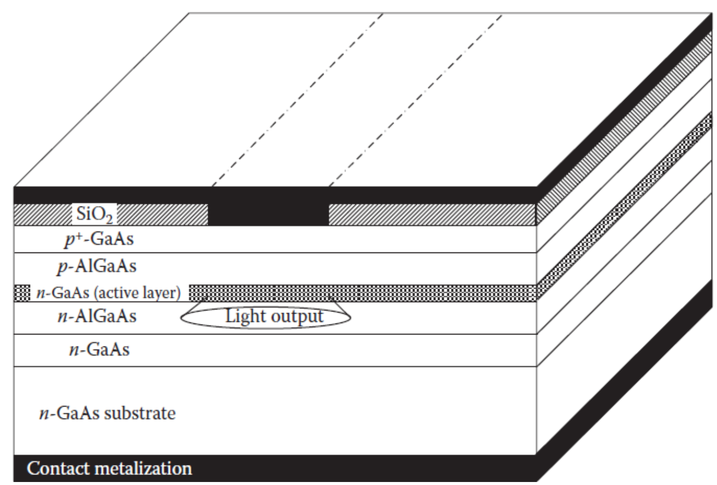
- LED Types



- Dome LED



- Planar LED



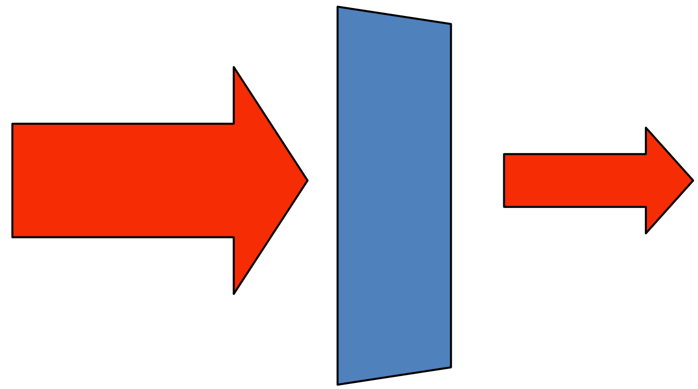
- Edge-Emitting LED

Definition of laser

- Light Amplification by Stimulated Emission of Radiation
- Principle → Stimulated emission
- Monochromatic light
- Coherent beam → All of the photons are in phase

Absorption of light

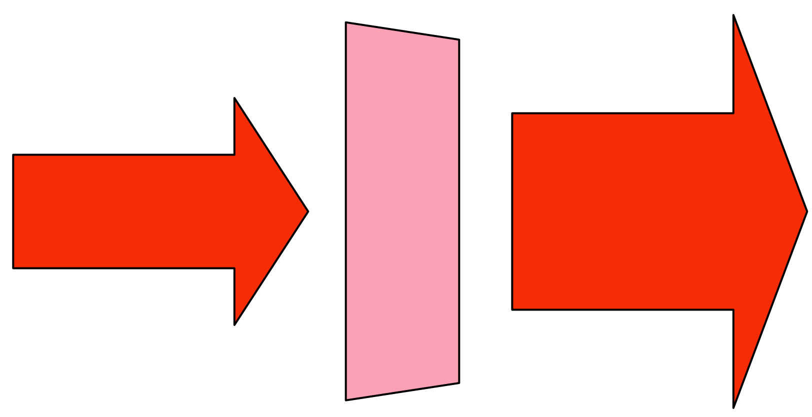
When light passes through materials it is usually absorbed.



In certain circumstances light may be amplified.

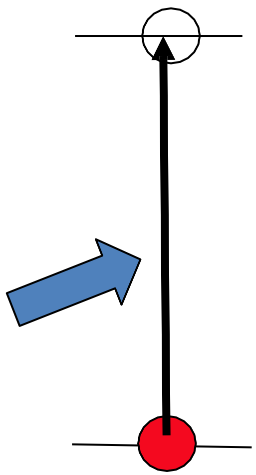
This was called “negative absorption”

It is the basis of laser action

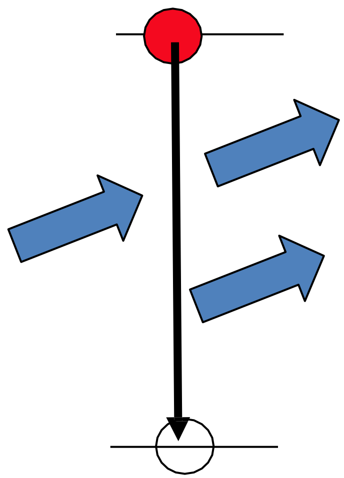


Light and an atom

Electron transitions between energy levels



Lower state full
Upper state empty
Light absorbed



Lower state empty
Upper state full
MORE light emitted

Light amplification by stimulated emission of radiation

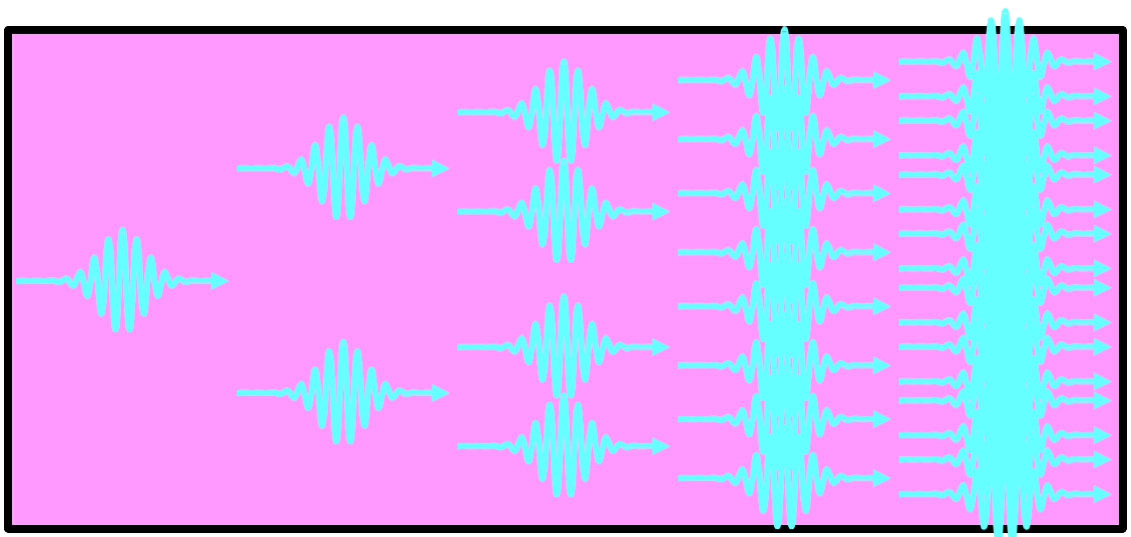
Einstein 1917

Background Physics

- In 1917 Einstein predicted that:
  - under certain circumstances a photon incident upon a material can generate a second photon of
    - **Exactly the same energy (frequency)**
    - **Phase**
    - **Polarisation**
    - **Direction of propagation**
  - **In other word, a coherent beam resulted.**

Stimulated emission leads to a chain reaction and laser emission.

If a medium has many excited molecules, one photon can become many.

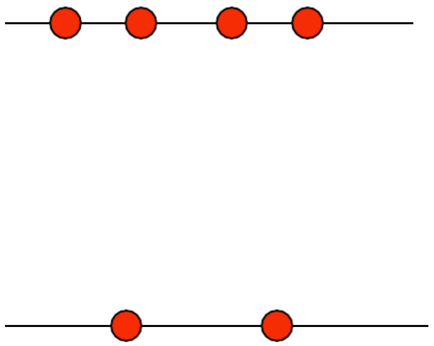


This is the essence of the laser. The factor by which an input beam is amplified by a medium is called the **gain** and is represented by G.

Can light amplify light?

Amplification:

Need more electrons at high energy than at low energy.

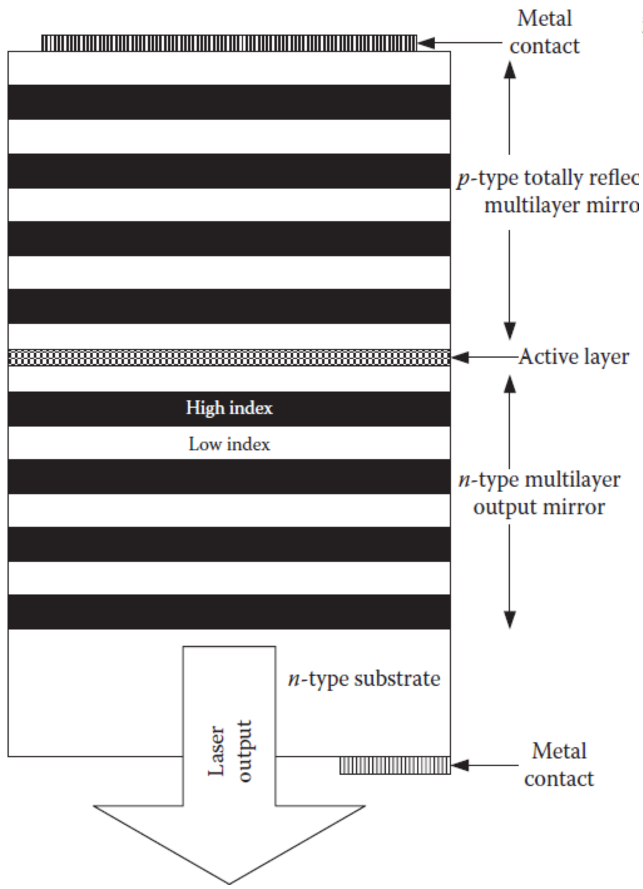


No one thought this could be done

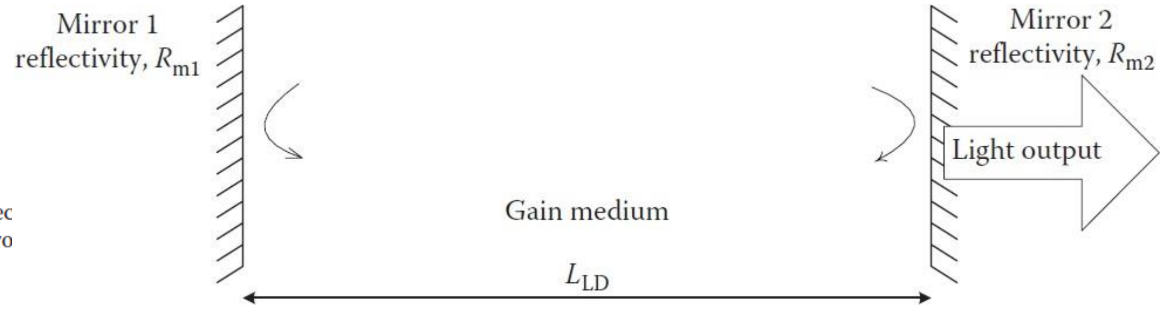
stimulated emission just a theoretical curiosity for about 30 years!

Optical Transmitters: Laser

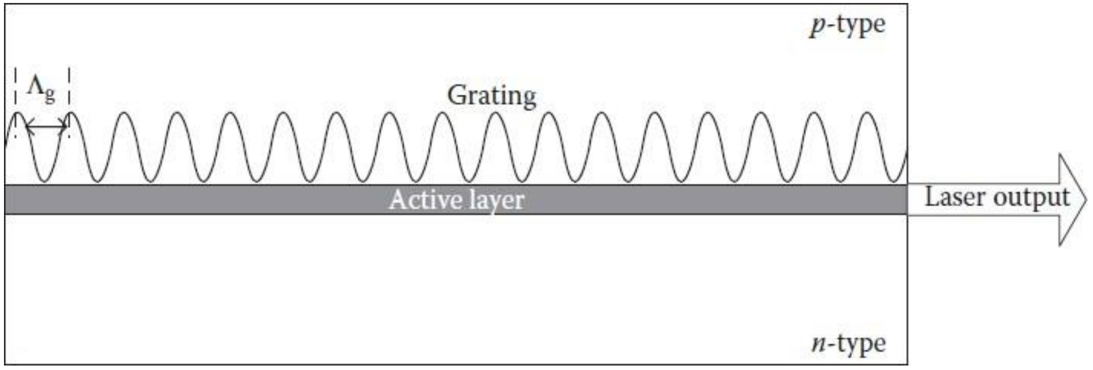
➢ Laser Types



- Vertical-cavity surface-emitting Laser (VCSEL)



- Fabry-Perot Laser



- Distributed Feedback Laser

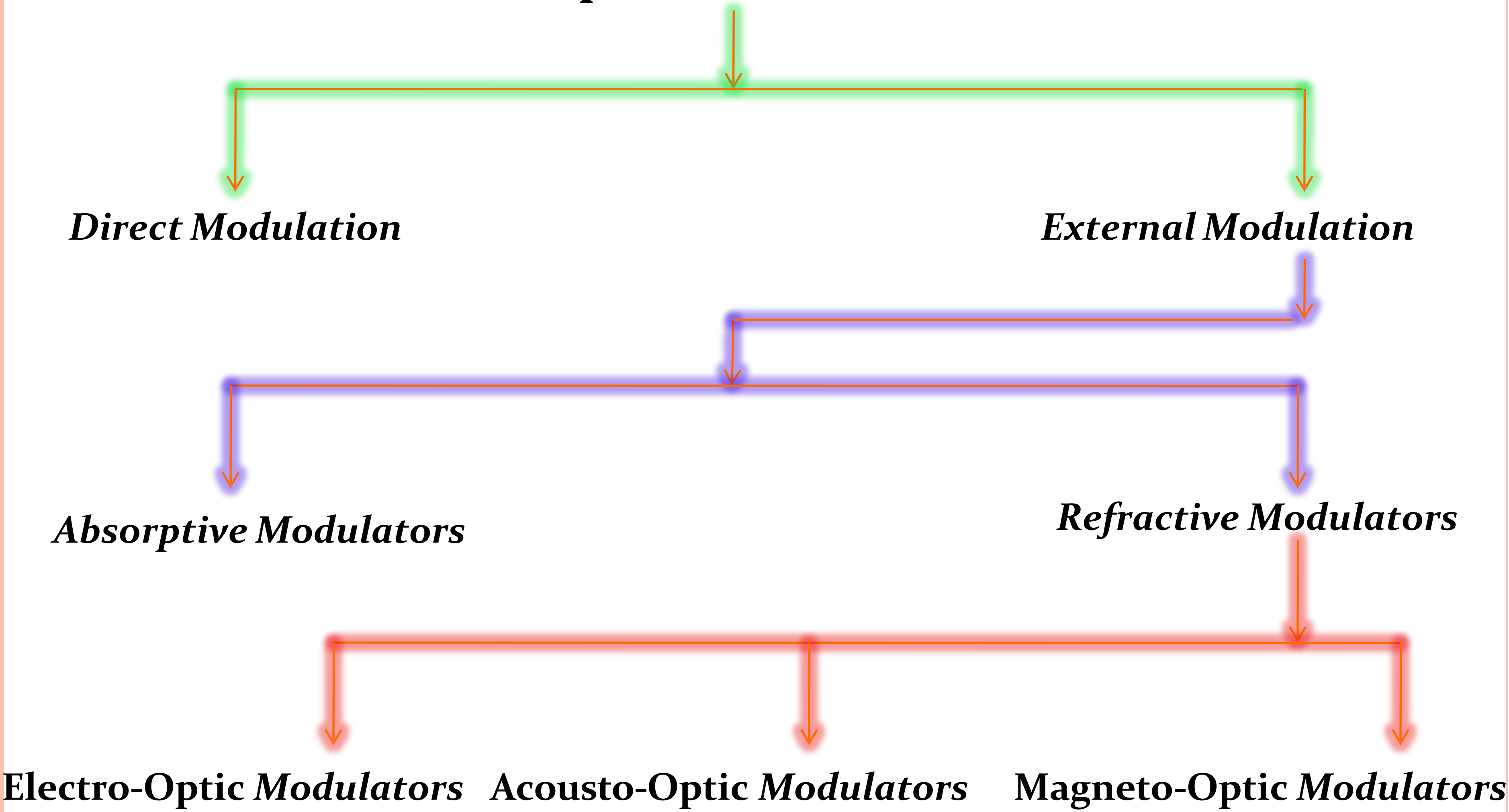
Optical Sources: Lamp

- Can be used in FSO communications, not in fiber optics
- Wideband and continuous spectrum
- Have very high power, but undirected
- The electro-optic process is inefficient, and huge amount of energy is dissipated as heat (causes high temperature in lamps)
- Has very low modulation bandwidth
- Divided as follows
  - Carbon button lamp
  - Halogen lamps
  - Globar
  - Nernst lamp

Optical Modulators

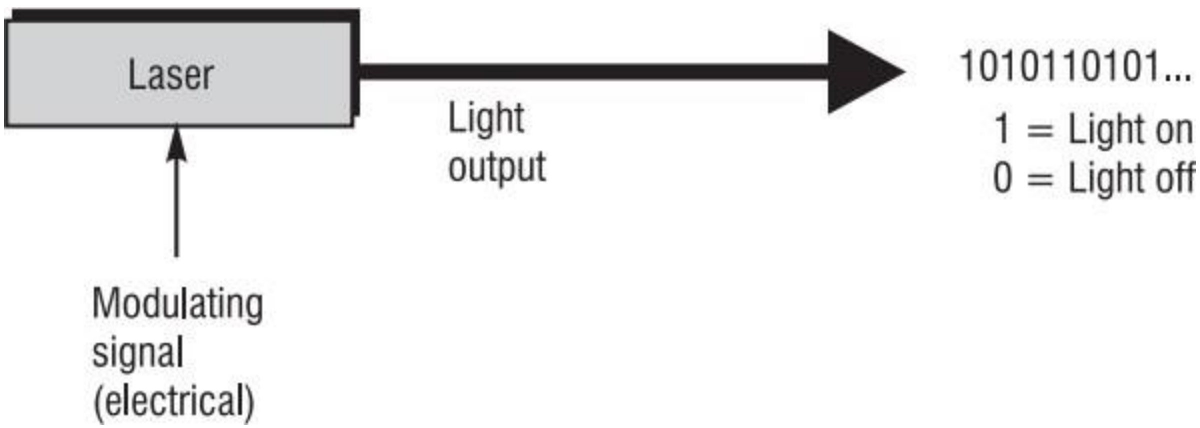
- Lasers and LEDs used in telecommunication applications are modulated using one of two methods:
  - Direct modulation
  - Indirect/External modulation.

Optical Modulators



Direct Modulation

- The output power of the device varies directly with the input drive current.
- Both LEDs and lasers can be directly modulated using analog and digital signals.



Direct Modulation

Benefits

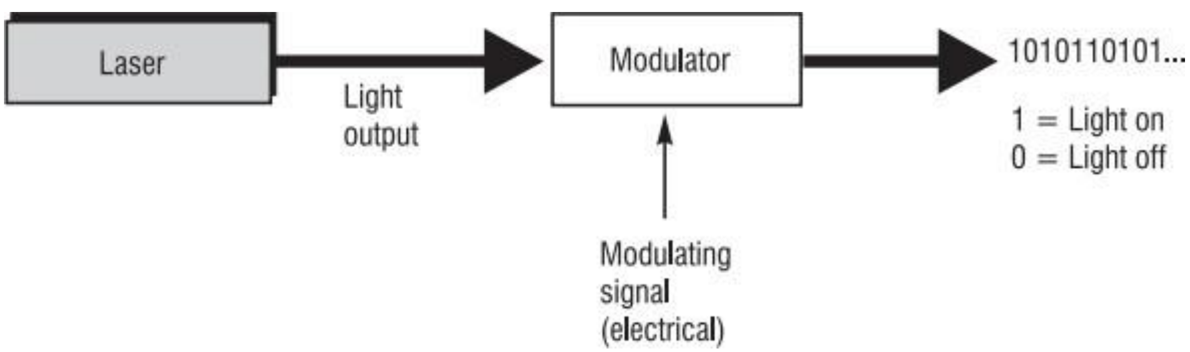
- Simple and cheap
- Cost effective
- Compact

Disadvantage

- Short distance applications
- Affects source original wavelength

EXTERNAL MODULATION

- An external device is used to modulate the intensity or phase of the light source.
- The light source remains on while the external modulator acts like a "shutter" controlled by the information being transmitted.
- External modulation is typically used in high-speed applications such as long-haul telecommunication or cable TV head ends.



External Modulation

Benefits

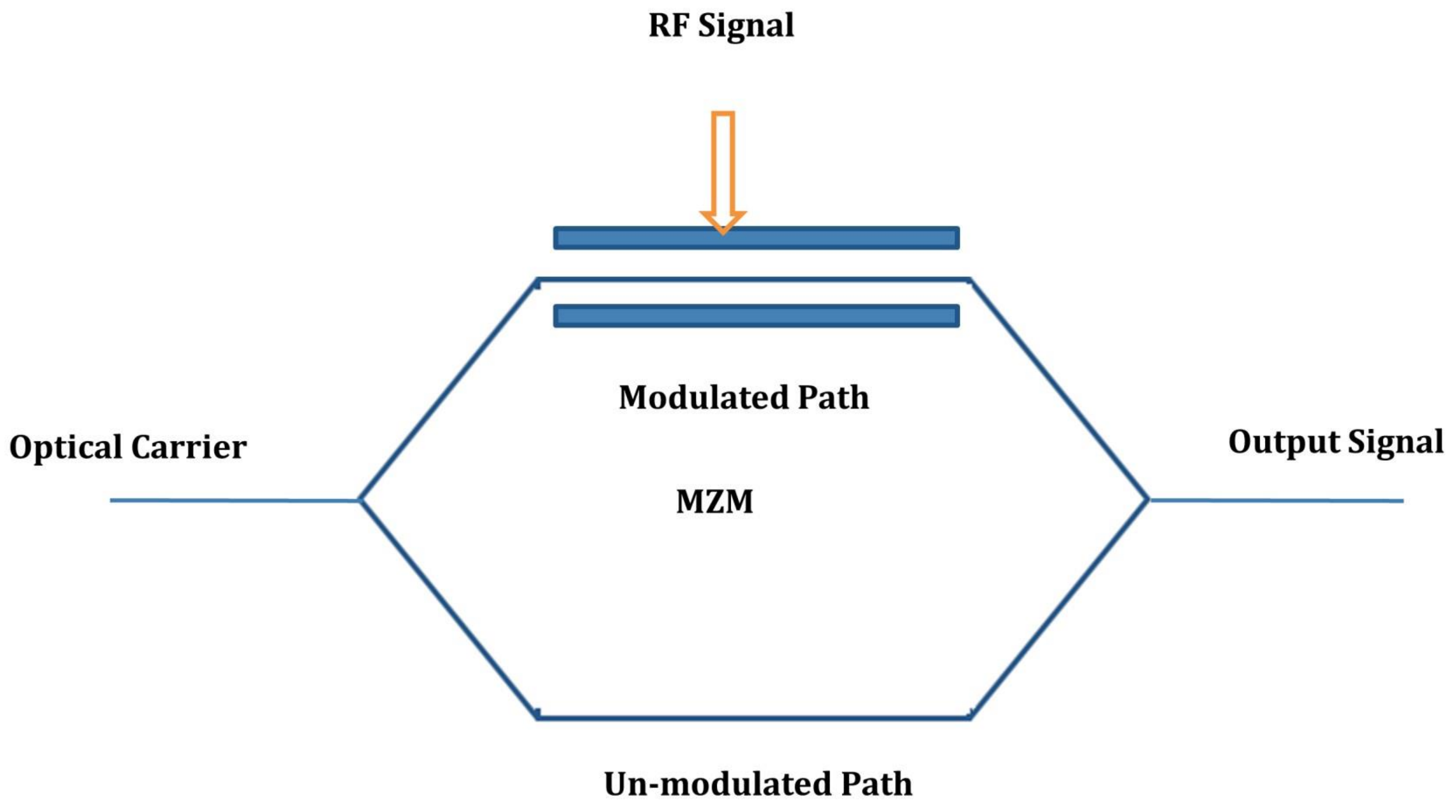
- Much faster and can be used with higher-power laser sources.
- Low Modulation distortion.

Disadvantage

- More expensive
- Requires complex circuitry to handle the high frequency RF modulation signal.

OPTICAL MODULATORS - MZM

- MZM consists of an input splitter arm, two arms (one modulated and one un-modulated arm) and an output combiner arm.
- At the modulating arm an RF signal is applied.

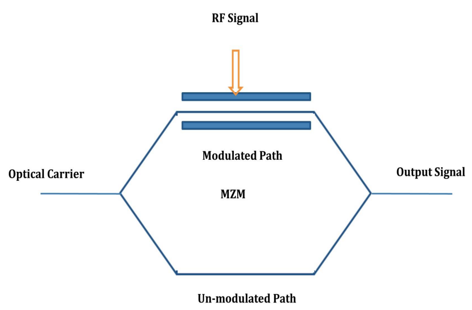


OPTICAL MODULATORS - MZM

- The other path has electrodes placed across it.
- Because LiNbO3 is an electro-optic material, when a voltage is placed across the waveguide its index of refraction is changed, causing a phase delay proportional to the amplitude of the applied voltage.
- When the light is then recombined, the two waves interfere with one another.
- If the two waves are in phase, the interference is constructive and the output is on.
- If the two waves are out of phase, the interference is destructive and the waves cancel each other.
- The input voltage associated with a 180° phase shift is known as V_{π} . The induced phase shift can be calculated using:

$$\boxed{\text{Phase shift} = \Delta\theta = 180° \times V_{in}/V_{\pi}}$$

- where V_{in} is the voltage applied to the modulator.



OPERATION OF MZM

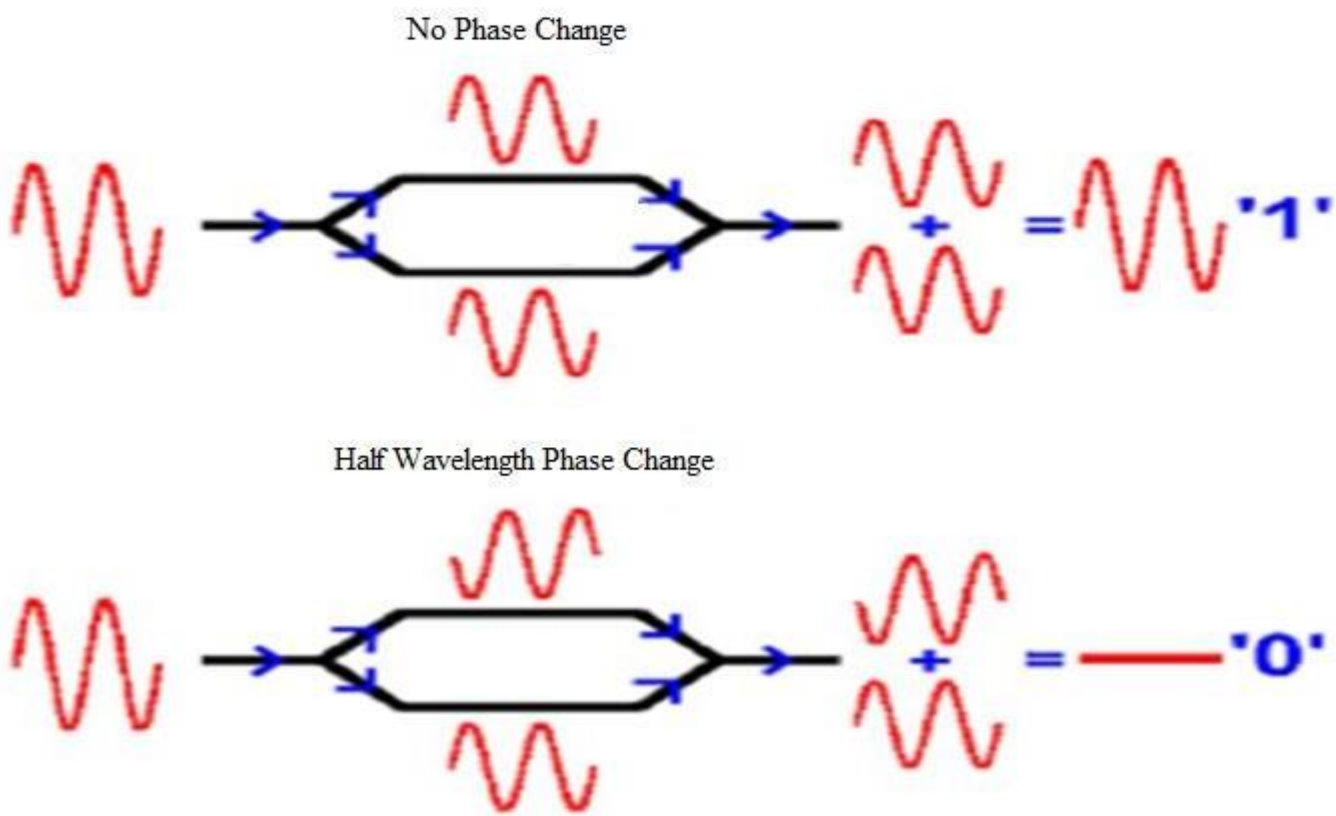
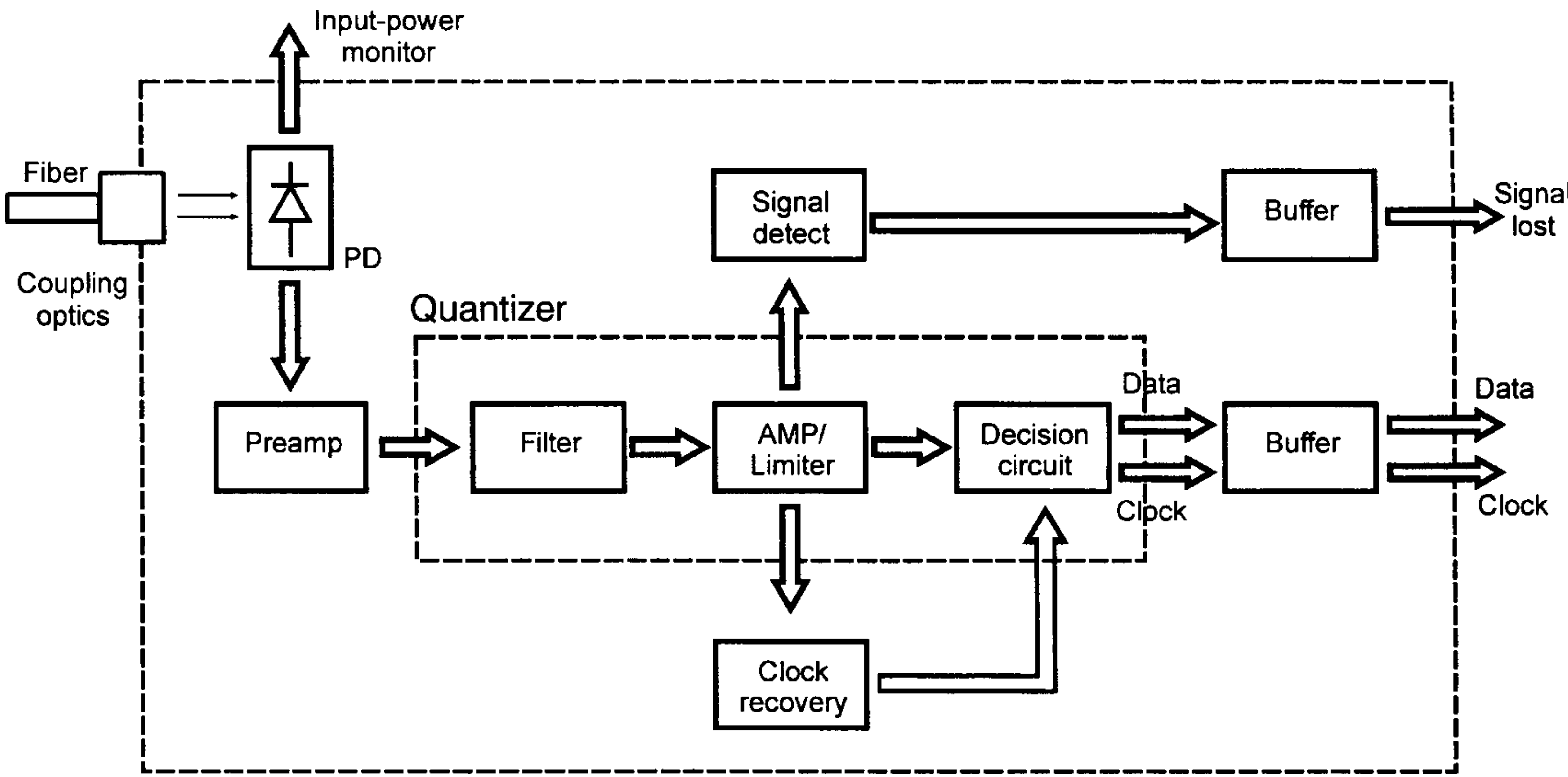


Image Courtesy : Wikipedia

RECEIVER FUNCTIONAL BLOCK DIAGRAM



Fiber-Optic Communications Technology-Mynbaev & Scheiner

OPTICAL FRONT END

- Optical front end-A photodiode along with the preamplifier
  - Converts light into electric voltage
    - Photodiode converts light into photocurrent
    - Preamplifier converts photocurrent into voltage, amplifies the signal, and presents it to quantizer.

- The load resistance of the photodiode plays a very important role in both noise and bandwidth considerations.

- The load resistance of the photodiode should be high in order to decrease thermal noise and increase photodiode's sensitivity.

- So a high input impedance amplifier is used-design is called high-impedance design.

QUANTIZER

- Includes a noise filter, a power amplifier/limiter and a decision circuit.

- Noise filter
  - Improves the SNR or ultimately Sensitivity.
  - By restricting bandwidth reduces intersymbol interference.

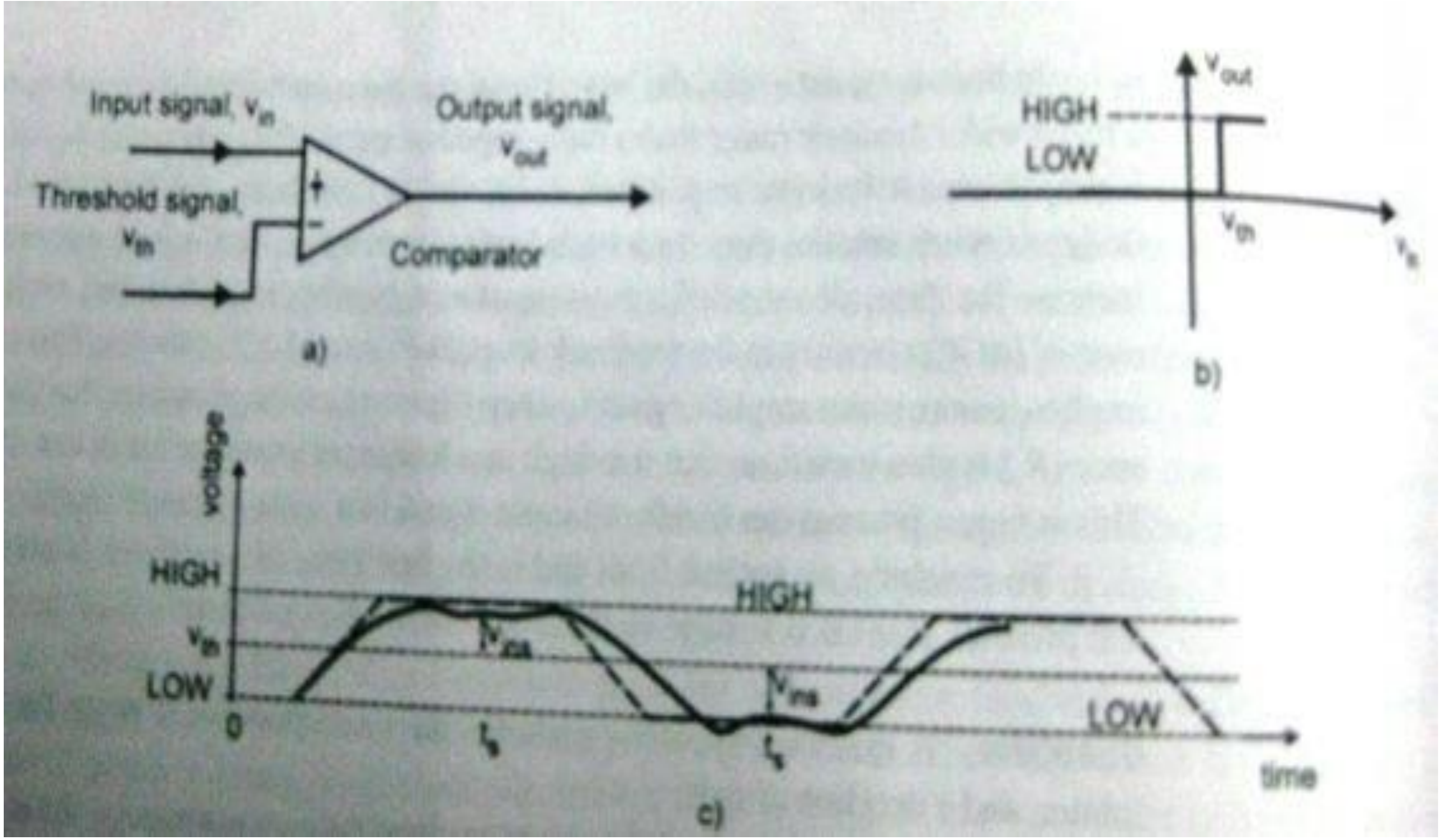
- Power amplifier/Limiter
  - Provides power amplification of a signal obtained from a preamp through the noise filter.
  - If the amplified signal is high enough, this circuit clips the signal-thus the name limiter.

QUANTIZER

- Includes a noise filter, a power amplifier/limiter and a decision circuit.

- Decision Circuit
  - Determines the logical meaning of the received signal.
  - Typically ,this is a comparator driven by the input signal.
  - When $V_{in}>V_{th}$, comparator's output is high, so decision is made that this signal carries logic HIGH or 1.
  - When $V_{in}<V_{th}$, comparator's output is low, so decision is made that this signal carries logic LOW or 0.

QUANTIZER



a)Basic circuit b)comparator output c)decision making process

Photo Detectors

- Optical receivers convert optical signal (light) to electrical signal (current/voltage)
  - Hence referred 'O/E Converter'
- Photodetector is the fundamental element of optical receiver, followed by amplifiers and signal conditioning circuitry
- There are several photodetector types:
  - Photodiodes, Phototransistors, Photon multipliers, Photo-resistors etc.

Requirements

- Compatible physical dimensions (small size)
- Low sensitivity (high responsivity) at the desired wavelength and low responsivity elsewhere → wavelength selectivity
- Low noise and high gain
- Fast response time → high bandwidth
- Insensitive to temperature variations
- Long operating life and low cost

Photodiodes

- *Photodiodes* meet most the requirements, hence widely used as photo detectors.
- Positive-Intrinsic-Negative (*pin*) photodiode
  - No internal gain, robust detector
- Avalanche Photo Diode (*APD*)
  - Advanced version with internal gain M due to self multiplication process
- Photodiodes are sufficiently *reverse biased* during normal operation → no current flow without illumination, the intrinsic region is fully depleted of carriers

MATERIALS OF CONSTRUCTION

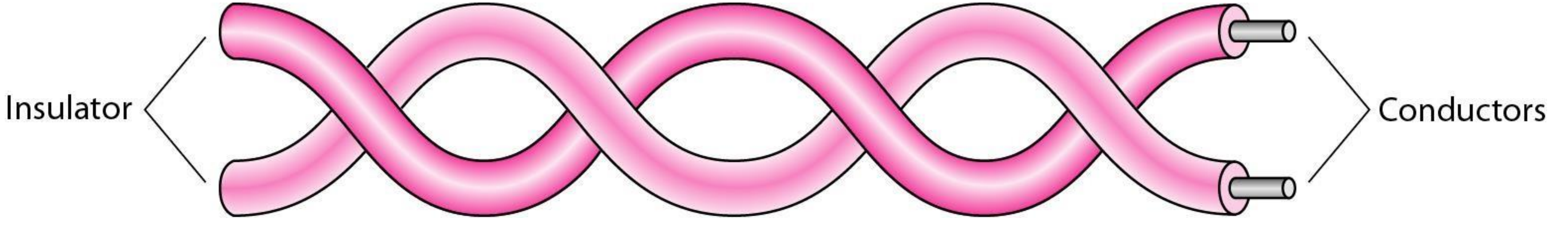
- The material used to make a photodiode is critical to defining its properties, because only **photons** with sufficient energy to excite **electrons** across the material's **bandgap** will produce significant photocurrents.
- Materials commonly used to produce photodiodes include:

Material	Wavelength range (nm) (for good sensitivity)
Silicon	190–1100
Germanium	400–1700
Indium gallium arsenide	800–2600
InGaAsP	<1000-3500

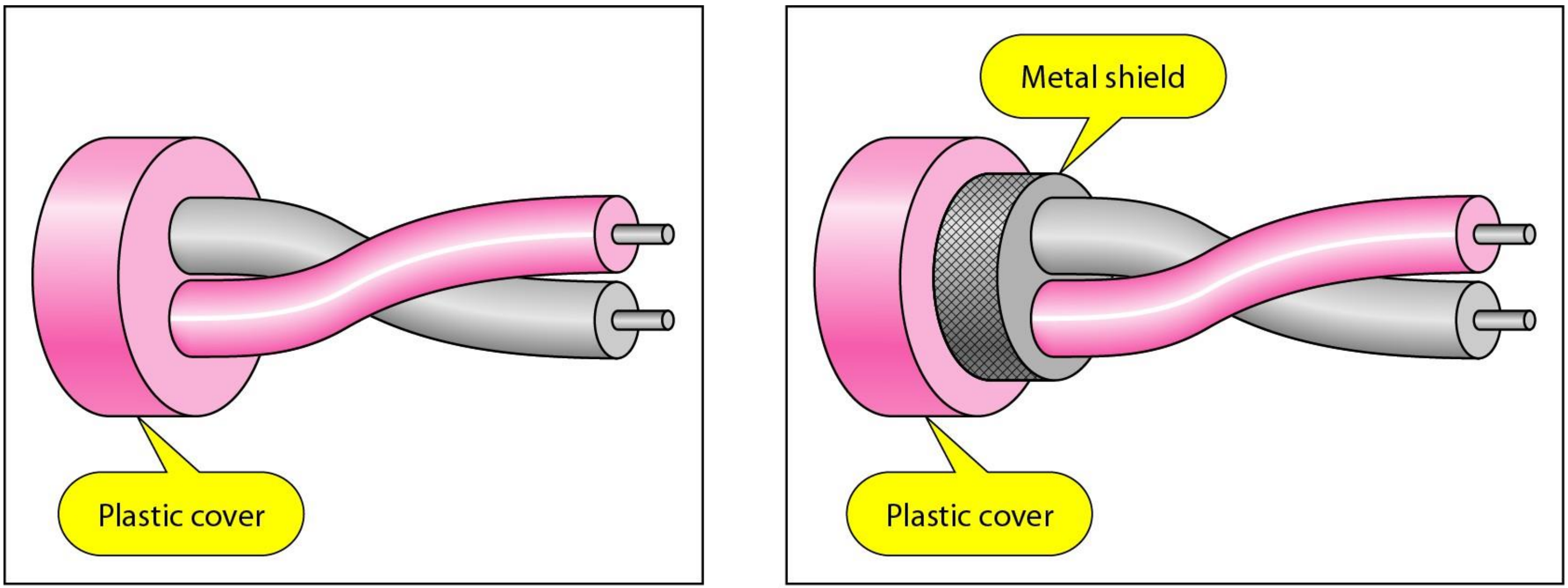
Transmission Media

- Two main categories:
  - Guided — wires, cables
  - Unguided — wireless transmission, e.g. radio, microwave, infrared, sound, sonar
- We will concentrate on guided media here:
  - Twisted-Pair cables:
    - Unshielded Twisted-Pair (UTP) cables
    - Shielded Twisted-Pair (STP) cables
  - Coaxial cables
  - Fiber-optic cables

Twisted-pair cable



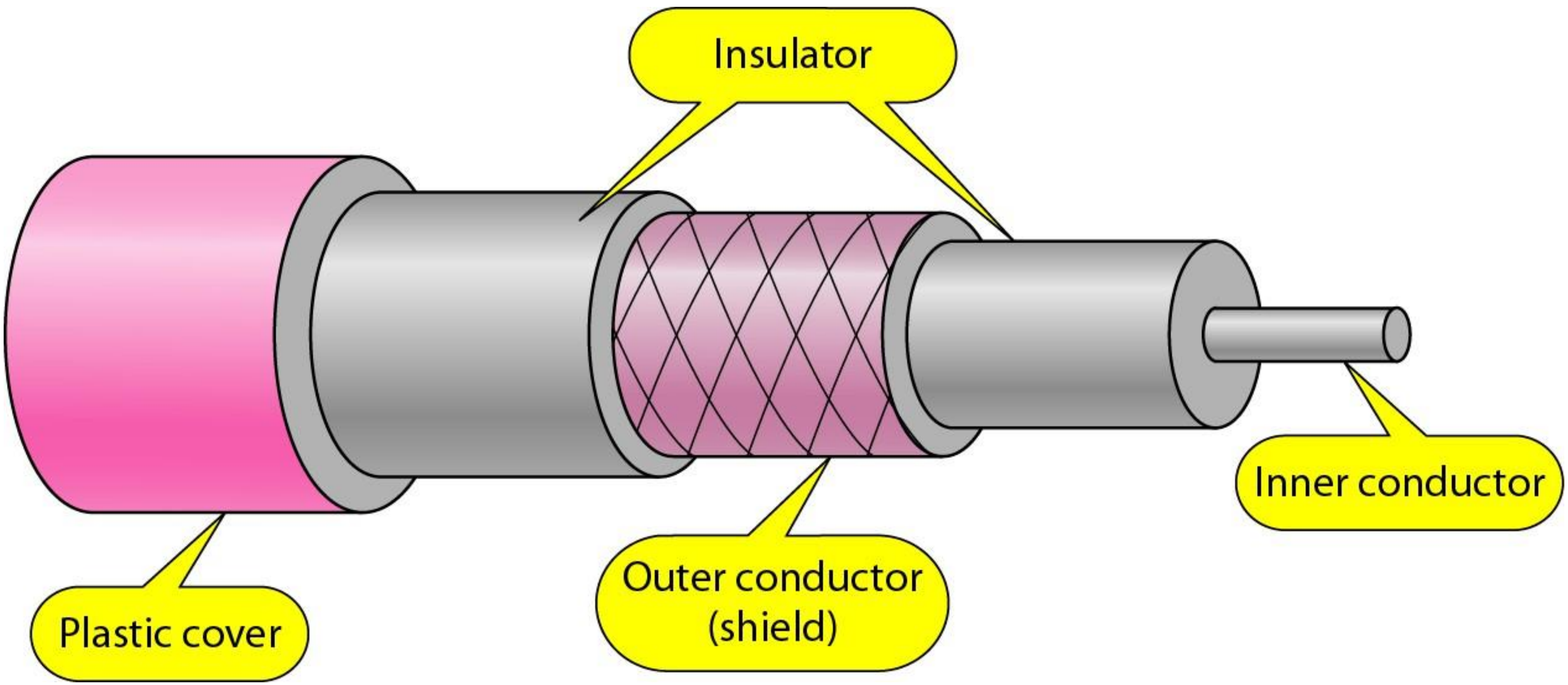
UTP and STP cables



a. UTP

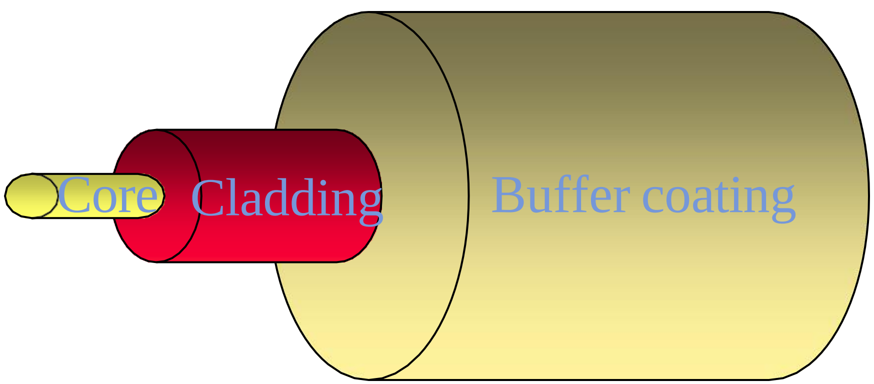
b. STP

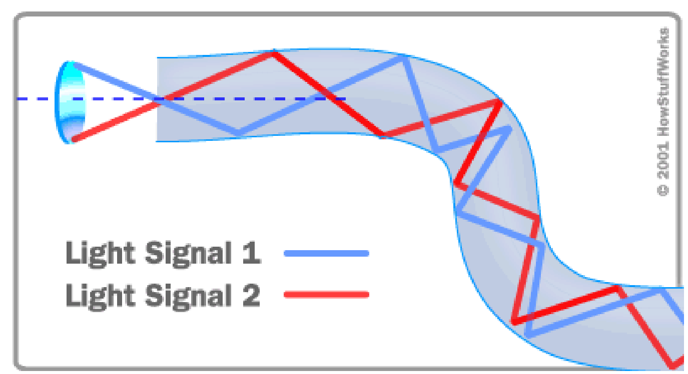
Coaxial cable

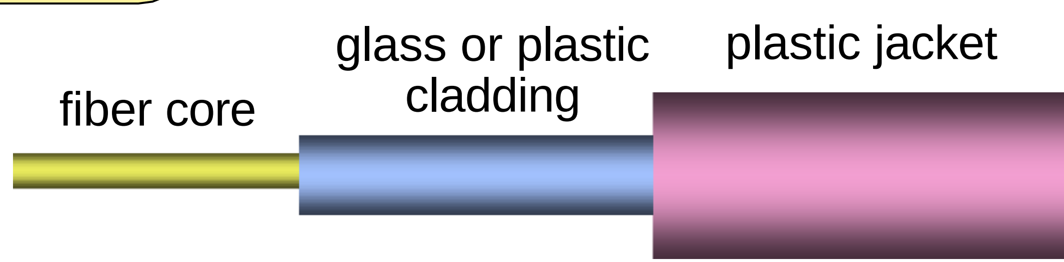


Basic Fibre Properties

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







Specialty Fibers

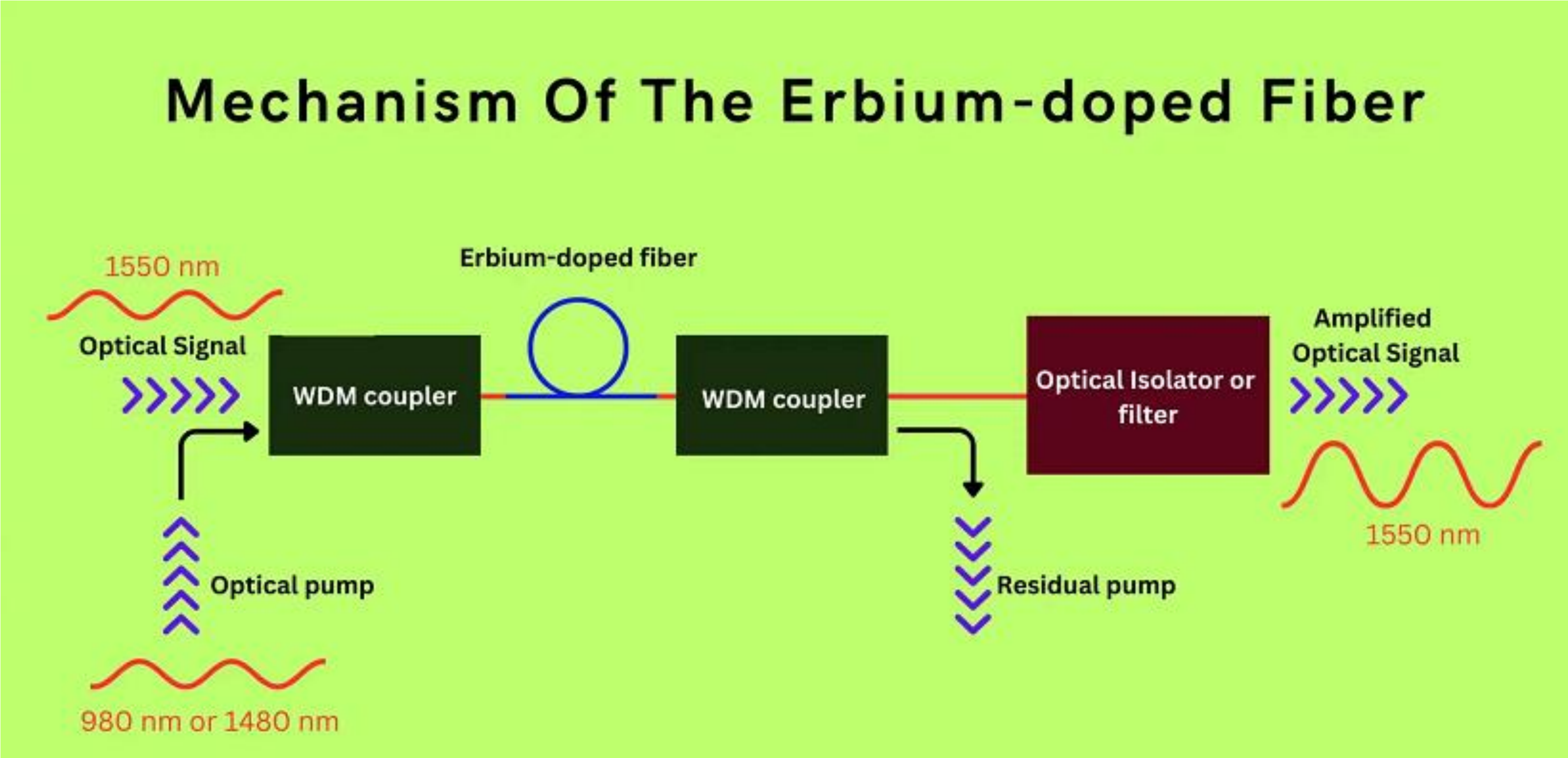
- There are countless types of optical fibers designed for specific functions beyond general communication transmission.

- While standard fibers efficiently transmit light signals over long distances, specialty fibers allow you to manipulate light in innovative ways through customized properties.

- These unique fibers open up possibilities like amplifying signals, preserving polarization, compensating dispersion, and more.

- Whether we need to couple high-power lasers, sense physical parameters, or process signals, there’s likely a specialty fiber suited for your application.

Erbium-Doped Fiber



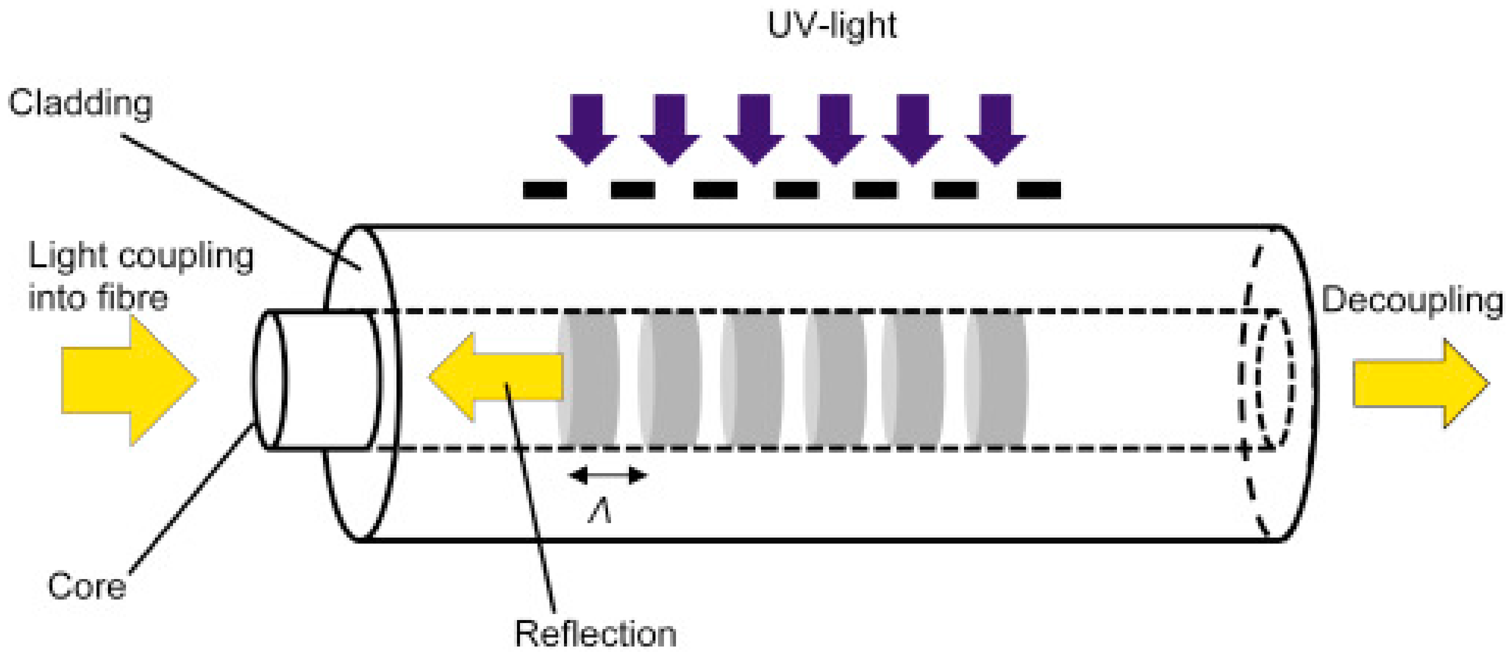
Erbium-doped fibers give optical signals a boost through a process called gain. They work by doping the silica glass material with erbium ions, which interact with light to provide optical amplification.

- A typical erbium-doped fiber length is 10 to 30 meters.
- This active medium is pumped with light around 980 nm or 1480 nm to activate the erbium ions.
- The ions then amplify signals in the C-band from 1530 to 1565 nm, which is commonly used in optical communications.

Key advantages:

- Allow transmission over 80-100 km without repeaters.
- Increase bandwidth substantially in networks.
- Used to make fiber amplifiers like EDFAs and fiber lasers.
- Compatible with broadband standards like DWDM.

Photosensitive Fiber



➢**Photosensitive fibers give you custom control over the refractive index profile through exposure to light. By modulating the UV exposure along the length, refractive index changes can be imprinted into the core.**

➢**This allows the creation of key devices like fiber Bragg gratings (FBGs). FBGs are periodic variations in the index that act as wavelength-selective mirrors.**

Key FBG applications:

- **Add/drop filters for DWDM**
- **Dispersion compensation modules**
- **Optical filters with tuned wavelengths**
- **Light coupling mechanisms for pump lasers**

- **FBGs engraved in photosensitive fibers are crucial for manipulating signals in wavelength division multiplexed networks.**

- **They enable the dropping and inserting of specific wavelength channels.**

Polarization-Preserving Fiber

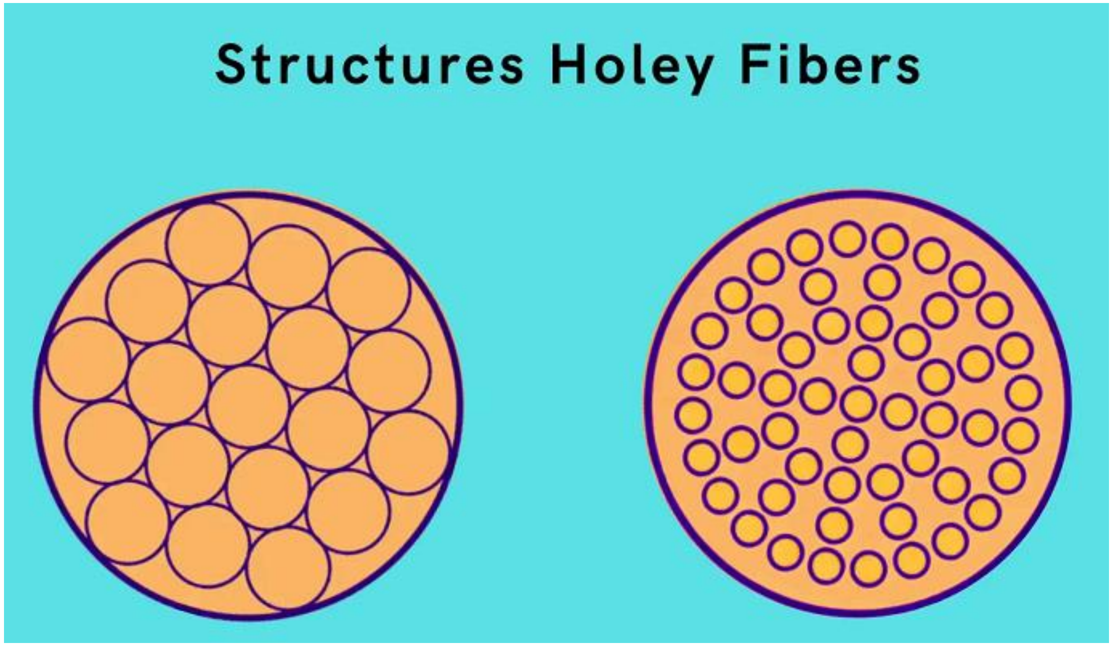
Polarization-preserving fiber is designed to maintain the polarization state of light as it travels through the fiber.

Unlike standard fibers, where polarization randomly fluctuates, these specialty fibers keep the light uniformly oriented.

Preserving polarization is critical for technologies like:

- **Fiber optic sensing to detect movement and other environmental factors.**
- **Interferometry using superimposed light for precision measurements.**
- **Quantum cryptography based on photon spin encoding.**

Holey Fiber



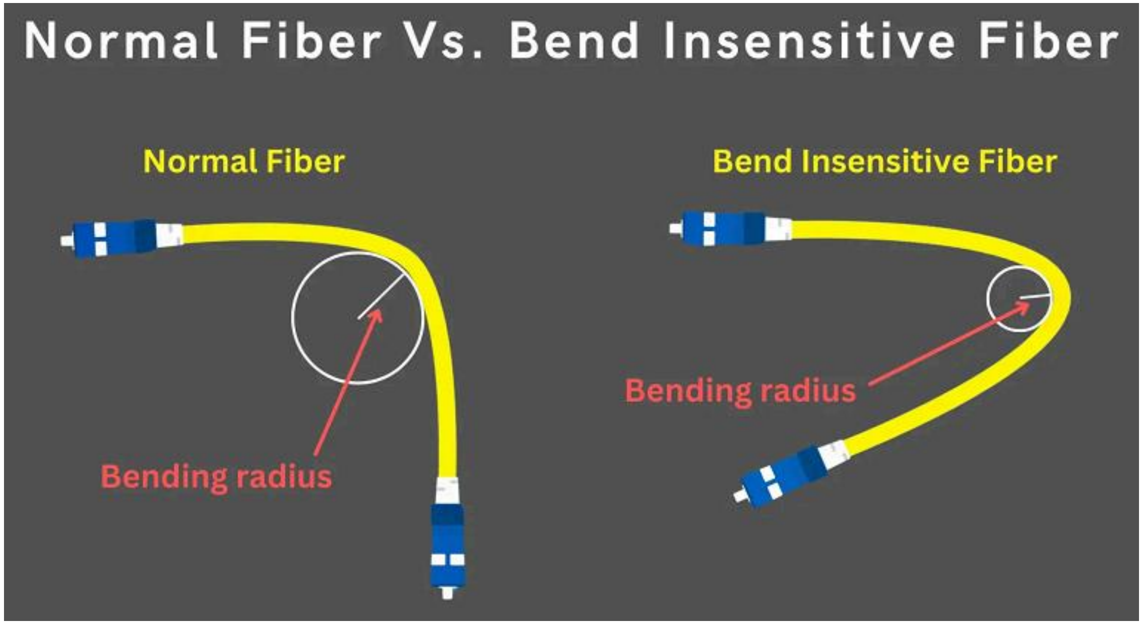
Holey fiber, also known as photonic crystal fiber, contains many microscopic air holes running along its length. The holes form a periodic pattern that acts as a cladding around a solid or hollow core.

The air holes lower the effective refractive index of the cladding compared to the higher index core. This allows light to be guided along the fiber core.

Potential applications of holey fiber include:

- **Dispersion compensation to reduce signal distortion.**
- **Wavelength conversion for flexible networking.**
- **Optical switching to dynamically redirect signals.**
- **High power amplification due to large mode areas.**

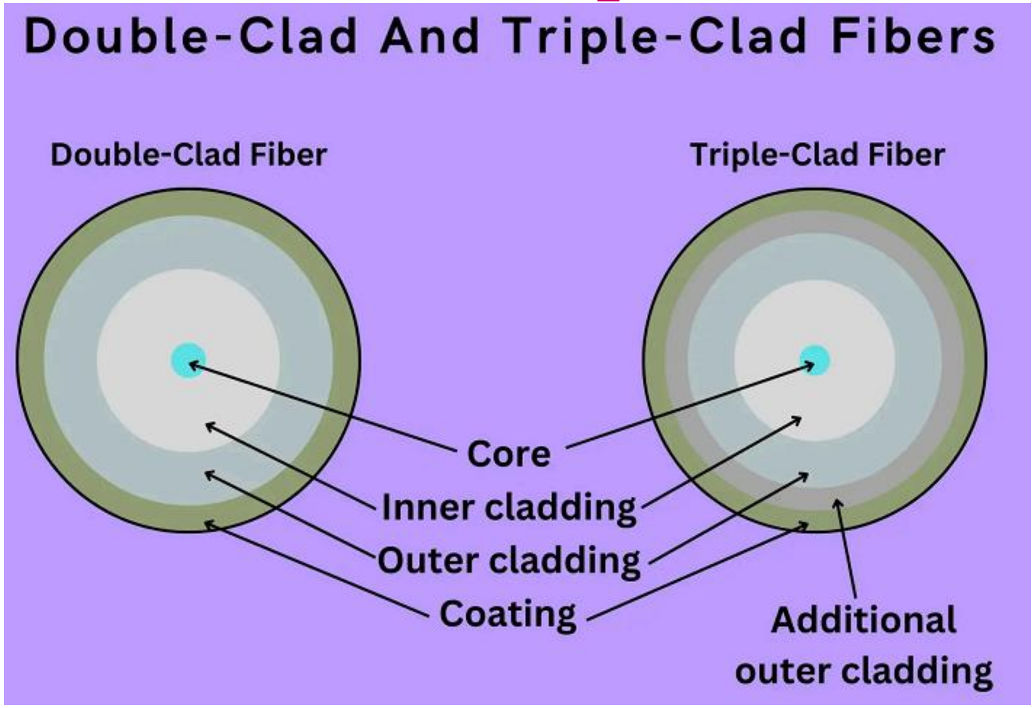
Bend-Insensitive Fiber



Bend-insensitive fiber is engineered to maintain low optical loss when bent around tight radii. This is unlike standard fiber which fails at small bend radii.

To achieve bend resistance, these fibers use a higher numerical aperture to strongly confine light in the core. This prevents bending losses.

Double-Clad And Triple-Clad Fibers

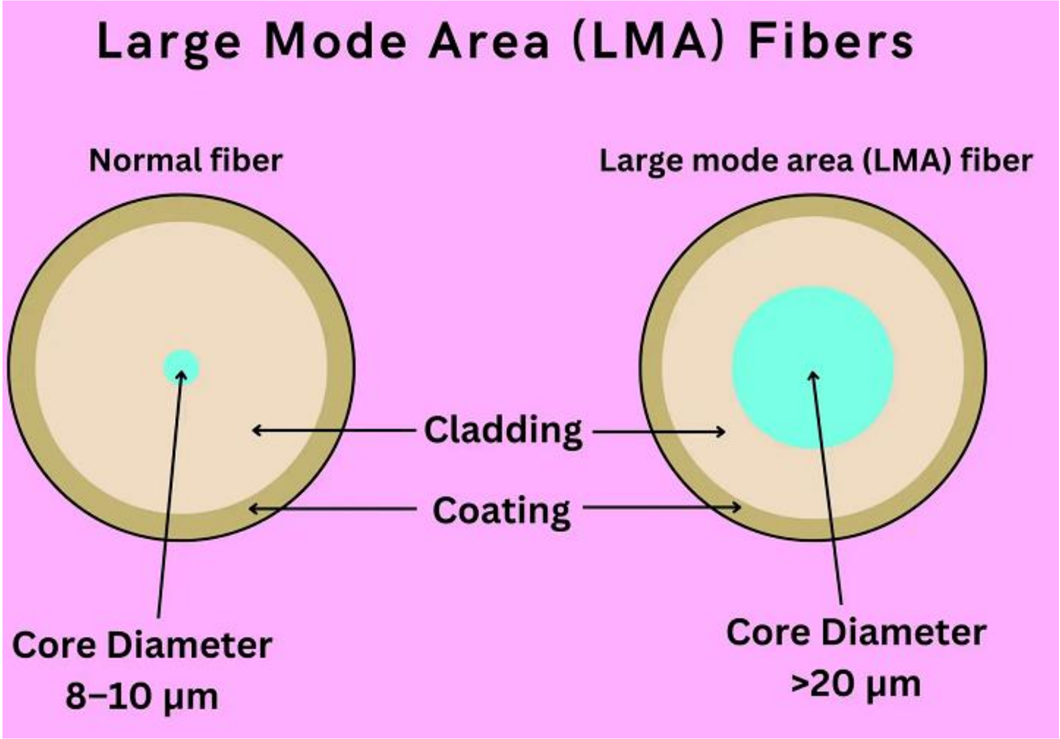


Double-clad fibers contain 3 layers – core, inner cladding, and outer cladding.

This provides two separate waveguides – the core guides signals while the inner cladding guides pump light.

Triple-clad fibers add another outer cladding layer to confine pump light leakage.

Large Mode Area Fibers



Large mode area (LMA) fibers contain a large core diameter compared to standard single-mode fiber.

LMA fibers balance single-mode operation with a large light-guiding area.

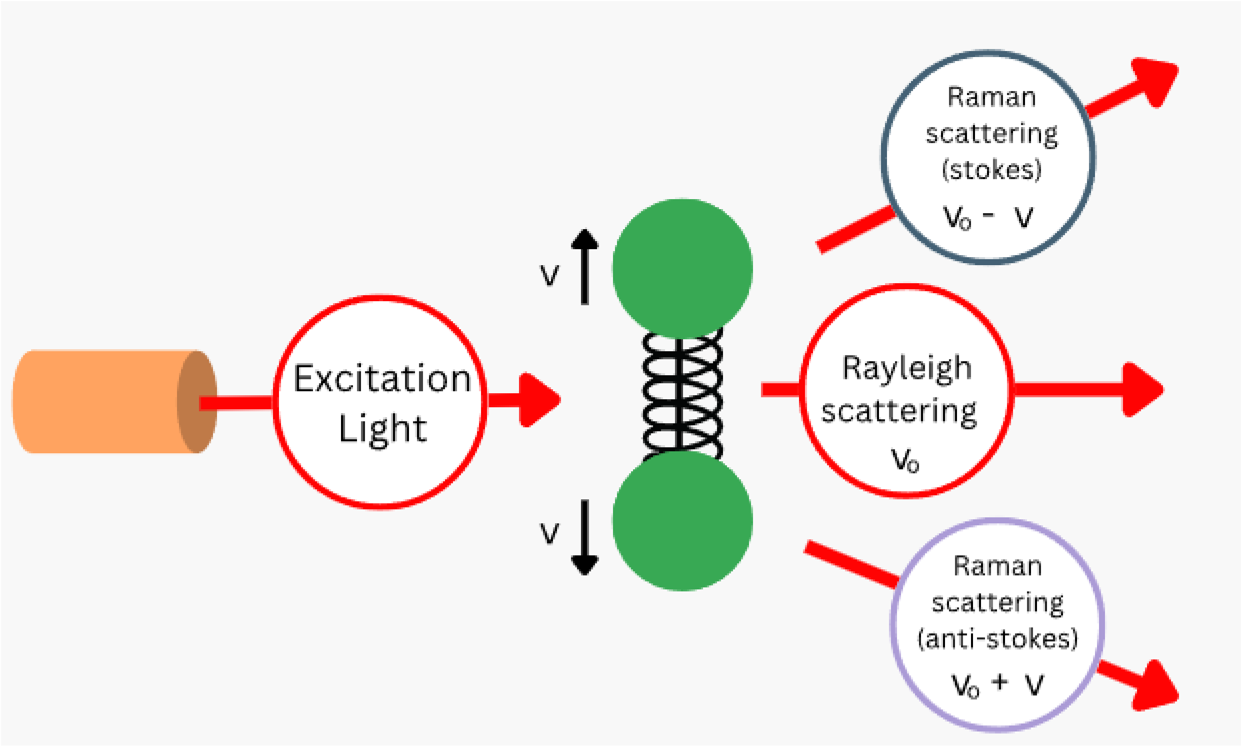
This provides exceptional performance for high peak and average power delivery.

Highly Nonlinear Fibers

Highly nonlinear fibers (HNLFs) contain design properties to maximize nonlinear optical effects. This allows efficient nonlinear processes like:

- **Super continuum generation**
- **Four -wave mixing**
- **Parametric amplification**

Raman Gain Fibers



Raman gain fibers utilize Raman scattering to amplify input signals and generate new wavelengths.

For wideband amplification or remote delivery, Raman gain fibers offer high performance by harnessing the Raman effect.

Types chart

Fiber Type	Key Features	Applications
Erbium-Doped Fiber	Doped with erbium ions, operates at 1550 nm, provides optical amplification	Long haul telecom networks, fiber optic amplifiers
Photosensitive Fiber	Changes refractive index when exposed to UV light	Fiber Bragg gratings for filtering, redirection, dispersion control
Polarization-Preserving Fiber	Maintains polarization state of light	Interferometry, fiber optic sensing, quantum cryptography
Holey Fiber	Air holes in cladding to guide light	Dispersion control, switching, high power amplification
High-Index Fiber	High core refractive index and numerical aperture	Efficient coupling to laser sources, wavelength multiplexing

Types chart

Bend-Insensitive Fiber	Resists bend losses	Fiber installations in tight spaces, data centers
Double/Triple-Clad Fiber	Multiple cladding layers	High power fiber lasers and amplifiers
Large Mode Area Fiber	Large core size	High power handling, reduced nonlinearity
Highly Nonlinear Fiber	Small core for high nonlinearity	Parametric amplifiers, wavelength conversion
Raman Gain Fiber	Optimized for Raman amplification	Distributed amplification, fiber lasers

Ray theory and Geometrical Optics

Prof.Dr.G.Aarthi
Associate Professor, SENSE
VIT

The Nature of Light

- **Quantum Theory – Light consists of particles (photons)**
- **Ray Theory – Light travels along a straight line and obeys laws of *geometrical optics.***
- **Mode Theory – Light travels as a *transverse electromagnetic wave***

Ray Theory Transmission

Properties of Light

Law of Reflection

The angle of Incidence = The angle of reflection

Law of Refraction -

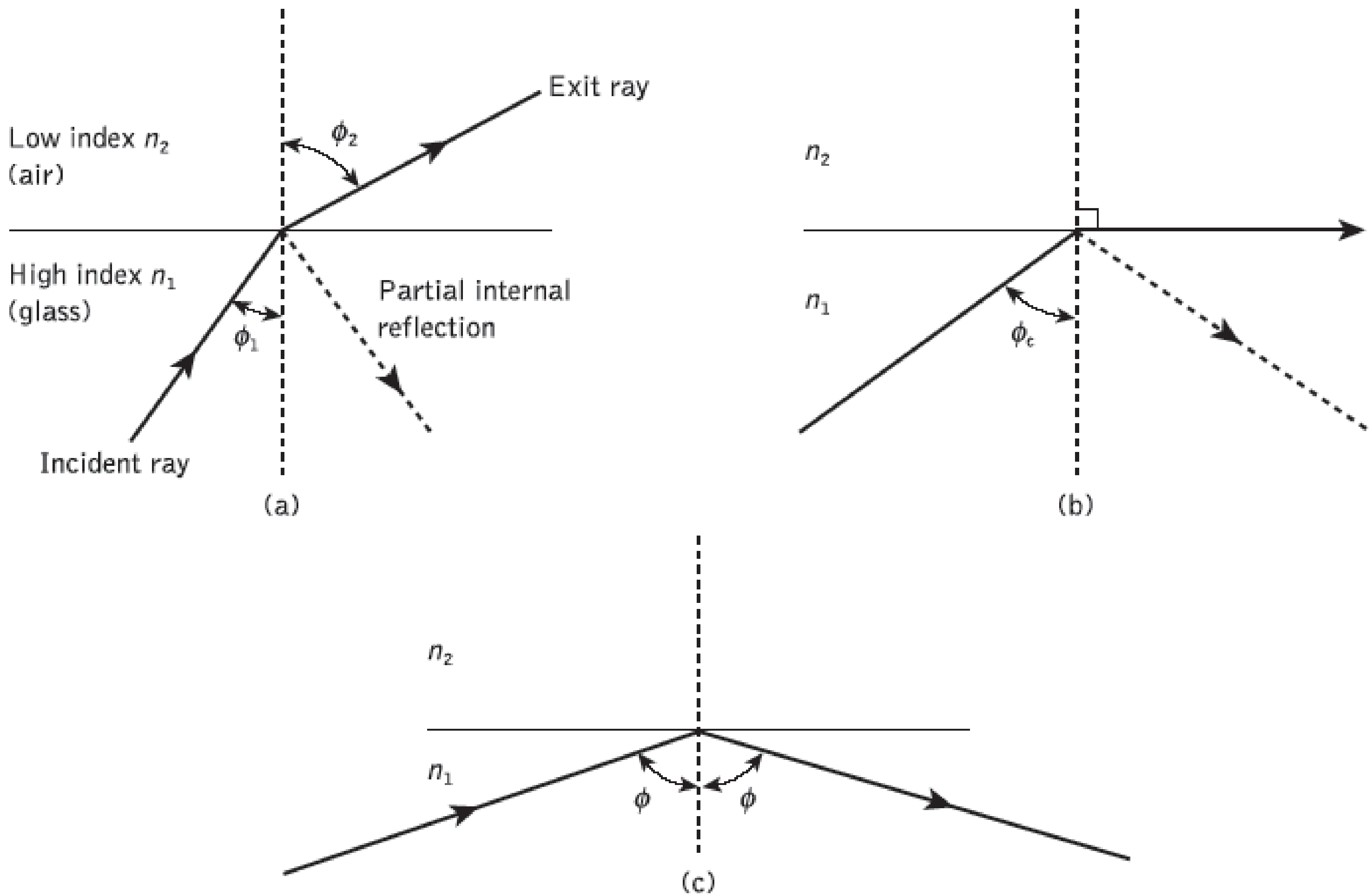
- Light beam is bent towards the normal when passing into a medium of higher refractive index.
- Light beam is bent away from the normal when passing into a medium of lower refractive index.

Index of Refraction –

n = Speed of light in a vacuum / Speed of light in a medium

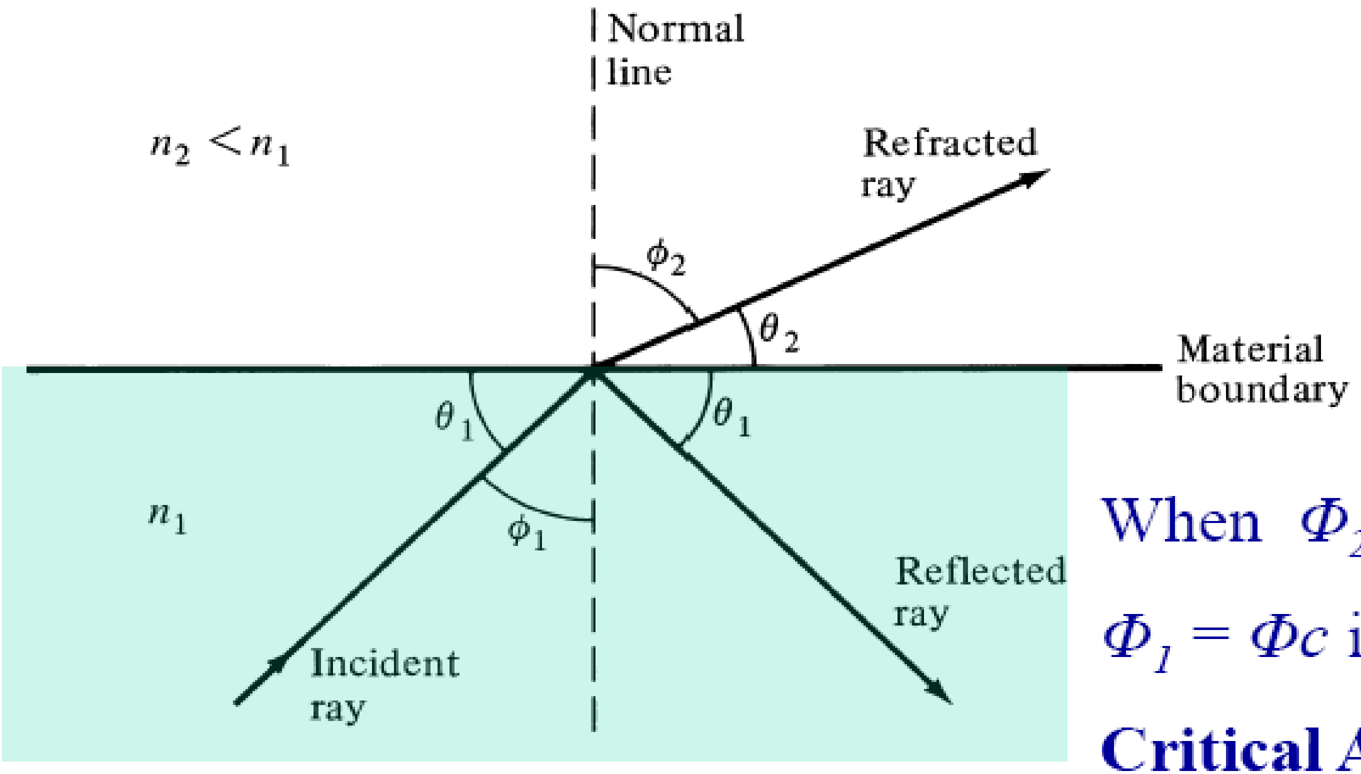
Inverse square law - Light intensity diminishes with square of distance from source.

Light rays incident on a high to low refractive index interface (e.g.glass–air):



(a) refraction; (b) the limiting case of refraction showing the critical ray at an angle φc; (c) total internal reflection where φ> φc

Refraction and Reflection



When $\Phi_2 = 90$,

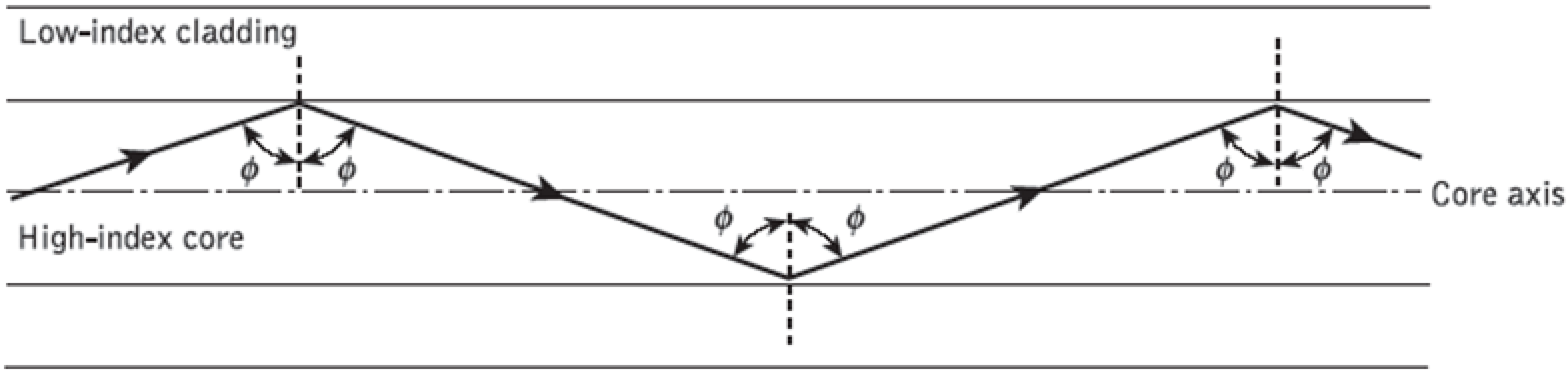
$\Phi_1 = \Phi c$ is the

Critical Angle

$\Phi c = \mathrm{Sin}^{-1}(n_2/n_1)$

Snell's Law: $n_1 \,\mathrm{Sin}\, \Phi_1 = n_2 \,\mathrm{Sin}\, \Phi_2$

Total Internal Reflection

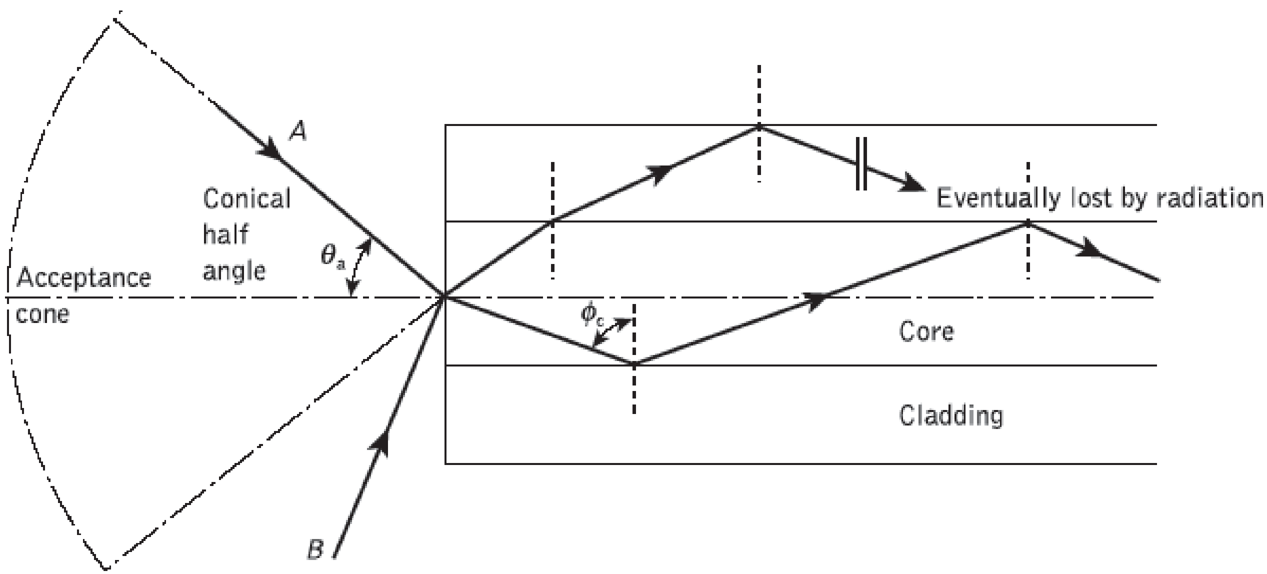


The transmission of a light ray in a perfect optical fiber

Acceptance angle

- The ray enters the fiber core at an angle θa to the fiber axis and is refracted at the **air–core** interface before transmission to the **core–cladding** interface at the critical angle.

- Hence, any rays which are incident into the fiber core at an angle greater than θa will be transmitted to the **core–cladding** interface at an angle less than φc, and **will not be totally internally reflected.**



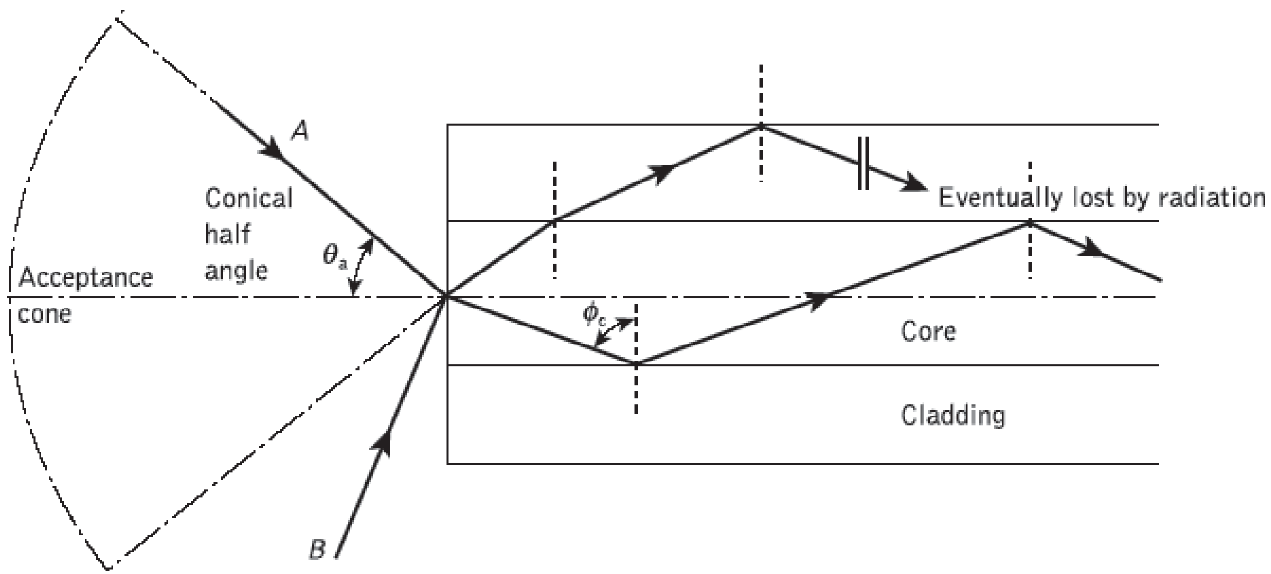
The acceptance angle θ_a when launching light into an optical fiber

Acceptance angle

- From Figure, the incident ray *B* at an angle greater than θa is refracted into the cladding and eventually lost by radiation.

- Thus for rays to be transmitted by total internal reflection within the fiber core they must be incident on the fiber core within an acceptance cone defined by the conical half angle θa.

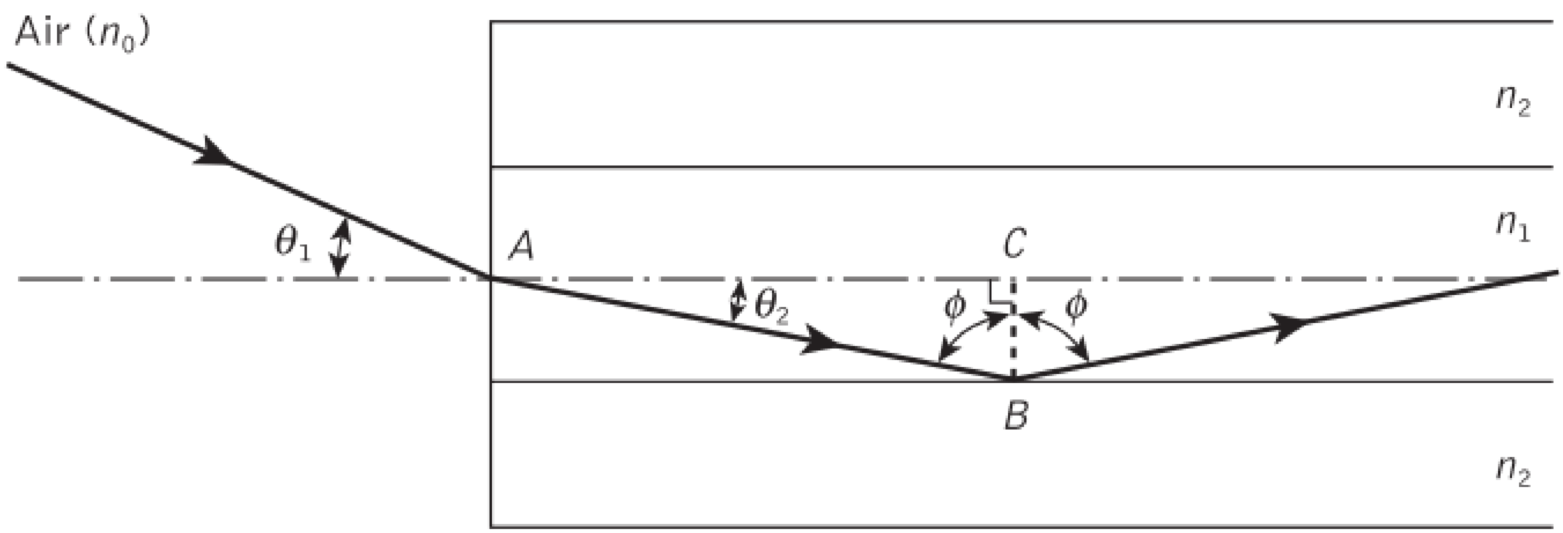
- Hence θa is the maximum angle to the axis at which light may enter the fiber in order to be propagated, and is often referred to as the acceptance angle* for the fiber.



The acceptance angle θ_a when launching light into an optical fiber

Numerical Aperture

NA determines the light gathering capabilities of the fiber



The ray path for a meridional ray launched into an optical fiber in air at an input angle less than the acceptance angle for the fiber

Numerical Aperture

NA determines the light gathering capabilities of the fibre

$$NA = n_0 \sin \theta_a = (n_1^2 - n_2^2)^{\frac{1}{2}}$$

The NA may also be given in terms of the relative refractive index difference Δ between the core and the cladding

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

$$\simeq \frac{n_1 - n_2}{n_1} \qquad \text{for } \Delta \ll 1$$

Hence combining the above two equations $$NA = n_1 (2\Delta)^{\frac{1}{2}}$$

Preferred Sizes of Optical fibers and their NA

Core diameter (μm)	Clad diameter (μm)	Numerical aperture
50	125	0.19 to 0.25
62.5	125	0.27 to 0.31
85	125	0.25 to 0.30
100	140	0.25 to 0.30

Meridional and Skew Rays

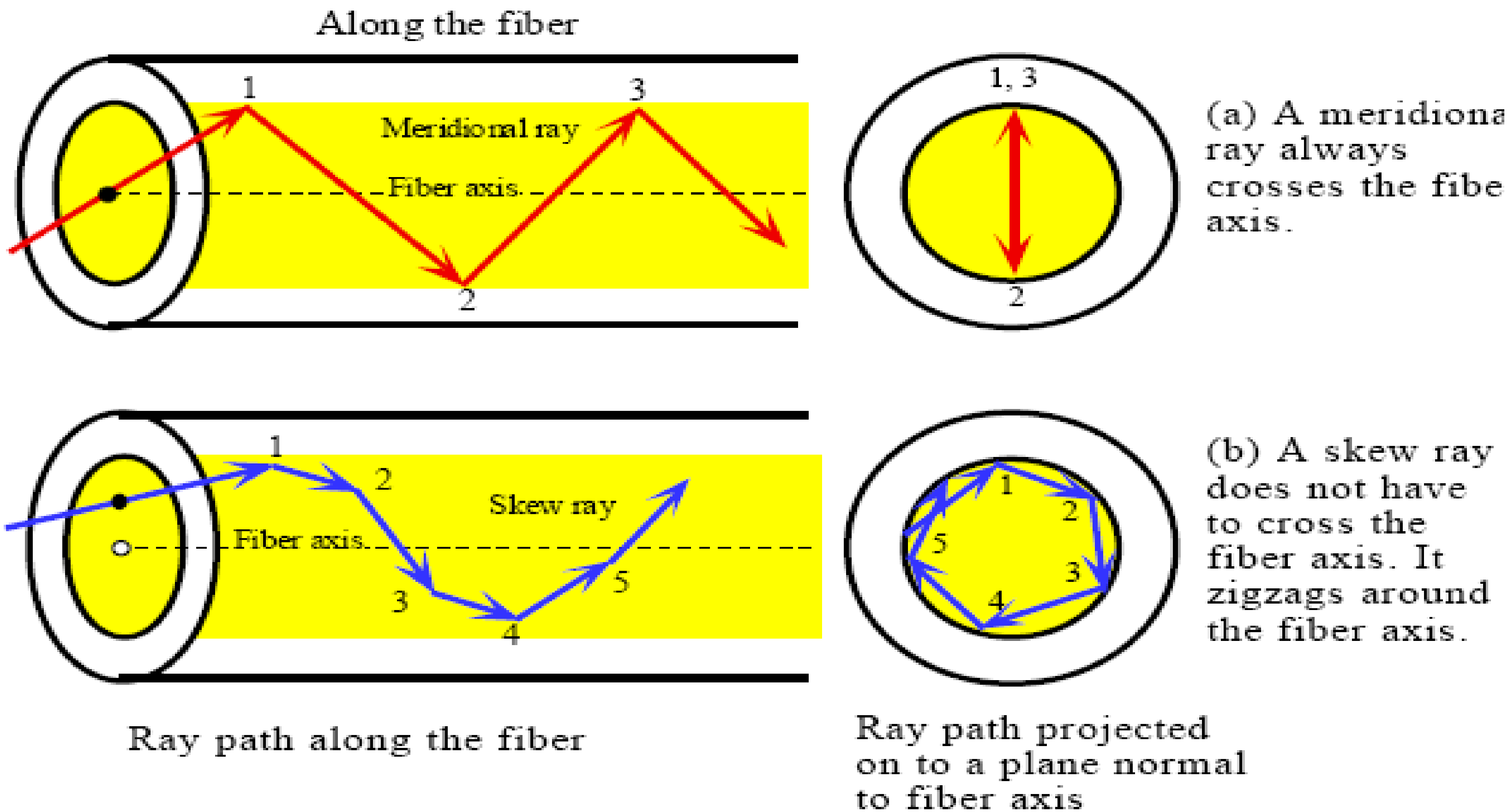
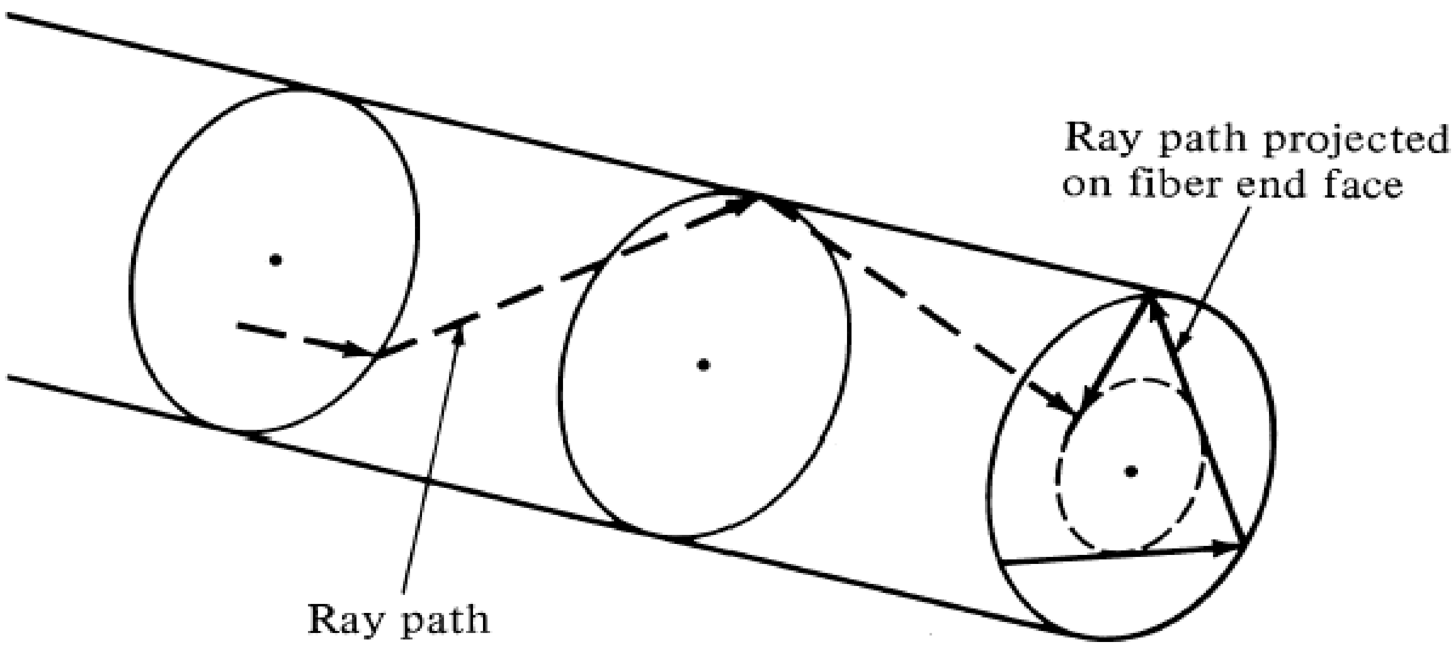


Illustration of the difference between a meridional ray and a skew ray.
Numbers represent reflections of the ray.

Skew Rays



Skew rays circulate around the core and
increase the dispersion

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

(a) The critical angle ϕ_c at the core–cladding interface is given by

$$\phi_c = \sin^{-1}\frac{n_2}{n_1} = \sin^{-1}\frac{1.47}{1.50} = 78.5°$$

(b) 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) the acceptance angle in air θ_a is given by: $NA = n_0 \sin\theta_a = (n_1^2 - n_2^2)^{\frac{1}{2}}$

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

A typical relative refractive index difference for an optical fiber designed for longdistance 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

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:

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

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

A typical relative refractive index difference for an optical fiber designed for longdistance 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

the relative refractive index difference Δ gives:

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

Hence

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

$$= 0.99$$

the critical angle at the core–cladding interface is:

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

$$= 81.9°$$

Mode theory and Types of Fibers

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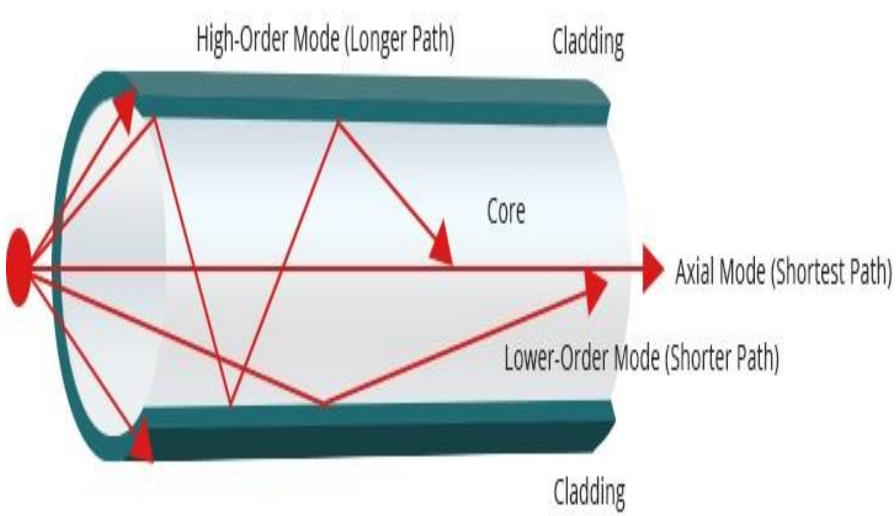
Associate Professor, SENSE
VIT

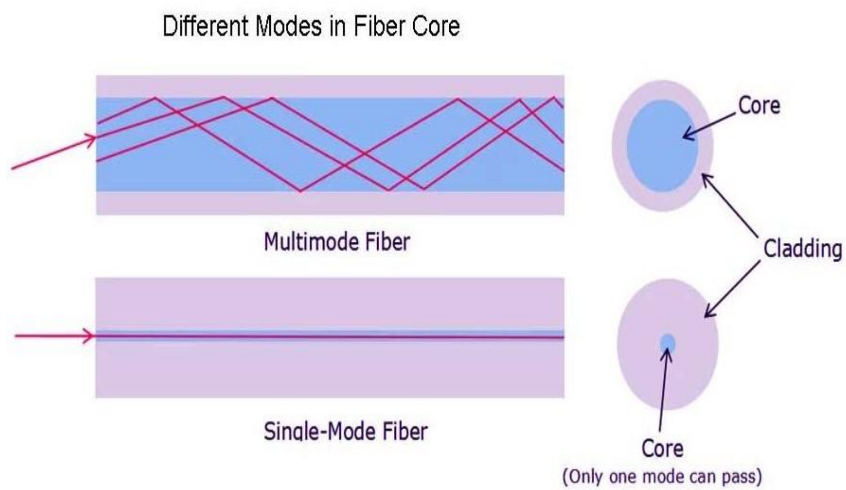
Optical Fibers: Modes and Configurations

- The propagation of light along a waveguide can be described in terms of a set of guided electromagnetic waves called the modes of the waveguide.

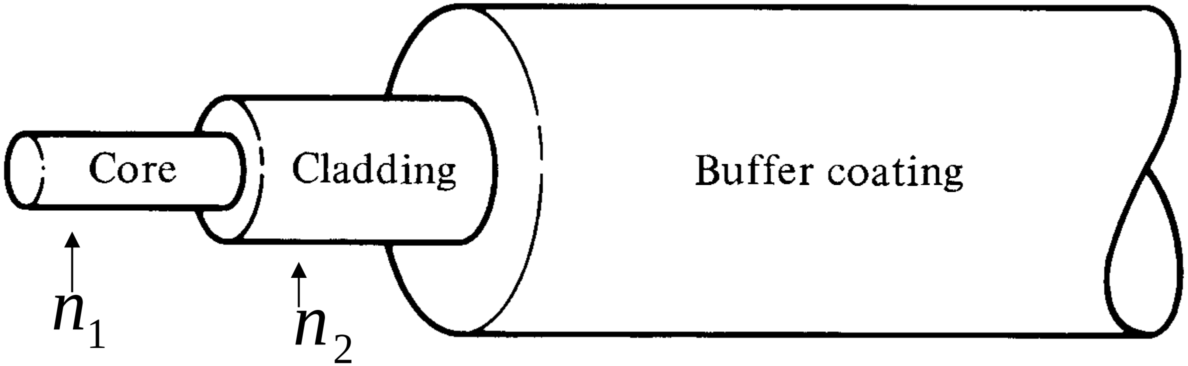
- Each guided mode is a pattern of electric and magnetic field distributions that is repeated along the fiber at equal intervals.

- The light or the optical signals are guided through the silica glass fibers by total internal reflection.





Optical Fibers: Structure



$$n_1 > n_2$$

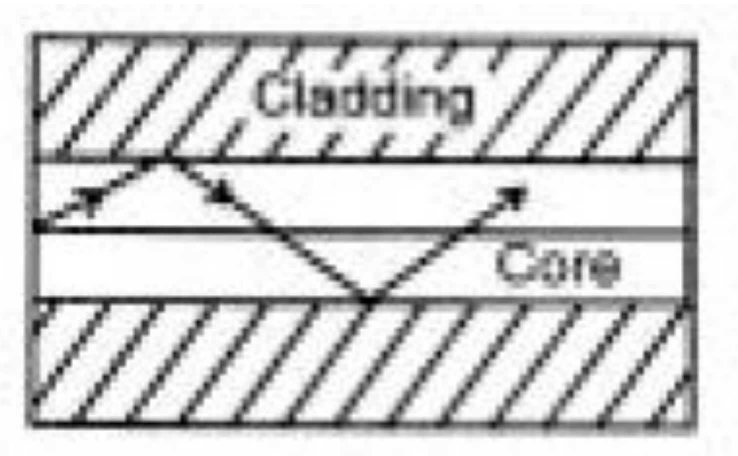
Fiber Types

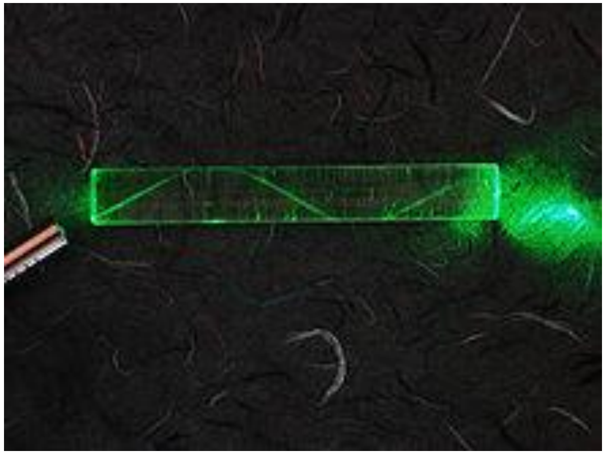
- Modes of operation (the path which the light is traveling on)
  - Single mode
  - Multimode
- Index profile
  - Step Index
  - Graded Index
- **Major Performance Concerns for Fibers**
  - **Wavelength range**
  - **Maximum Propagation Distance**
  - **Maximum bit rate**
  - **Crosstalk**

Step index fiber

▪*In the step index fiber, the refractive index of the core is uniform* throughout and undergoes an abrupt or step change at the core cladding boundary.

▪The light rays propagating through the fiber are in the form of meridional rays which will cross the fiber axis during every reflection at the core cladding boundary and are propagating in a zig-zag manner as shown in figure below

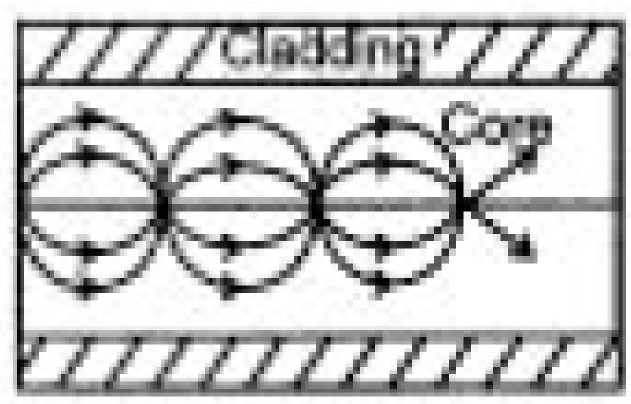




Graded index fiber

- *In the graded index fiber, the refractive index of the core is made* to vary in the parabolic manner such that the maximum value of refractive index is at the centre of the core.

- The light rays propagating through it are in the form of skew rays or helical rays which will not cross the fiber axis at any time and are propagating around the fiber axis in a helical (or) spiral manner.



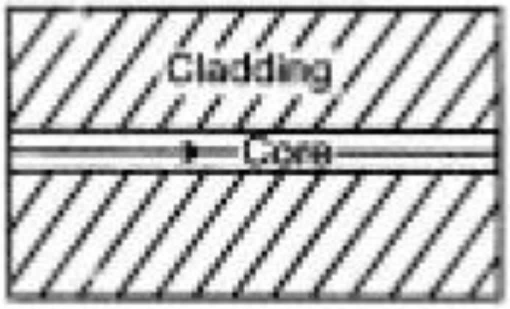
Single mode fibers

For the transmission of a single mode the fiber must be designed to allow propagation of only one mode(fundamental mode LP_{01}), while all other modes are attenuated by leakage or absorption.

Hence the limit of single-mode operation depends on the lower limit of guided propagation for the LP_{11} mode

The cutoff normalized frequency for the LP_{11} mode in step index fibers occurs at Vc = 2.405 .

Thus single-mode propagation of the LP_{01} mode in step index fibers is possible over the range: $0 \leq V < 2.405$ as there is no cutoff for the fundamental mode.



Single mode fibers

The normalized frequency is a dimensionless parameter and hence is also sometimes simply called the V number or value of the fiber.

$$\text{V-number} = \frac{2\pi}{\lambda} a(NA)$$

$$\text{V-number} = \frac{2\pi}{\lambda} n_1 a \sqrt{2\Delta}$$

Here a = radius of the core of the fiber; n_1 = refractive index of the core, λ = wavelength of light propagating through the fiber; Δ = relative refractive index difference = $\frac{n_1^2 - n_2^2}{2n_1^2} \approx \frac{n_1 - n_2}{n_1}$, where n_2 = refractive index of cladding.

Single mode fibers

- *In the case of a single mode fiber, V-number <=2.405.*

- The single mode fiber has a smaller core diameter (10 mm) and the difference between the refractive indices of the core and the cladding is very small.

- Fabrication of single mode fibers is very difficult and so the fiber is expensive.

- The launching of light into single mode fibers is also difficult.

- Generally in the single mode fibers, the transmission loss and dispersion or degradation of the signal are very small.

- So the single mode fibers are very useful in long distance communication.

Multi mode fibers

- Multimode fibers allow a large number of modes for the light rays traveling through it.
- Here the V-number is greater than 2.405.
- The total number of guided modes or mode volume M_s for a multimode step index fiber is related to the V value for the fiber by

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

- *For a multimode graded index fiber having* parabolic refractive index profile core,

$$M_g \simeq \frac{V^2}{4}$$

Multi mode fibers

- The core diameter is generally larger than in the single mode fiber.

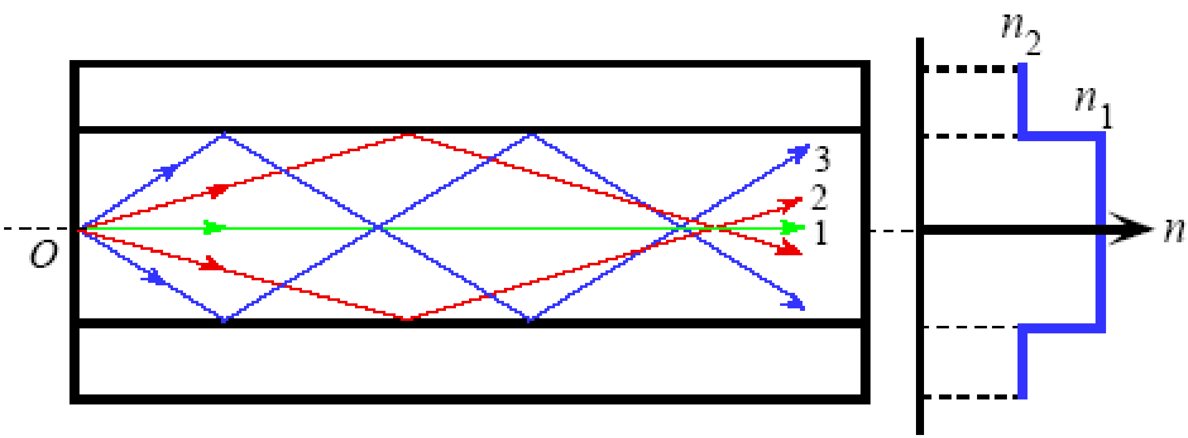
- In the case of multimode graded index fiber, signal distortion is very low because of self-focusing effects.

- Here the light rays travel at different speeds in different paths of the fiber because of the parabolic variation of refractive index of the core.

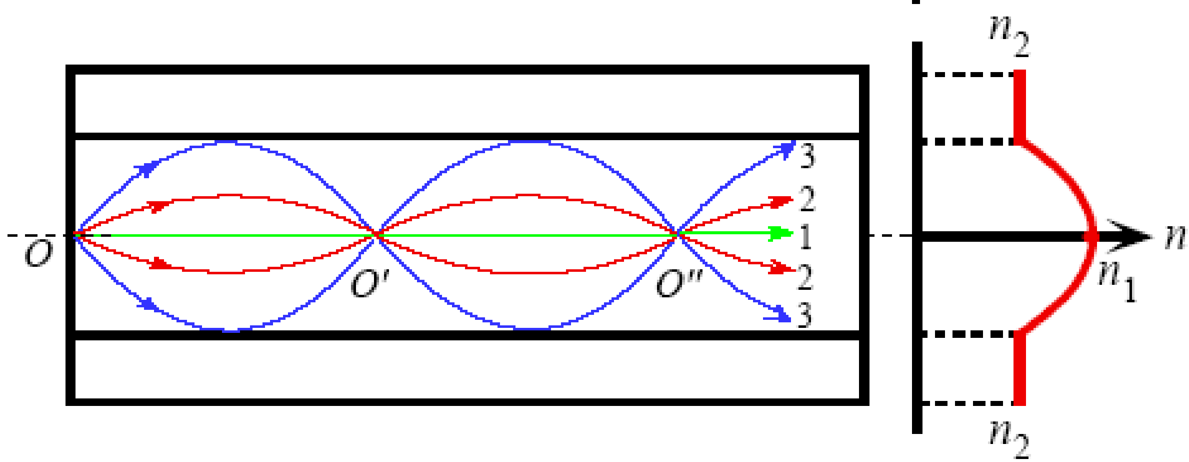
- Launching of light into the fiber and fabrication of the fiber are easy.

- These fibers are generally used in local area networks and applications where high power must be transmitted.

Step and Graded Index Fibers



(a) Multimode step index fiber. Ray paths are different so that rays arrive at different times.



(b) Graded index fiber. Ray paths are different but so are the velocities along the paths so that all the rays arrive at the same time.

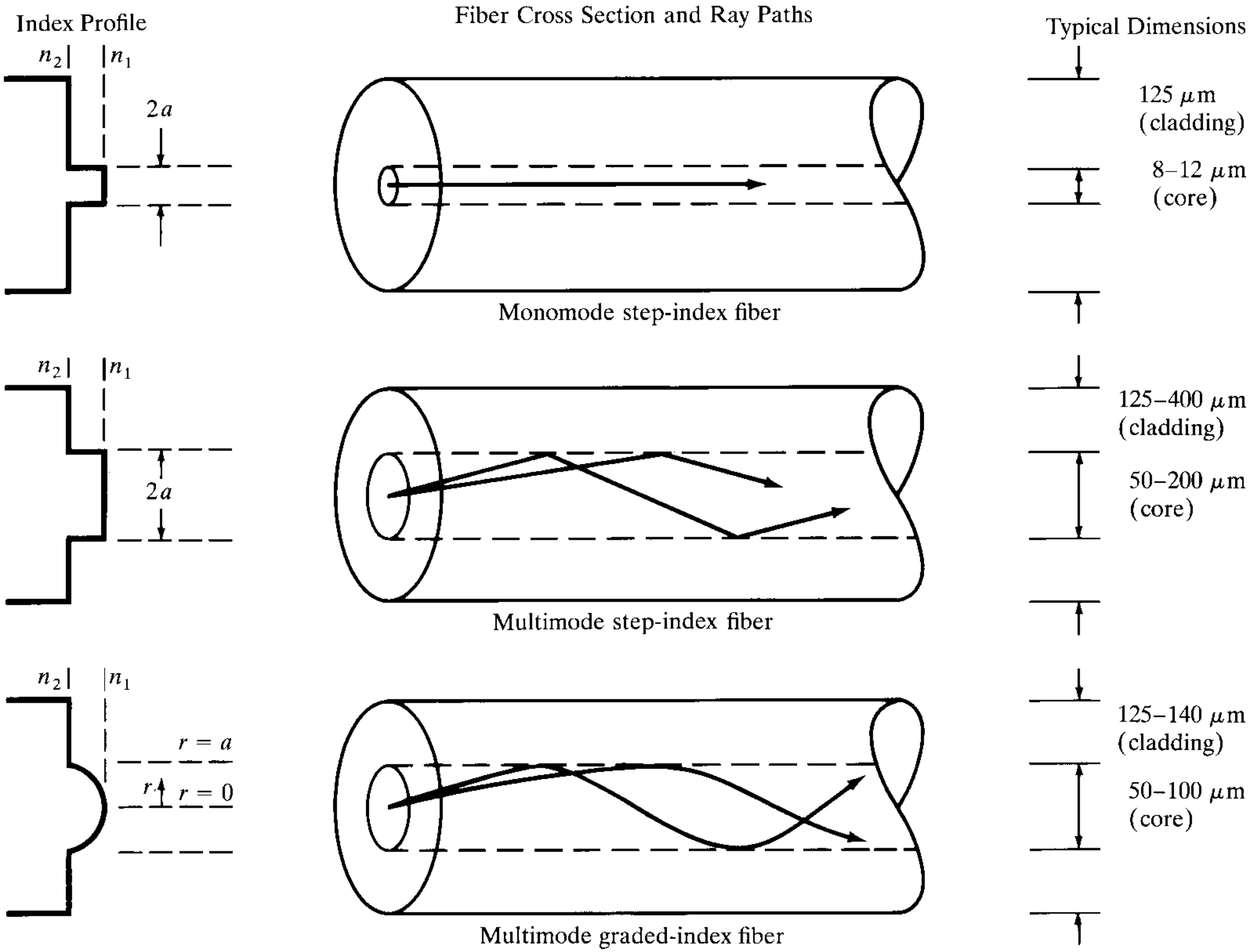
Graded-index fiber

- Compromise between the large core diameter and N.A. of multimode fiber and the higher bandwidth of single-mode fiber.

- With creation of a core whose index of refraction decreases parabolically from the core center toward the cladding, light traveling through the center of the fiber experiences a higher index than light traveling in the higher modes.

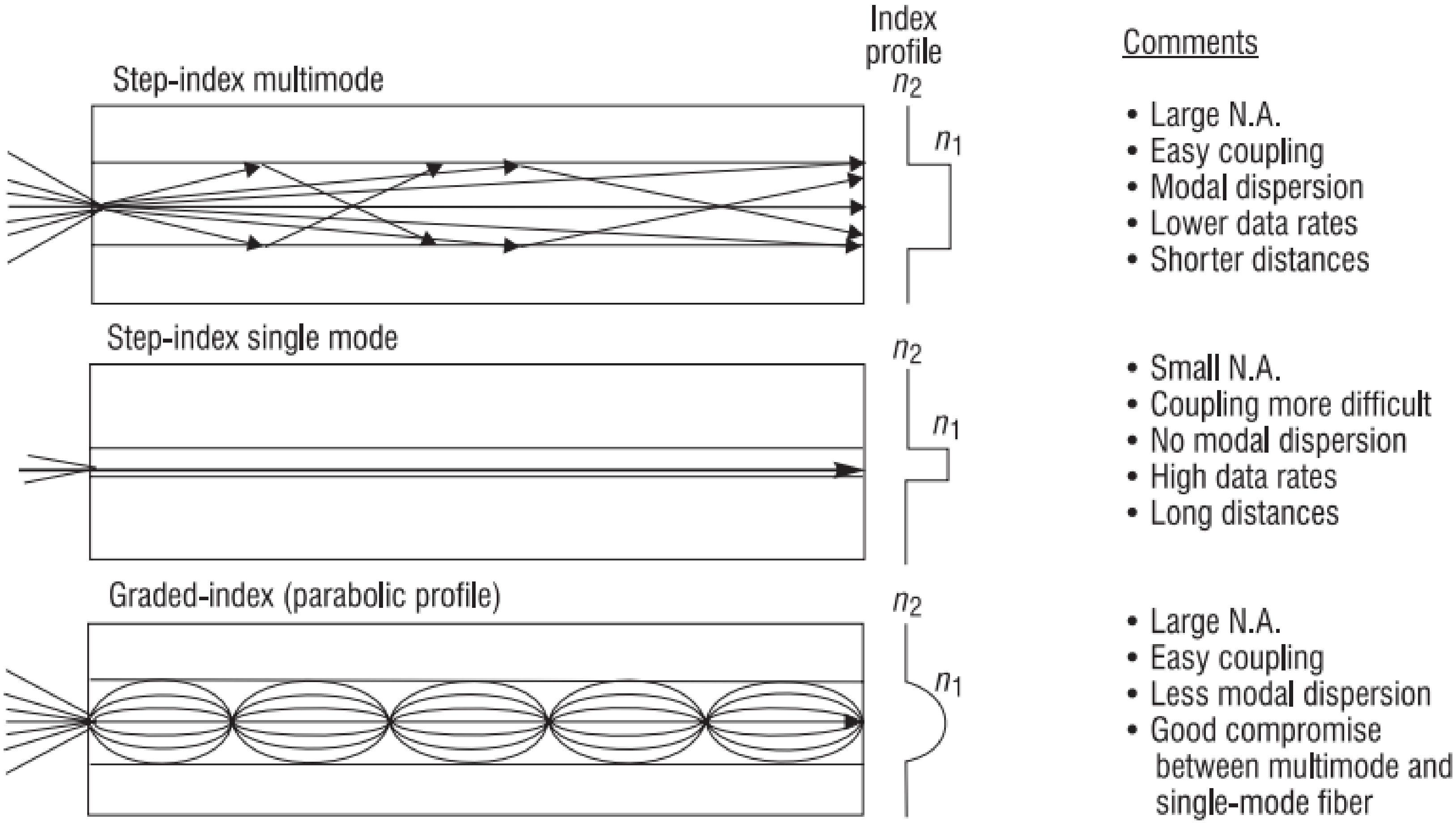
- So the higher-order modes travel faster than the lower-order modes, which allows them to “catch up” to the lower-order modes, thus decreasing the amount of modal dispersion, which increases the bandwidth of the fiber.

Different Structures of Optical Fiber



Optical Fiber communications, 3rd ed.,G.Keiser,McGrawHill, 2000

Different Structures of Optical Fiber



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.

(a) The normalized frequency may be obtained from

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

(b) The total number of guided modes is given by

$$M_s \simeq \frac{V^2}{2} \quad = \frac{5745.6}{2} \quad = 2873$$

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

Estimate the maximum core diameter for an optical fiber with the relative refractive index difference of 1.5% and core refractive index of 1.48. It may be assumed that the fiber is operating at 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.

The maximum V value for a fiber which gives single-mode operation is 2.4. Hence the core radius a is given by :

$$a = \frac{V\lambda}{2\pi n_1 (2\Delta)^{\frac{1}{2}}} = \frac{2.4 \times 0.85 \times 10^{-6}}{2\pi \times 1.48 \times (0.03)^{\frac{1}{2}}} = 1.3\ \mu\text{m}$$

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 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

A Multimode 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

The normalized frequency for the fiber is

$$V = \frac{2\pi}{\lambda} a(NA) \quad = \frac{2\pi \times 25 \times 10^{-6} \times 0.2}{1 \times 10^{-6}} \quad = 31.4$$

The mode volume for a parabolic profile is given by :

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

Hence the fiber supports approximately 247 guided modes

Signal Degradation in Optical Fibers

Prof. Dr. G. Aarthi

Associate Professor,

SENSE,VIT

Signal Attenuation & Degradation in Optical Fibers

- Signal attenuation (fiber loss) largely determines the maximum repeaterless separation between optical transmitter & receiver.

- Signal distortion cause that optical pulses to broaden as they travel along a fiber, the overlap between neighboring pulses, creating errors in the receiver output, resulting in the limitation of information-carrying capacity of a fiber.

Signal degradation in optical fibers

Attenuation

- Signal attenuation is one of the most important properties of an optical fiber
- The degree of attenuation in a fiber has a large influence on the system cost.
- Signal Attenuation

$$\alpha = \frac{10}{L} \log\left(\frac{P_{\text{in}}}{P_{\text{out}}}\right)$$

- Therefore, the unit of attenuation is decibels/kilometer (dB/km).

When the mean optical power launched into an 8 km length of fiber is 120 μW, the mean optical power at the fiber output is 3 μW. Determine: (a) the overall signal attenuation or loss in decibels through the fiber assuming there are no connectors or splices; (b) the signal attenuation per kilometer for the fiber. (c) the overall signal attenuation for a 10 km optical link using the same fiber with splices at 1 km intervals, each giving an attenuation of 1 dB; (d) the numerical input/output power ratio in (c).

(a) $$\text{Signal attenuation} = 10\log_{10}\frac{P_i}{P_o} = 10\log_{10}\frac{120\times10^{-6}}{3\times10^{-6}}$$

$$= 10\log_{10}40 = 16.0\ \text{dB}$$

(b) The signal attenuation per kilometer for the fiber may be simply obtained by dividing the result in (a) by the fiber length

$$\alpha_{dB}L = 16.0\ \text{dB} \quad \alpha_{dB} = \frac{16.0}{8} = 2.0\ \text{dB km}^{-1}$$

When the mean optical power launched into an 8 km length of fiber is 120 μW, the mean optical power at the fiber output is 3 μW. Determine: (a) the overall signal attenuation or loss in decibels through the fiber assuming there are no connectors or splices; (b) the signal attenuation per kilometer for the fiber. (c) the overall signal attenuation for a 10 km optical link using the same fiber with splices at 1 km intervals, each giving an attenuation of 1 dB; (d) the numerical input/output power ratio in (c).

(c) As $\alpha_{dB} = 2 \text{ dB km}^{-1}$, the loss incurred along 10 km of the fiber is given by:

$$\alpha_{dB} L \quad = 2 \times 10 = 20 \text{ dB}$$

However, the link also has nine splices (at 1 km intervals) each with an attenuation of 1 dB. Therefore, the loss due to the splices is 9 dB.

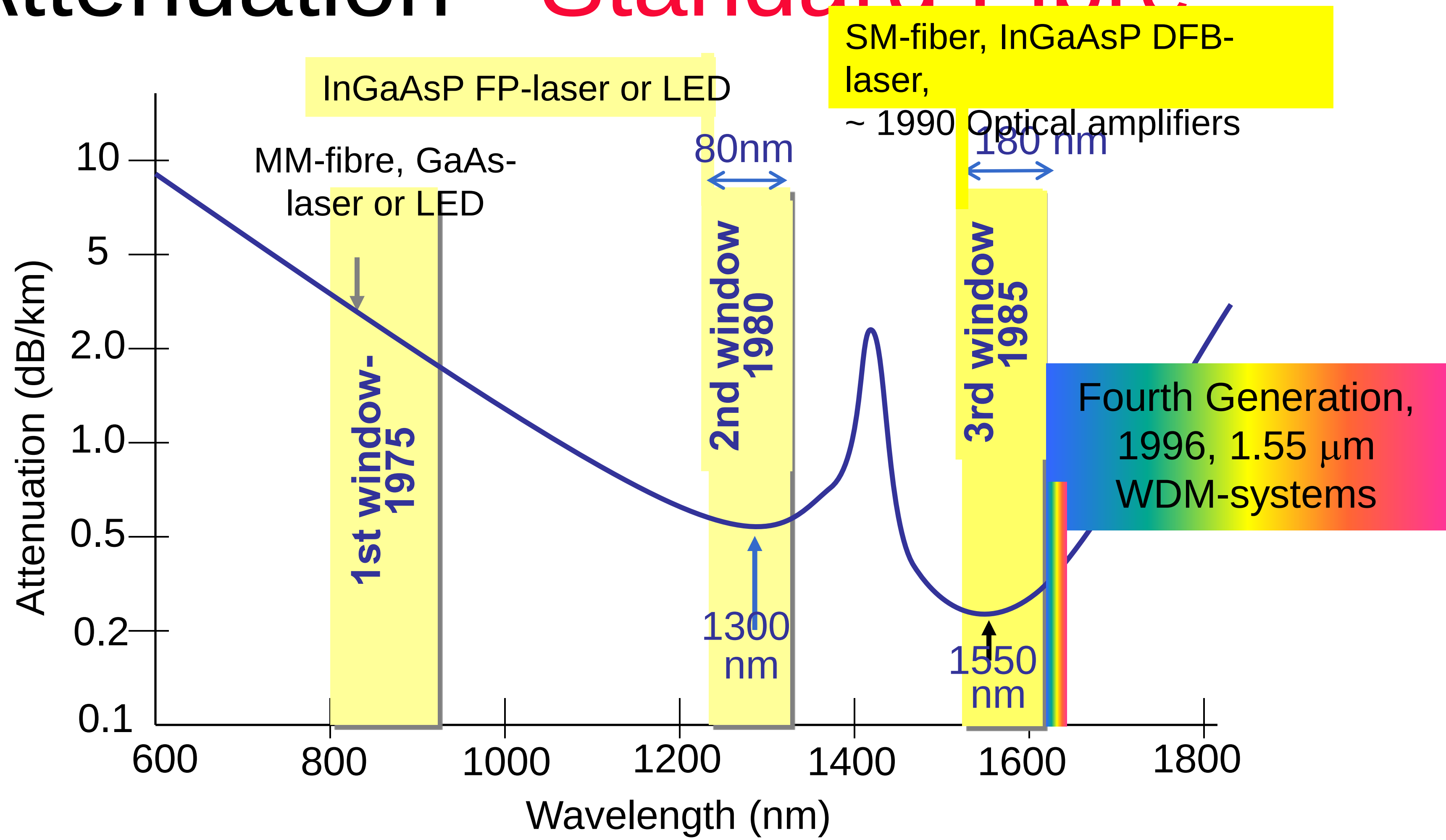
Hence, the overall signal attenuation for the link is:

$$\begin{aligned}\text{Signal attenuation} &= 20 + 9 \\ &= 29 \text{ dB}\end{aligned}$$

(d) To obtain a numerical value for the input/output power ratio,

$$\frac{P_i}{P_o} = 10^{29/10} \quad = 794.3$$

Attenuation - Standard Fibre



Types of Attenuation

Absorption Loss:

Caused by the fibre itself or by impurities in the fiber, such as water and metals.

Scattering Loss:

Arise from microscopic variations in the material density, from compositional fluctuations and from structural defects occurring during fiber manufacture.

Bending loss:

Loss induced by physical stress on the fibre.

Material Absorption Losses

- Material absorption is caused by absorption of photons within the fibre.
  - When a material is illuminated, photons can make the valence electrons of an atom transition to higher energy levels
  - Photon is destroyed, and the radiant energy is transformed into electric potential energy. This energy can then
    - **Be re-emitted (scattering)**
    - **Frees the electron (photoelectric effects) (not in fibers)**
    - **Dissipated to the rest of the material (transformed into heat)**
- In an optical fibre Material Absorption is the optical power that is effectively converted to heat dissipation within the fibre.
- Two types of absorption exist:
  - **Intrinsic Absorption**, caused by interaction with one or more of the components of the glass
  - **Extrinsic Absorption**, caused by impurities within the glass

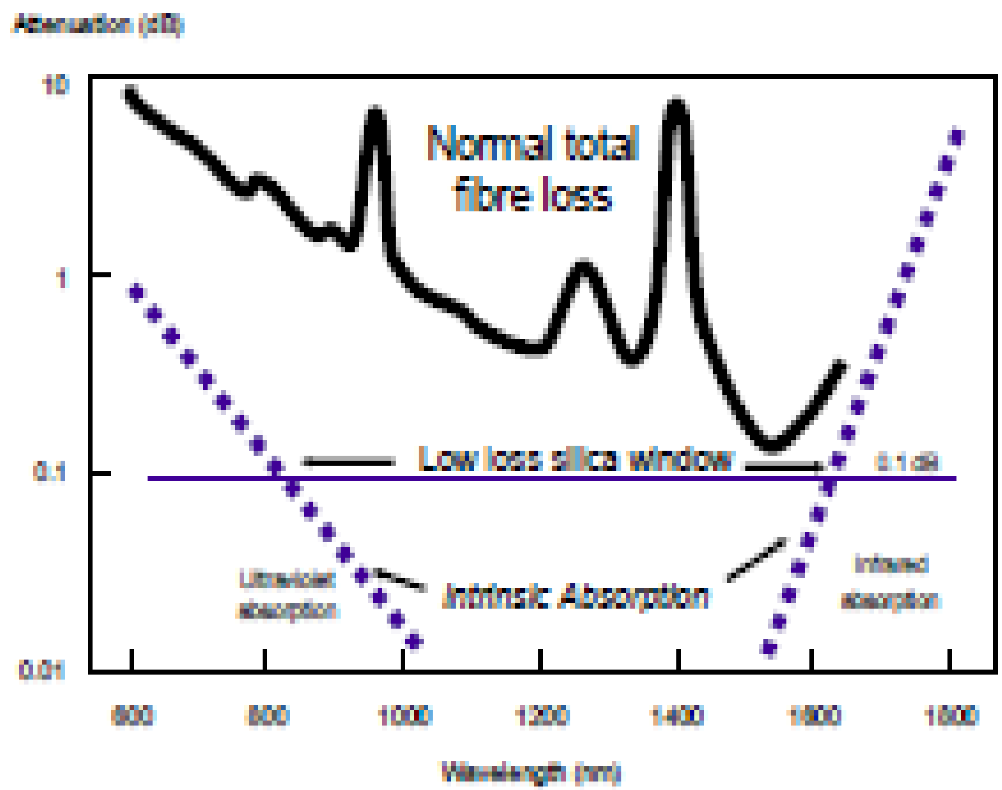
Intrinsic Absorption

Less significant than extrinsic absorption. For a pure (no impurities) silica fibre a low loss window exists between 800 nm and 1600 nm.

- Graph shows attenuation spectrum for pure silica glass

- Intrinsic absorption is very low compared to other forms of loss.

- It is for this reason that fibers are made up of silica and optical communications systems work between about 800 to 1600 nm.



Intrinsic Absorption(minimized by suitable choice of core and clad comp)

- In the **ultraviolet region** → caused when a light particle (photon) interacts with an electron and excites it to a higher energy level.

- In the **infrared region** →Due to the interaction of photons with molecular vibrations within the glass.

Extrinsic Absorption (metallic ions)

- 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 fibre the table shows the peak attenuation wavelength and the attenuation caused by an impurity concentration of 1 part 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

Extrinsic Absorption (OH ions)

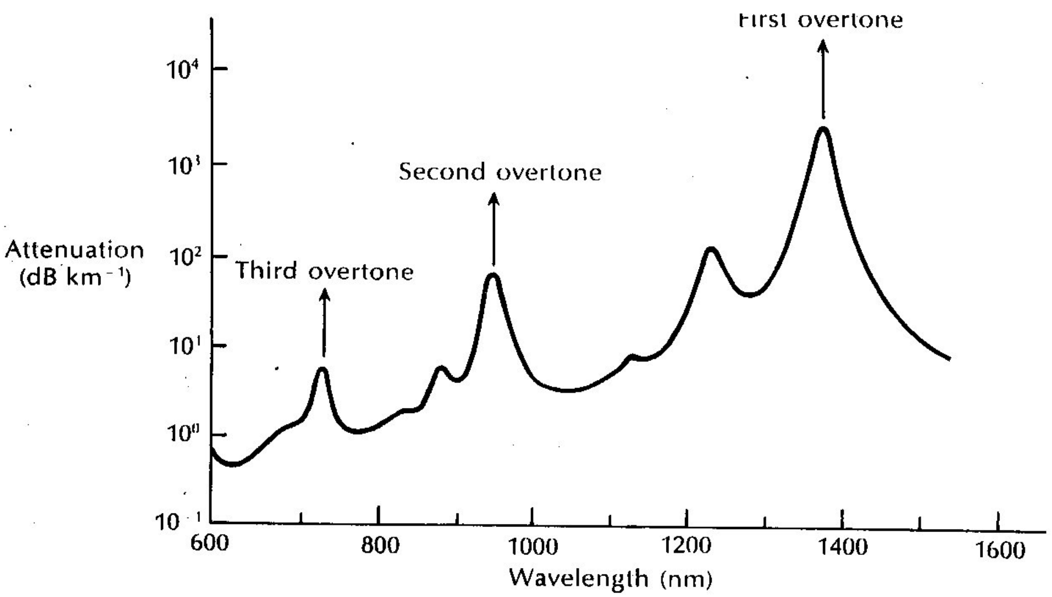
•Extrinsic absorption caused by dissolved water in the glass, as the hydroxyl or OH ion.

•In this case absorption due to the same fundamental processes (between 2700 nm and 4200 nm) gives rise to so called absorption overtones at 1380, 950 and 720 nm.

•Typically a 1 part per million impurity level causes 1 dB/km of attenuation at 950 nm. Typical levels are a few parts per billion

Absorption Spectrum for OH in Silica

Narrow windows 800, 1300 nm and 1550 nm exist which are unaffected by this type of absorption.



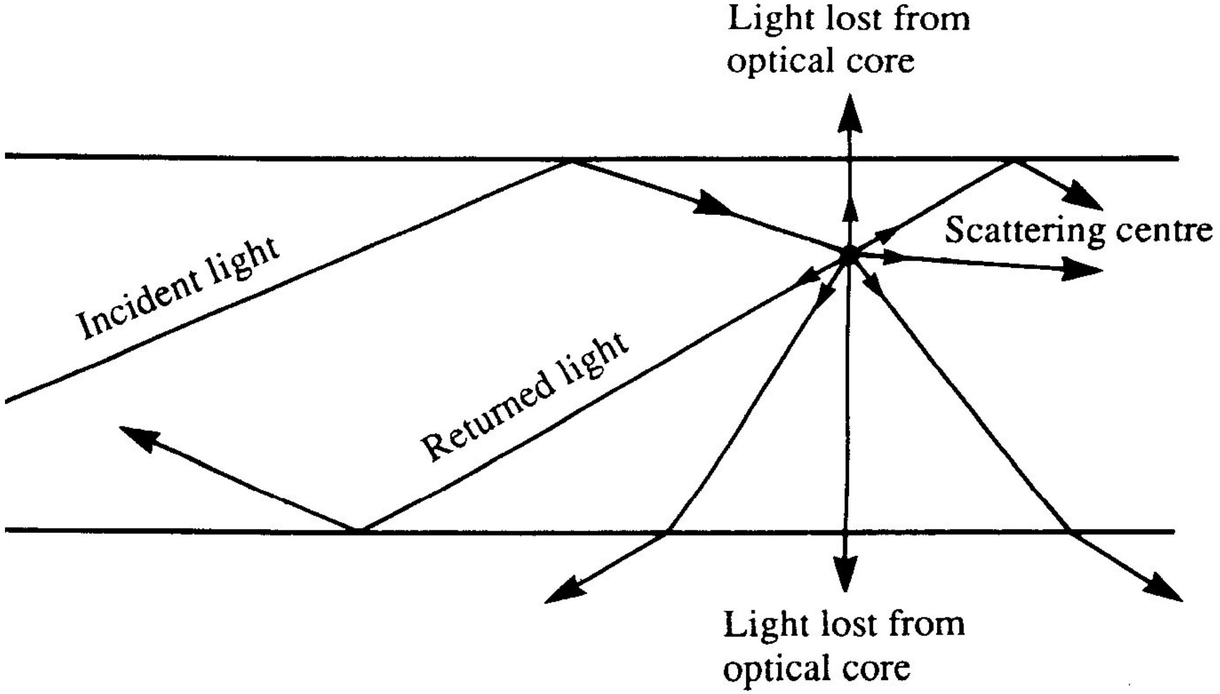
Scattering Losses in Fibre

Linear Scattering:

•cause the transfer of some or all of the optical power contained within one propagating mode to be transferred linearly (proportionally to the mode power) into a different mode.

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

• It must be noted that as with all linear processes, there is no change of frequency on scattering.



Scattering Losses in Fibre

Nonlinear Scattering:

- In case of non-linear scattering, the optical power will transfer from one to other mode with different frequency
- This scattering takes place in forward and backward direction
- Due to shift in the frequency, there is a loss of signal and attenuation

Types of Scattering Loss in Fibre

- Two basic types of scattering exist:

    Linear scattering: *Rayleigh and Mie*

    Non-linear scattering: *Stimulated Brillouin and 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

Rayleigh Scattering

- Dominant scattering mechanism in silica fibers.
- Scattering caused by inhomogeneities in the glass, of a size smaller than the wavelength.
- Inhomogeneities manifested as refractive index variations, present in the glass after manufacture.
- The light from the sun is scattered in the atmosphere which gives the blue sky. This scattering takes place in all directions
- Difficult to eliminate with present manufacturing methods. Rayleigh loss falls off as a function of the fourth power of wavelength:

$$\gamma_R = \frac{8\pi^3}{3\lambda^4} n^8 p^2 \beta_c K T_F$$

where γ_R is the Rayleigh scattering coefficient

λ is the optical wavelength

p is the average photoelastic coefficient

β_c is the isothermal compressibility at a fictive temperature T_F

K is the Boltzmann's constant

n is the refractive index of the medium

K is the Boltzmann constant

Rayleigh Scattering

The Rayleigh scattering coefficient is related to the transmission loss factor (transmissivity) of the fiber.

$$\mathscr{L} = \exp(-\gamma_R L)$$

L is the length of the fiber.

Silica has an estimated fictive temperature of 1400 K with an isothermal compressibility of $7 \times 10^{-11}\ \mathrm{m^2\ N^{-1}}$. The refractive index and the photoelastic coefficient for silica are 1.46 and 0.286 respectively. Determine the theoretical attenuation in decibels per kilometer due to the fundamental Rayleigh scattering in silica at optical wavelength of 0.63 μm. Boltzmann's constant is $1.381 \times 10^{-23}\ \mathrm{J\ K^{-1}}$

$$\gamma_R = \frac{8\pi^3 n^8 p^2 \beta_c K T_F}{3\lambda^4}$$

$$= \frac{248.15 \times 20.65 \times 0.082 \times 7 \times 10^{-11} \times 1.381 \times 10^{-23} \times 1400}{3 \times \lambda^4}$$

$$= \frac{1.895 \times 10^{-28}}{\lambda^4}\ \mathrm{m^{-1}}$$

At a wavelength of 0.63 μm:

$$\gamma_R = \frac{1.895 \times 10^{-28}}{0.158 \times 10^{-24}} = 1.199 \times 10^{-3}\ \mathrm{m^{-1}}$$

Silica has an estimated fictive temperature of 1400 K with an isothermal compressibility of 7×10^{-11} m^2 N^{-1} . The refractive index and the photoelastic coefficient for silica are 1.46 and 0.286 respectively. Determine the theoretical attenuation in decibels per kilometer due to the fundamental Rayleigh scattering in silica at optical wavelength of 0.63 μm. Boltzmann's constant is 1.381×10^{-23} J K^{-1}

The transmission loss factor for 1 kilometer of fiber may be obtained using

$$\mathscr{L}_{\text{km}} = \exp(-\gamma_R L)$$

$$= \exp(-1.199 \times 10^{-3} \times 10^3)$$
$$= 0.301$$

$$\text{Attenuation} = 10 \log_{10}(1/\mathscr{L}_{\text{km}})$$

$$= 10 \log_{10} 3.322$$

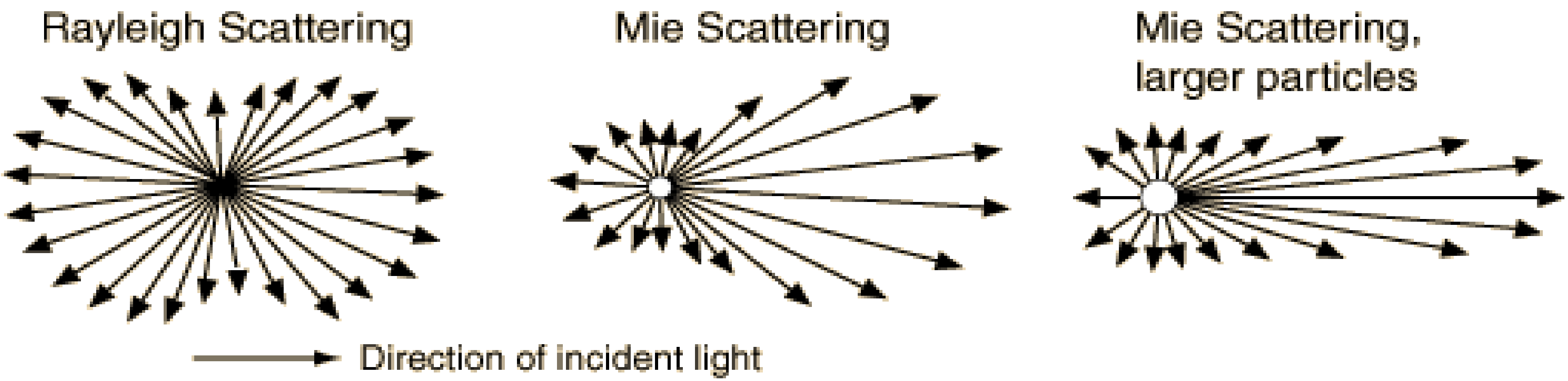
$$= 5.2 \text{ dB km}^{-1}$$

Mie Scattering

(caused by inhomogeneities comparable to wavelength)

- This scattering takes place only in forward direction
- Factors responsible for Mie scattering
  - Cylindrical structure of cable is not perfect
  - Imperfect core/cladding interface
  - Core and cladding refractive index is not uniform throughout the fiber
  - Fluctuations in core diameter
  - Bubbles or strains in fiber
- Mie scattering results significant attenuation depending upon the fiber material, size, design and manufacturing process. It can be reduced by
  - Removing imperfections in glass
  - Careful extrusion and coating of the fiber
  - Increase the core/cladding index

Rayleigh & Mie Scattering



Stimulated Brillouin Scattering(SBS)

- When the light signal is travelling inside the fiber cable, there are variations in the electric field of the beam.
- These variations in electric field produces acoustic vibrations in the fiber cable
- These acoustic vibrations creates the acoustic frequency which results in the scattered photon.
- This scattering usually takes place in the opposite direction of the incident light
- During this scattering, a frequency shift is produced and it varies with the scattering angle. This frequency shift in maximum in the backward direction.

Stimulated Brillouin Scattering (Backward scattering)

Brillouin Scattering is only significant above a threshold power density. The threshold power is given by

$$P_B = 4.4 \times 10^{-3} d^2 \lambda^2 \alpha_{dB} \nu \text{ watts}$$

where d and λ are the fiber core diameter and the operating wavelength, respectively both measured in micrometers,

α dB is the fiber attenuation in decibels per kilometer

ν is the source bandwidth (i.e. injection laser) in gigahertz.

Stimulated Raman Scattering (SRS)

- When the light signal is travelling inside the fiber cable, the spontaneous scattering takes place

- In this process, some of the photons transferred to the near frequencies

- When the scattered photons lose energy it is called as **Stokes shift** and if the scattered photons gains energy it is called as **Anti stokes shift**

- If the photons of other frequencies are already present then the scattering of such photons takes place and in this case two photons are generated. It is called as SRS.

- This is similar to SBS. But in SBS high frequency acoustic phonon is created and in SRS high frequency optical phonon is created.

- SRS happens in both forward and backward direction

Stimulated Raman scattering

(Both backward and forward scattering)

- Optical power threshold-3 times than brillouin scattering threshold.
- Produces optical phonon and scattered photon in single mode fiber. The threshold power is given by

$$P_R = 5.9 \times 10^{-2} d^2 \lambda \alpha_{dB} \text{ watts}$$

A long single-mode optical fiber has an attenuation of 0.5 dB km−1 when operating at a wavelength of 1.3 μm. The fiber core diameter is 6 μm and the laser source band width is 600 MHz. Compare the threshold optical powers for stimulated Brillouin and Raman scattering within the fiber at the wavelength specified.

The threshold optical power for SBS is given by

$$P_B = 4.4 \times 10^{-3} d^2 \lambda^2 \alpha_{dB} \nu \quad = 4.4 \times 10^{-3} \times 6^2 \times 1.3^2 \times 0.5 \times 0.6 \quad = 80.3 \text{ mW}$$

The threshold optical power for SRS is given by

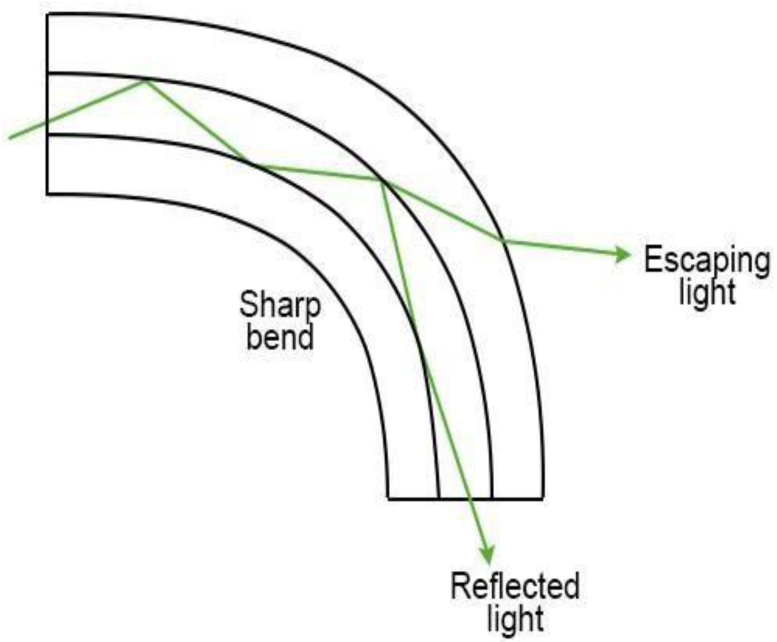
$$P_R = 5.9 \times 10^{-2} d^2 \lambda \alpha_{dB} \quad = 5.9 \times 10^{-2} \times 6^2 \times 1.3 \times 0.5 \quad = 1.38 \text{ W}$$

- The Brillouin threshold occurs at an optical power level of around 80 mW while the Raman threshold is approximately 17 times larger.

- It is therefore apparent that the losses introduced by nonlinear scattering may be avoided by use of a suitable optical signal level (i.e. working below the threshold optical powers).

Radiative Loss/Bending 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.
- If there is sharp bend in the fiber, then there is probability of mechanical failure of the cable.

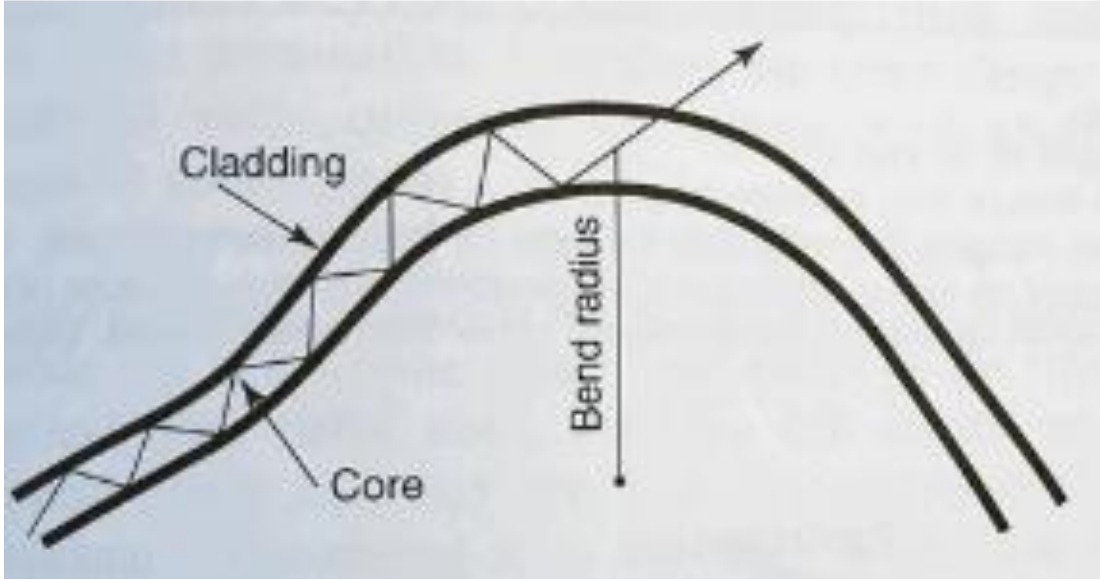


Types of Bending Loss

- Macro-bending Losses
  - Bend radius >> core radius
- Micro-bending Losses
  - Bend radius comparable to core radius

Fiber Bend Loss(Macro Bending)

- The curvature of the bend is much larger than fiber diameter.
- Light wave suffers severe loss due to radiation of the evanescent field in the cladding region.
- Part of the mode in the cladding needs to travel faster than the velocity of light in that medium.
- As this is not possible, the energy associated with this part of the mode is lost through radiation.



Fiber Bend Loss(Macro Bending)

- The loss can generally be represented by a radiation attenuation coefficient which has the form

$$\alpha_r = c_1 \, exp(-c_2 R)$$

- where *R is the radius of curvature of the fiber bend and* c_1, c_2 *are constants which are* independent of *R.*

- Large bending losses tend to occur in multimode fibers at a critical radius of curvature R_c

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

Fiber Bend Loss(Macro Bending)

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

Potential macrobending losses may be reduced by:

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

(b) operating at the shortest wavelength possible.

Fiber Bend Loss(Macro Bending)

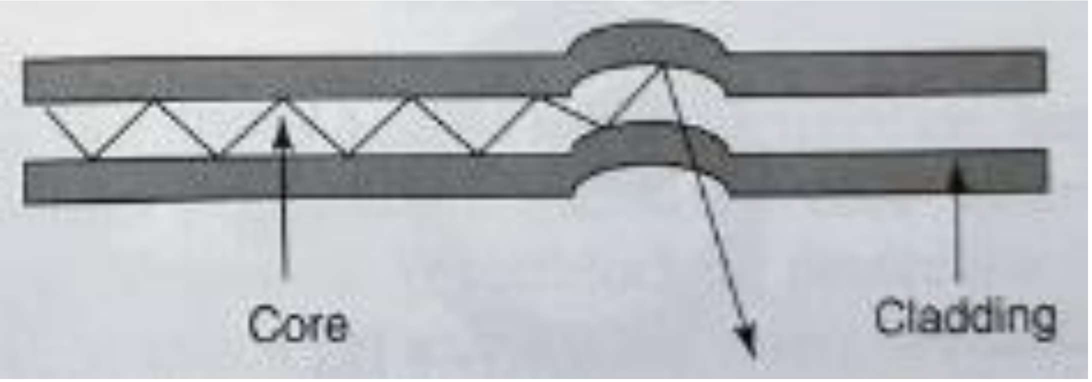
The critical radius of curvature R_{cs} for a single mode fiber is

$$R_{cs} \simeq \frac{20\lambda}{(n_1 - n_2)^{\frac{3}{2}}}\left(2.748 - 0.996\,\frac{\lambda}{\lambda_c}\right)^{-3}$$

where λ_c is the cutoff wavelength for the single-mode fiber.

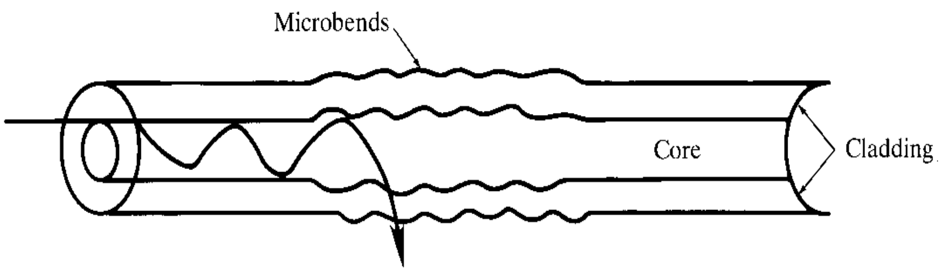
Fiber Bend Loss(Micro Bending)

- When the bending radius is comparable to the core radius it is Micro Bending..

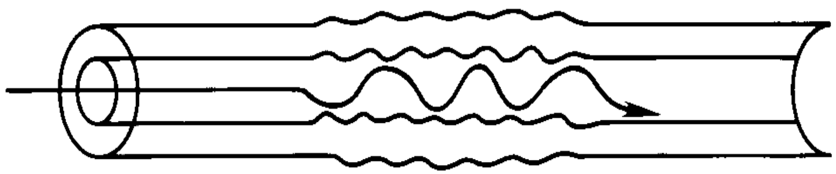


Fiber Bend Loss(Micro Bending)

- Microbends are repetitive small scale fluctuations in the radius of curvature of the fiber axis
- Caused either by nonuniformities in the manufacturing of the fiber or during cabling.
- An increase in attenuation results due to repetitive coupling of energy between the guided modes and the leaky or nonguided modes in the fiber

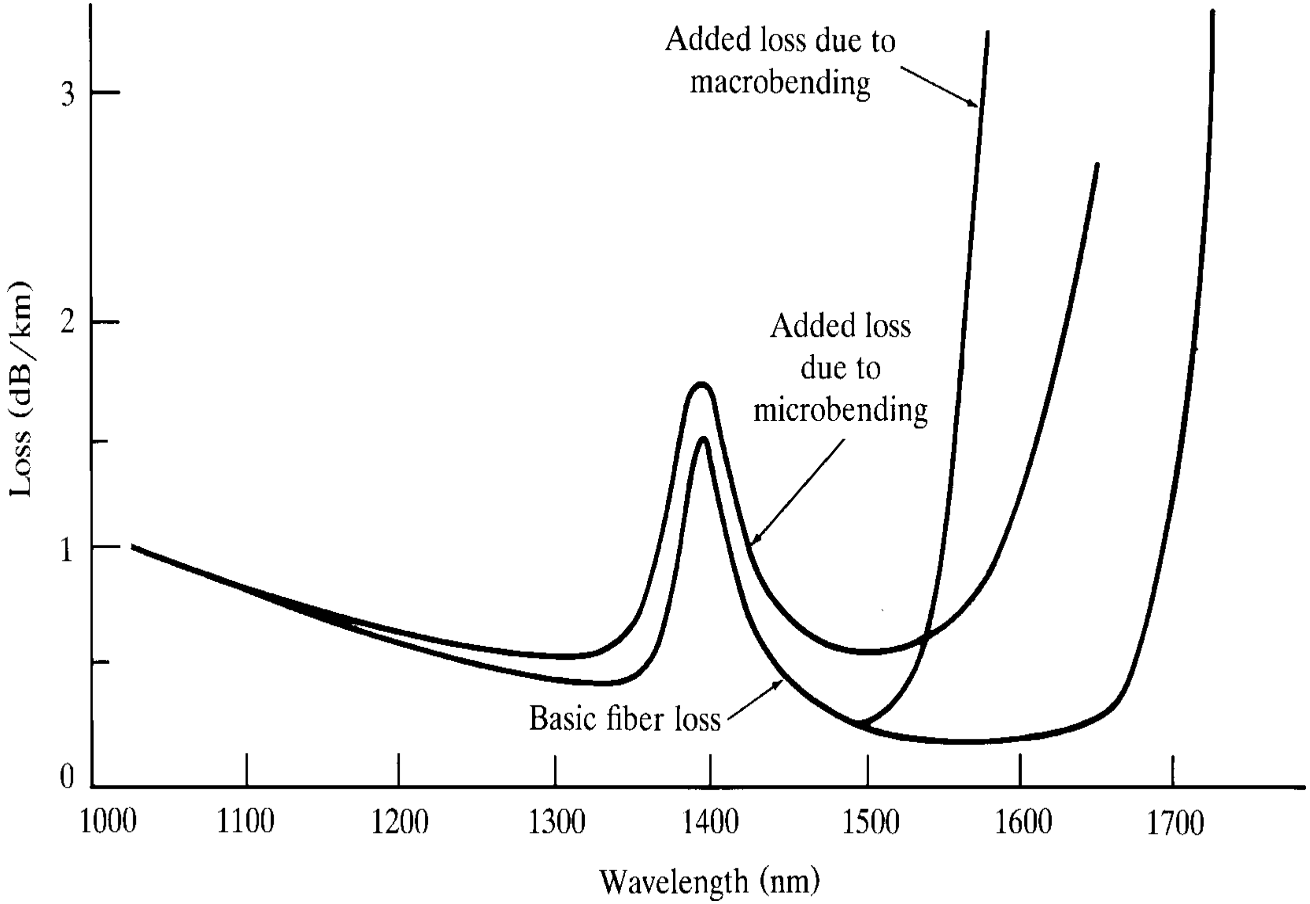


Power loss from higher-order modes



Power coupling to higher-order modes

Bending Induced Attenuation



Two step index fibers exhibit the following parameters:

- MMF → Core RI = 1.500
  Δ = 3 %
  λ = 0.82 μm

- SMF → Core RI = 1.500
  Δ = 0.3 %
  λ = 1.55 μm
  Core dia. = 8 μm

- Comment on their Critical Bending Radii ?

MMF → Core RI = 1.500

Δ = 3 %

λ = 0.82 μm

The relative refractive index difference is given by

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

$$n_2^2 = n_1^2 - 2\Delta n_1^2$$

$$= 2.250 - 0.06 \times 2.250$$
$$= 2.115$$

for the multimode fiber critical radius of curvature:

$$R_c \simeq \frac{3n_1^2\lambda}{4\pi(n_1^2 - n_2^2)^{\frac{1}{2}}}$$

$$= \frac{3 \times 2.250 \times 0.82 \times 10^{-6}}{4\pi \times (0.135)^{\frac{1}{2}}}$$
$$= 9\ \mu\text{m}$$

SMF → Core RI = 1.500

Δ = 0.3 %

λ = 1.55 μm

Core dia. = 8 μm

The relative refractive index difference is given by

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

$$n_2^2 = n_1^2 - 2\Delta n_1^2 \qquad = 2.250 - (0.006 \times 2.250) = 2.237$$

The cutoff wavelength for the single-mode fiber is given by

$$\lambda_c = \frac{2\pi a n_1 (2\Delta)^{\frac{1}{2}}}{2.405} \qquad = \frac{2\pi \times 4 \times 10^{-6} \times 1.500\ (0.06)^{\frac{1}{2}}}{2.405} = 1.214\ \mu\text{m}$$

the critical radius of curvature for the single-mode fiber gives:

$$R_{cs} \simeq \frac{20\lambda}{(n_1 - n_2)^{\frac{3}{2}}}\left(2.748 - 0.996\frac{\lambda}{\lambda_c}\right)^{-3}$$

$$R_{cs} \simeq \frac{20 \times 1.55 \times 10^{-6}}{(0.043)^{\frac{3}{2}}}\left(2.748 - \frac{0.996 \times 1.55 \times 10^{-6}}{1.214 \times 10^{-6}}\right)^{-3} = 34\ \text{mm}$$

Two step index fibers exhibit the following parameters:

- MMF → Core RI $= 1.500$
  $\Delta = 3\ \%$
  $\lambda = 0.82\ \mu m$
  $R_c = 9\ \mu m$

- SMF → Core RI $= 1.500$
  $\Delta = 0.3\ \%$
  $\lambda = 1.55\ \mu m$
  Core dia. $= 8\ \mu m$
  $R_{cs} = 34\ mm$

- Comment on their Critical Bending Radii ?

Dispersion in Optical Fibers

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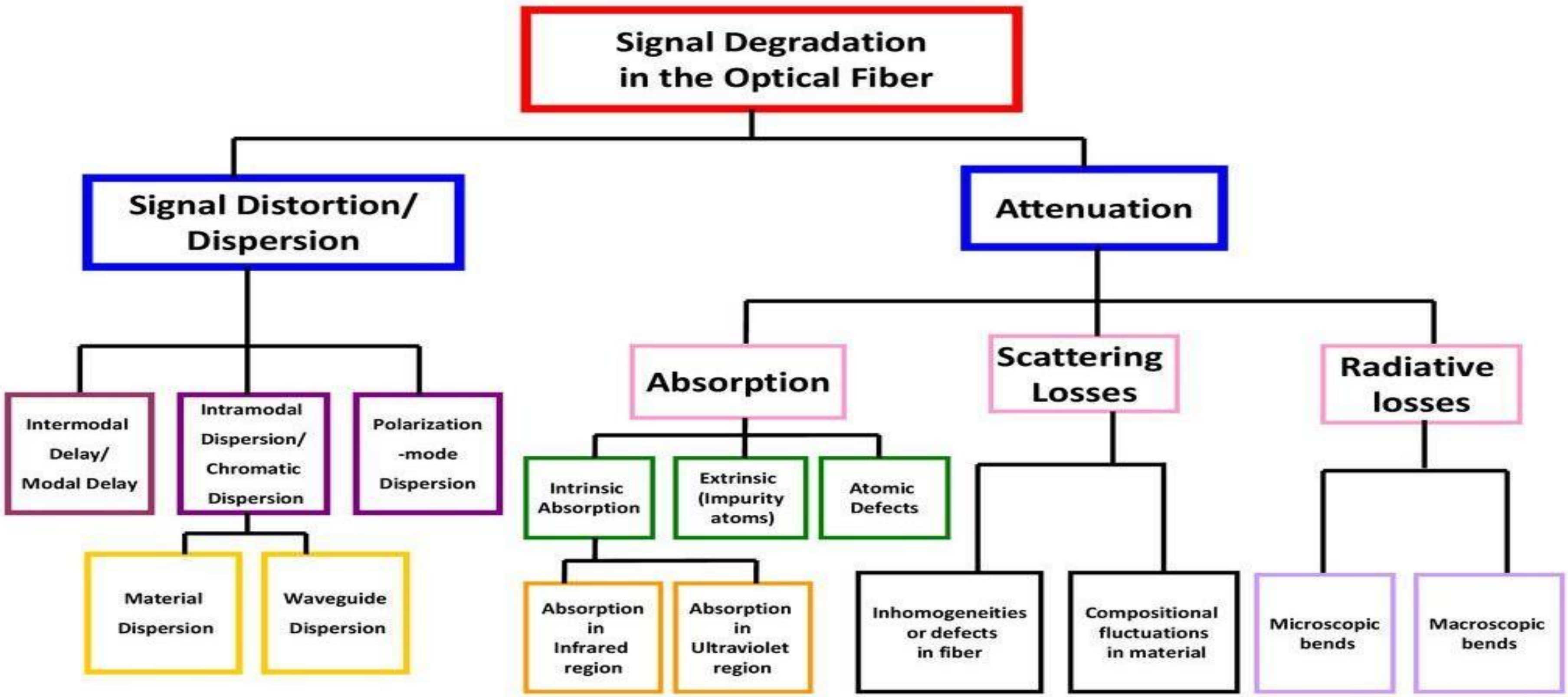
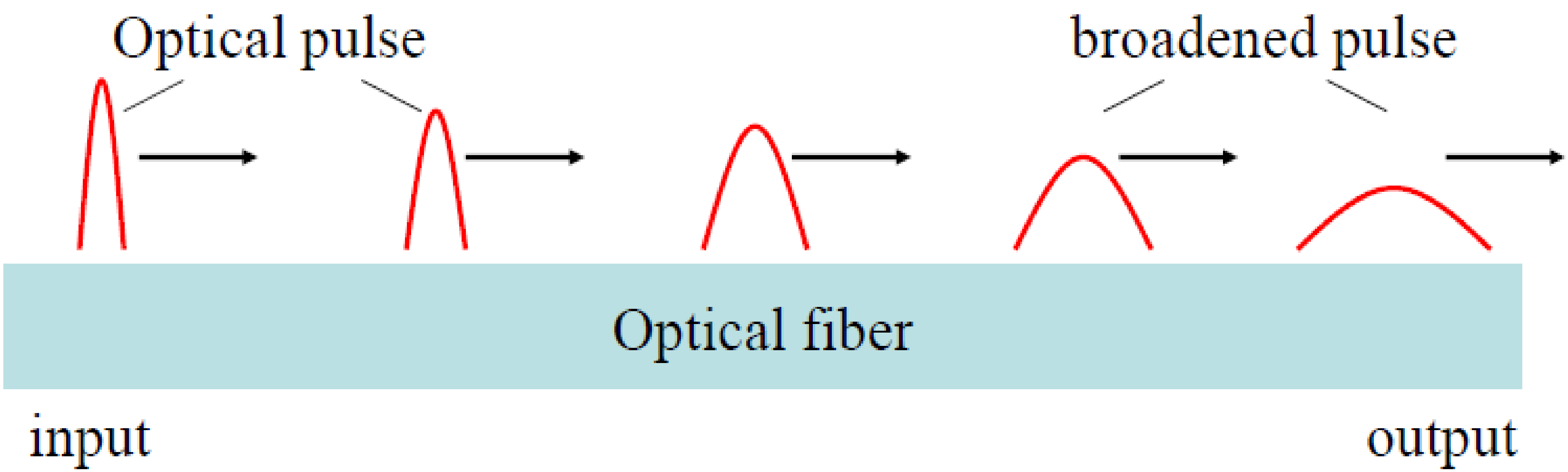

Signal Degradation in the Optical Fiber
Signal Distortion/ Dispersion
Attenuation
Intermodal Delay/ Modal Delay
Intramodal Dispersion/ Chromatic Dispersion
Polarization -mode Dispersion
Material Dispersion
Waveguide Dispersion
Absorption
Scattering Losses
Radiative losses
Intrinsic Absorption
Extrinsic (Impurity atoms)
Atomic Defects
Absorption in Infrared region
Absorption in Ultraviolet region
Inhomogeneities or defects in fiber
Compositional fluctuations in material
Microscopic bends
Macroscopic bends

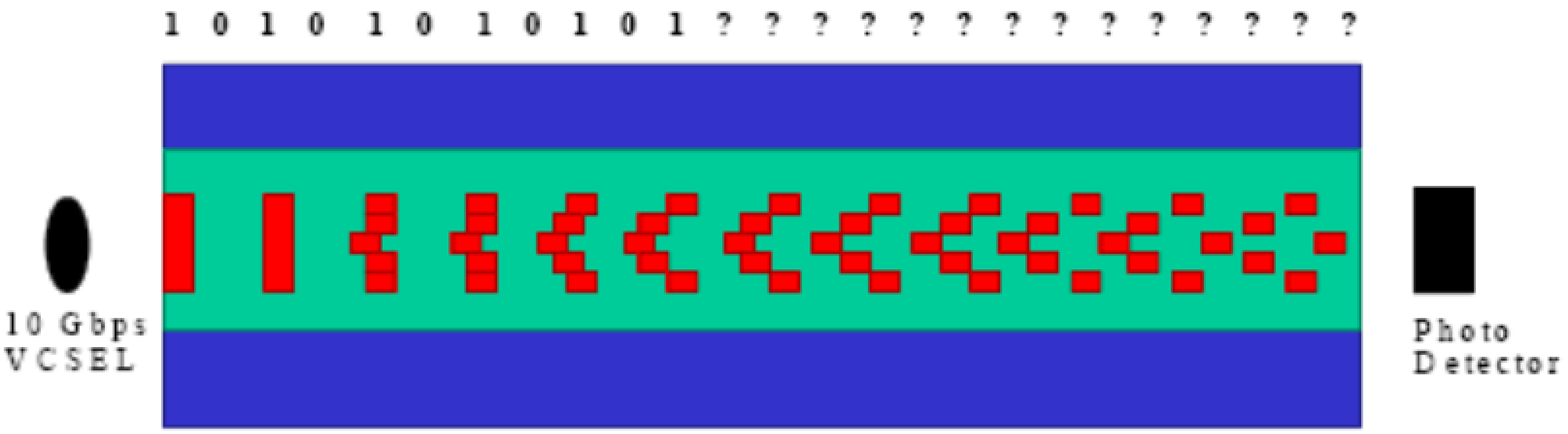
Fibre Dispersion

➢ Dispersion of the transmitted optical signal causes distortion for both digital and analog transmission along optical fibers.

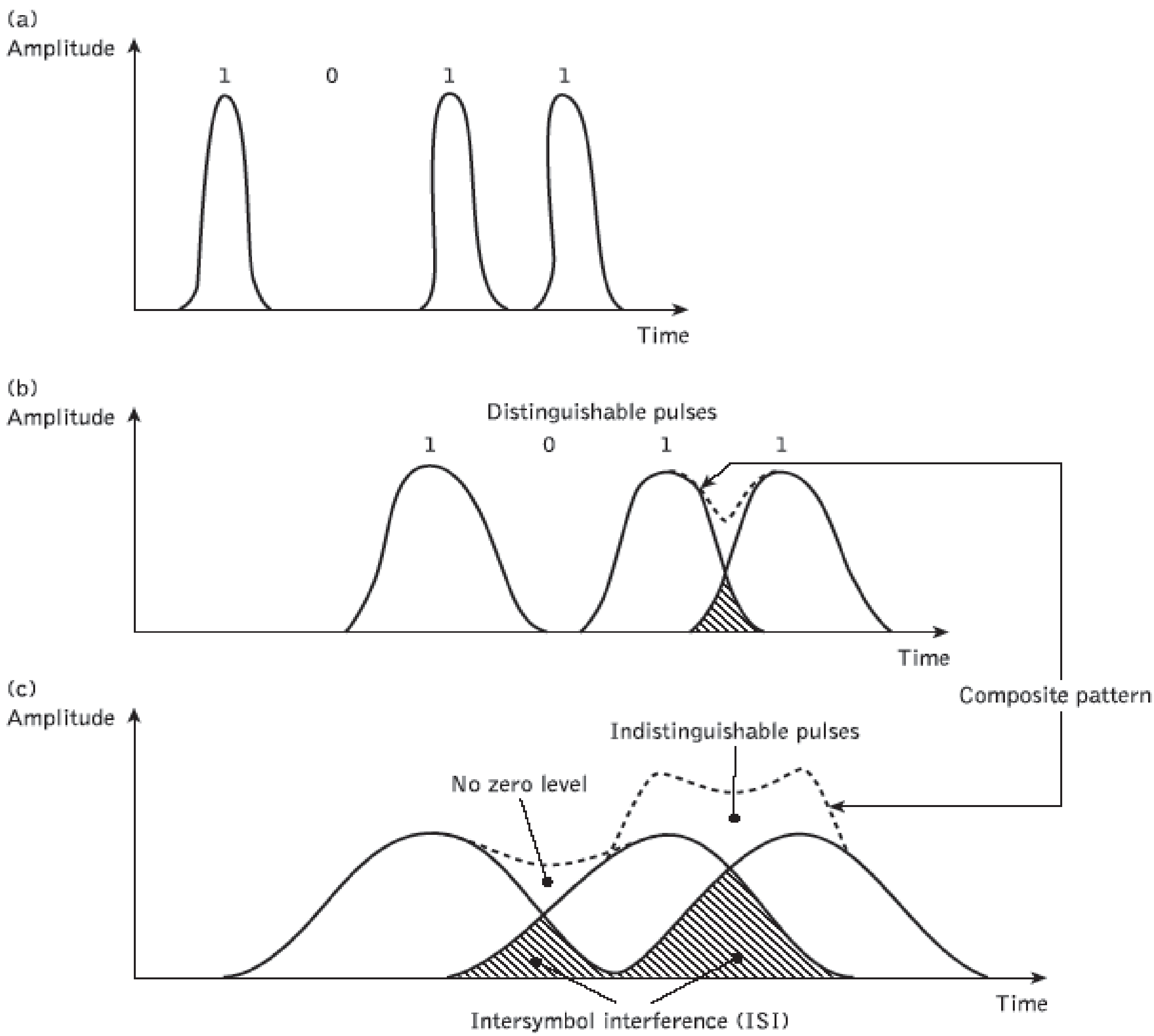
➢Dispersion mechanisms within the fiber cause broadening of the transmitted light pulses as they travel along the channel.



Dispersion in Digital systems



Effects of Dispersion and Attenuation



An illustration using the digital bit pattern 1011 of the broadening of light pulses as they are transmitted along a fiber: (a) fiber input; (b) fiber output at a distance L1; (c) fiber output at a distance L2 > L1

Bit Rate Limitations

For no overlapping of light pulses down on an optical fiber link the digital bit rate

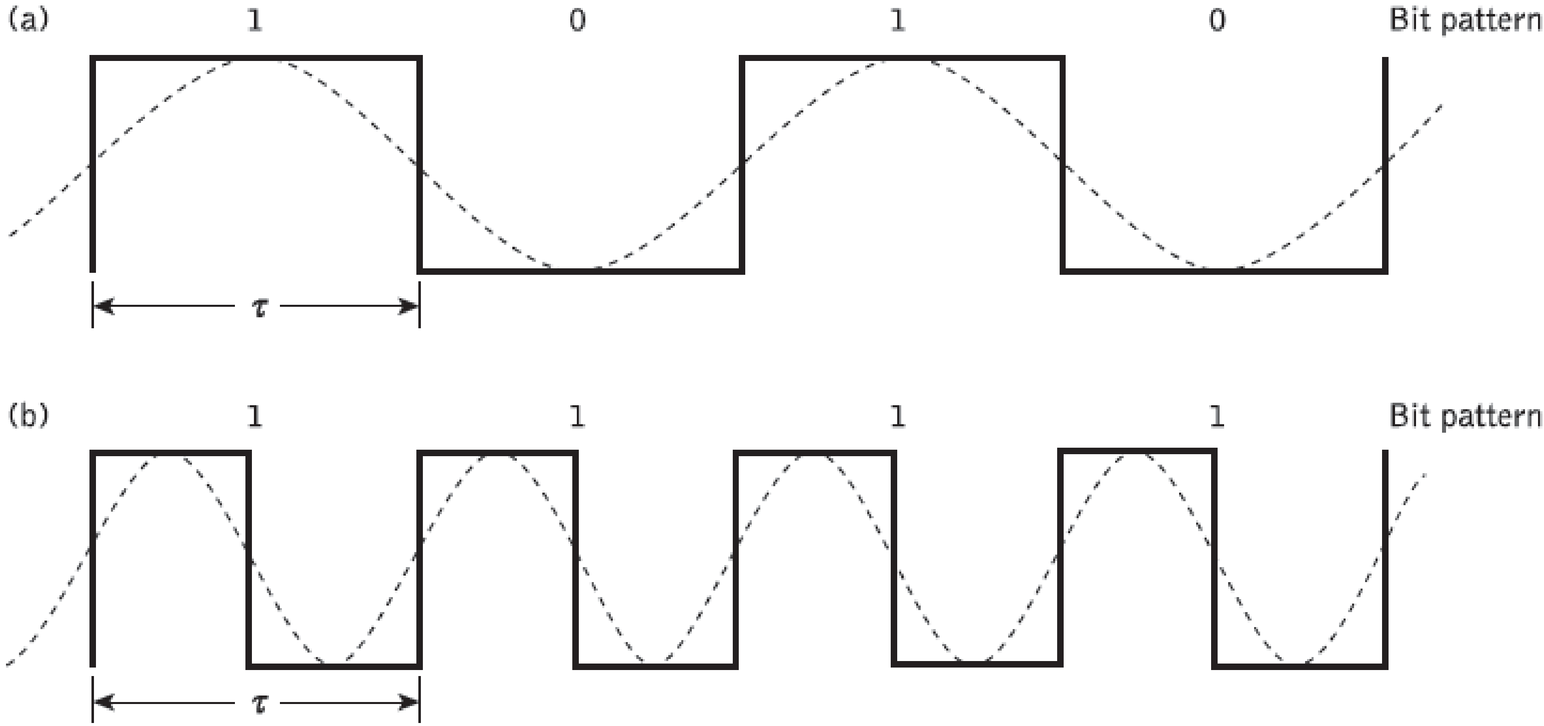
$$B_T \leq \frac{1}{2\tau}$$

Where τ is the broadened pulse duration due to dispersion.

Considering the light pulses at the output to have a Gaussian shape with an rms width of σ. The maximum bit rate is given by

$$B_T(\text{max}) \simeq \frac{0.2}{\sigma} \text{ bit s}^{-1}$$

Relationships of the bit rate to wavelength for digital codes



(a) nonreturn-to-zero (NRZ); (b) return-to-zero (RZ)

Bandwidth Limitations

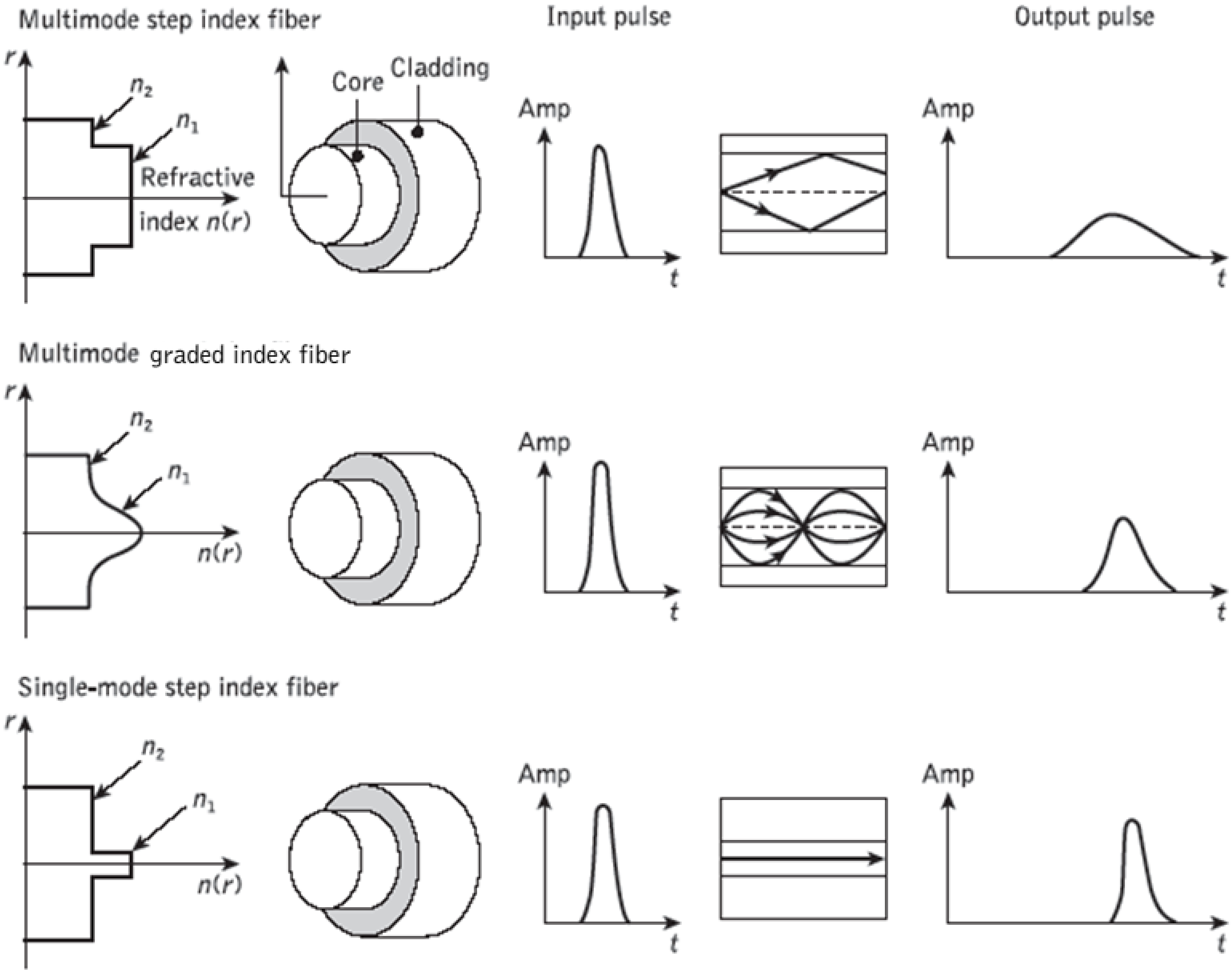
The conversion of bit rate to bandwidth in hertz depends on the digital coding format used.

When a nonreturn-to-zero code is employed, the binary 1 level is held for the whole bit period . In this case there are two bit periods in one wave length (i.e. 2 bits per second per hertz). Hence the maximum bandwidth B is one-half the maximum data rate.

However, when a return-to-zero code is considered, the binary 1 level is held for only part (usually half) of the bit period. For this signaling scheme the data rate is equal to the bandwidth in hertz (i.e. 1 bit per second per hertz)

Maximum channel bandwidth *B:*

- For non-return-to-zero (NRZ) data format: $B_T(max) = 2B$
- For return-to-zero (RZ) data format: $B_T(max) = B$



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

A multimode graded index fiber exhibits total pulse broadening of 0.1 μs over a distance of 15 km. Estimate: (a) the maximum possible bandwidth on the link assuming no intersymbol interference; (b) the pulse dispersion per unit length; (c) the bandwidth–length product for the fiber.

(a) The maximum possible optical bandwidth which is equivalent to the maximum possible bit rate (for return to zero pulses)

$$B_{opt} = B_T = \frac{1}{2\tau} \qquad = \frac{1}{0.2 \times 10^{-6}} = 5\ \text{MHz}$$

(b) The dispersion per unit length may be acquired simply by dividing the total dispersion by the total length of the fiber:

$$\text{Dispersion} = \frac{0.1 \times 10^{-6}}{15} \qquad = 6.67\ \text{ns km}^{-1}$$

A multimode graded index fiber exhibits total pulse broadening of 0.1 μs over a distance of 15 km. Estimate: (a) the maximum possible bandwidth on the link assuming no intersymbol interference; (b) the pulse dispersion per unit length; (c) the bandwidth–length product for the fiber.

(c) The bandwidth–length product may be obtained in two ways. Firstly by simply multiplying the maximum bandwidth for the fiber link by its length

$$B_{opt}L \quad = 5 \text{ MHz} \times 15 \text{ km} \quad = 75 \text{ MHz km}$$

Alternatively, it may be obtained from the dispersion per unit length using

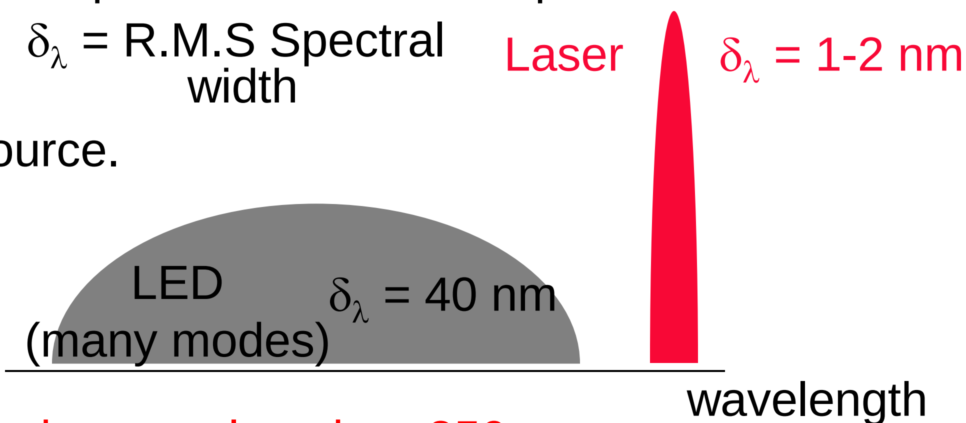
$$B_{opt}L = \frac{1}{2 \times 6.67 \times 10^{-6}} = 75 \text{ MHz km}$$

Chromatic/Intramodal Dispersion

- Intramodal dispersion arises due to the propagation delay differences between the different spectral components of the transmitted signal.

- Further it increases with the increase in spectral width of the optical source.

- This spectral width is the range of wavelengths emitted by the optical source.



- For example in the case of LED, it has a large spectral width about 40 nm since it emits wavelengths from 830–870 nm with the peak emission wavelength at 850 nm.

- In the case of laser diode which has a very narrow spectral width, the spectral width is about 1 or 2 nm only.

- Thus the Intramodal dispersion can be reduced in an optical fiber using single mode laser diode as an optical source.

Chromatic/Intramodal Dispersion

Chromatic dispersion : Different spectral components of a pulse travel at different group velocities. This is known as group velocity dispersion (GVD).

Main causes:

- Material dispersion (delay differences caused by the dispersive properties of the waveguide material)
- Waveguide dispersion (delay differences caused by the guidance effects within the fiber structure)

Material Dispersion

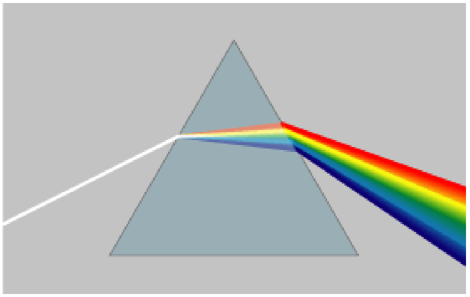
- Material dispersion is due to the wavelength dependency on the index of refraction of glass.

- This dispersion arises due to the different group velocities of the various spectral components launched into the fiber.

- A material is said to exhibit material dispersion when $\mathrm{d}^2 n_1 / \mathrm{d}\lambda^2 \neq 0.$

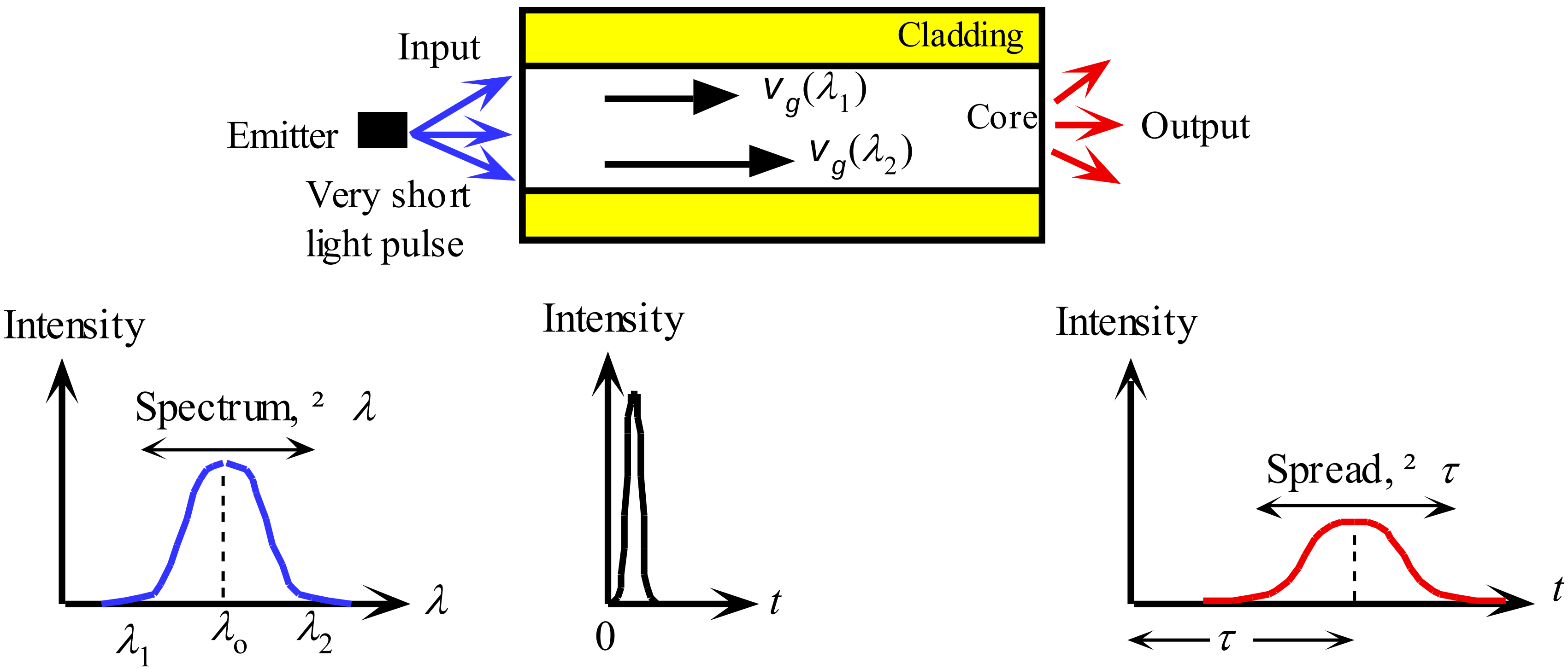
- Pulse spreading occurs even when different wavelengths follow the same path.

- Sometimes referred to as Chromatic dispersion , since this is the same effect by which a prism spreads out a spectrum.



In a prism, material dispersion (a wavelength-dependent refractive index) causes different colors to refract at different angles, splitting white light into a rainbow

Material Dispersion



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

Material Dispersion

The rms pulse broadening due to material dispersion is given by:

$$\sigma_m \simeq \frac{\sigma_\lambda L}{c} \left| \lambda \frac{d^2 n_1}{d\lambda^2} \right| \qquad \text{ns/Km}$$

Material dispersion parameter *M which is* defined as:

$$M = \frac{1}{L}\frac{d\tau_m}{d\lambda} = \frac{\lambda}{c}\left| \frac{d^2 n_1}{d\lambda^2} \right|$$

and which is often expressed in units of ps nm^{-1} km^{-1}.

A glass fiber exhibits material dispersion given by $|\lambda^2 (d^2n1/d\lambda^2)|$ of 0.025. Determine the material dispersion parameter at a wavelength of 0.85 μm, and estimate the rms pulse broadening per kilometer for a good LED source with an rms spectral width of 20 nm at this wavelength

The material dispersion parameter may be obtained as

$$M = \frac{\lambda}{c}\left|\frac{\mathrm{d}^2 n_1}{\mathrm{d}\lambda^2}\right| = \frac{1}{c\lambda}\left|\lambda^2 \frac{\mathrm{d}^2 n_1}{\mathrm{d}\lambda^2}\right|$$

$$= \frac{0.025}{2.998 \times 10^5 \times 850} \text{ s nm}^{-1}\text{ km}^{-1}$$

$$= 98.1 \text{ ps nm}^{-1}\text{ km}^{-1}$$

The rms pulse broadening is given by

$$\sigma_{\mathrm{m}} \simeq \frac{\sigma_\lambda L}{c}\left|\lambda \frac{\mathrm{d}^2 n_1}{\mathrm{d}\lambda^2}\right|$$

Therefore in terms of the material dispersion parameter M defined by

$$\sigma_{\mathrm{m}} \simeq \sigma_\lambda L M$$

A glass fiber exhibits material dispersion given by $|\lambda^2 (d^2n1/d\lambda^2)|$ of 0.025. Determine the material dispersion parameter at a wavelength of 0.85 μm, and estimate the rms pulse broadening per kilometer for a good LED source with an rms spectral width of 20 nm at this wavelength

Hence, the rms pulse broadening per kilometer due to material dispersion

$$\sigma_m(1\ \text{km}) = 20 \times 1 \times 98.1 \times 10^{-12} = 1.96\ \text{ns km}^{-1}$$

Estimate the rms pulse broadening per kilometer for the fiber when the optical source used is an injection laser with a relative spectral width $\sigma\lambda/\lambda$ of 0.0012 at a wavelength of 0.85 μm.

The rms spectral width may be obtained from the relative spectral width by

$$\sigma_\lambda = 0.0012\lambda \qquad \begin{aligned} &= 0.0012 \times 0.85 \times 10^{-6} \\ &= 1.02 \text{ nm} \end{aligned}$$

The rms pulse broadening in terms of the material dispersion parameter

$$\sigma_{\mathrm{m}} \simeq \sigma_\lambda L M$$

Therefore, the rms pulse broadening per kilometer due to material dispersion is

$$\sigma_{\mathrm{m}} \simeq 1.02 \times 1 \times 98.1 \times 10^{-12} = 0.10 \text{ ns km}^{-1}$$

Waveguide Dispersion

•Waveguide dispersion is due to the physical structure of the waveguide.

•Signal in the cladding travels with a different velocity than the signal in the core

• The amount of waveguide dispersion depends on the fiber design like core radius and the size of the fiber.

•This can usually be ignored in multimode fibres, since it is very small compared with material dispersion.

•However it is significant in monomode fibres.

In a simple step-indexprofile fiber, waveguide dispersion is not a major factor, but in fibers with more complex index profiles, waveguide dispersion can be more significant

Modifying Chromatic Dispersion

Chromatic Dispersion = Material dispersion + Waveguide dispersion

- Material dispersion depends on the material properties and difficult to alter
- Waveguide dispersion can be altered by changing the fiber refractive index profile
  - 1300 nm optimized
  - Dispersion Shifting (to 1550 nm)
  - Dispersion Flattening (from 1300 to 1550 nm)

Phase Velocity

- When the optical waves are propagating through the fiber, there are certain points having constant phase

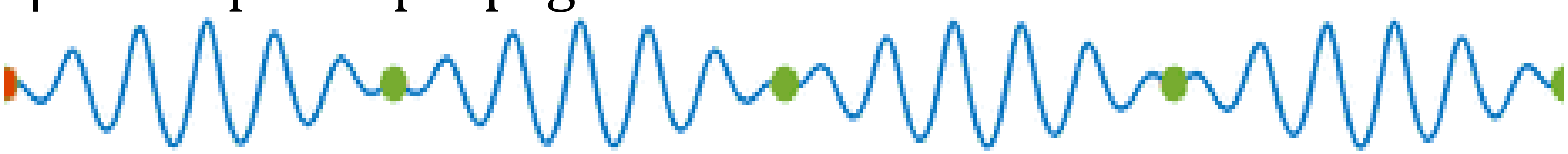
- These points of constant travels with a velocity called as phase velocity

$$\boxed{v_p = \omega / \beta}$$

$$\omega = \frac{2\pi c}{\lambda} \qquad \beta = \frac{2\pi n}{\lambda}$$

$$\boxed{v_p = c / n}$$

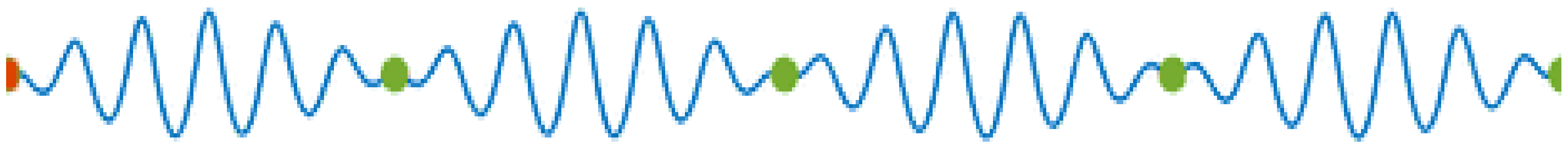
- β is the phase propagation constant



Group Velocity

- Optical waves are travelling as wave packets
- A group of waves with closely similar wavelengths (or frequencies) always combine to form a packet of wave
- The rate at which envelope of the waves propagates called as group velocity

$$V_g = \frac{\partial \omega}{\partial \beta} \quad = 2\pi c \frac{\partial}{\partial \beta}\left(\frac{1}{\lambda}\right)$$



Group velocity

- The energy in a wave packet is transported at group velocity v_g.

- The constant-phase wavefront travels at the phase velocity, but the group velocity is the velocity at which energy (and information) travels.

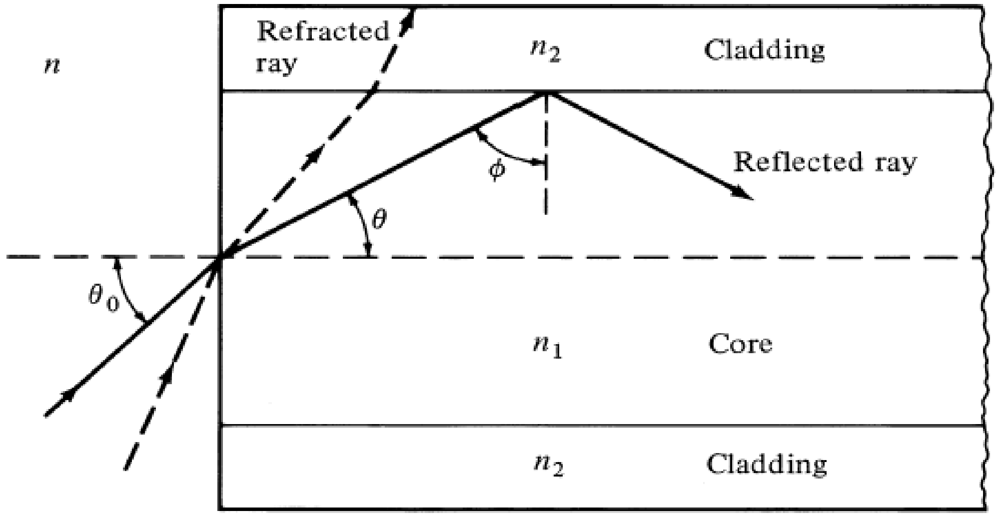
- Any information signal is a wave packet, and thus travels at the group velocity, not at the phase velocity.

Group delay

- The transit time or group delay Ʈg for a light pulse propagating along a unit length of fiber is the inverse of the group velocity v_g.

$$\tau_g = \frac{1}{v_g} = \frac{d\beta}{d\omega} = \frac{1}{c}\frac{d\beta}{dk}$$

Modal (Intermodal) Dispersion



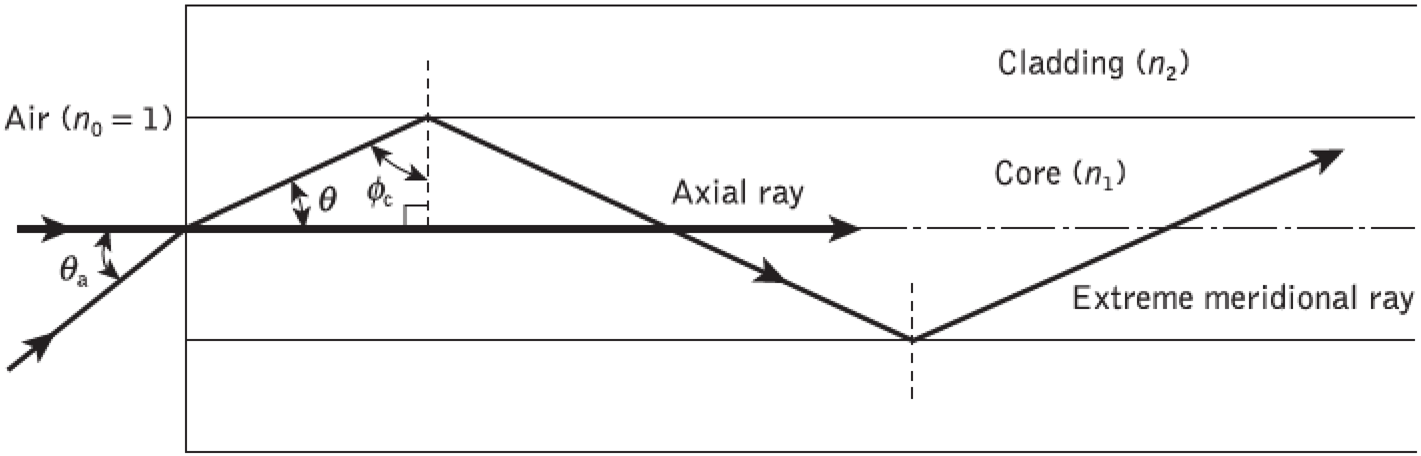
- Result of different values of the group delay for each individual mode at a single frequency.
- This variation in the group velocities of the different modes results in a group delay spread of intermodal distortion.
- This distortion mechanism is eliminated by single-mode operation, but it is important in multimode fibers.

Modal (Intermodal) Dispersion

- Lower order modes travel almost parallel to the centre line of the fibre cover the shortest distance, thus reaching the end of fibre sooner.

- The higher order modes (more zig-zag rays) take a longer route as they pass along the fibre and so reach the end of the fibre later.

- Mainly in multimode fibers



Modal Dispersion - SIMMF

The time taken for the axial ray to travel along a fiber of length *L* gives the minimum delay time

$$T_{\mathrm{Min}} = \frac{\text{distance}}{\text{velocity}} = \frac{L}{(c/n_1)} = \frac{Ln_1}{c}$$

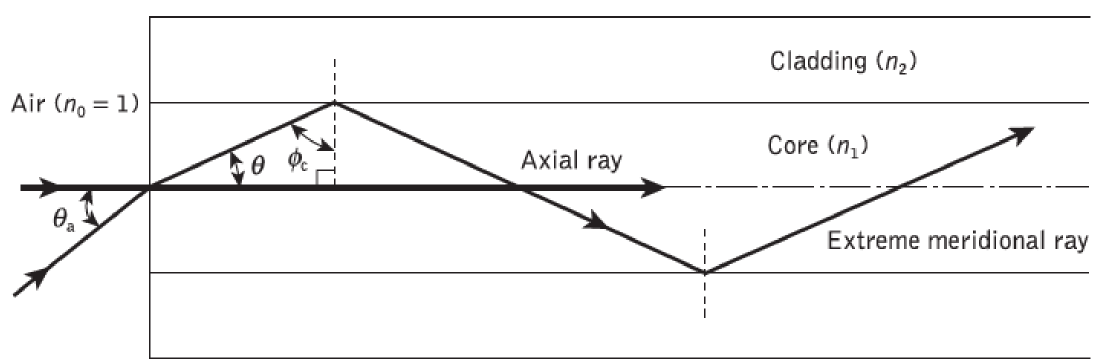
The extreme meridional ray exhibits the maximum delay time

$$T_{\mathrm{Max}} = \frac{L/\cos\theta}{c/n_1} = \frac{Ln_1}{c\cos\theta}$$

Using Snell's law of refraction

Since

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



Substituting for cos θ gives:

$$T_{\mathrm{Max}} = \frac{Ln_1^2}{cn_2}$$

Modal Dispersion - SIMMF

The delay difference δT_s between the extreme meridional ray and the axial ray

$$\delta T_s = T_{\mathrm{Max}} - T_{\mathrm{Min}} = \frac{Ln_1^2}{cn_2} - \frac{Ln_1}{c}$$

$$= \frac{Ln_1^2}{cn_2}\left(\frac{n_1 - n_2}{n_1}\right)$$

$$\simeq \frac{Ln_1^2\Delta}{cn_2} \quad \text{when } \Delta \ll 1$$

Modal Dispersion - SIMMF

For $\Delta \ll 1$, $\Delta = \frac{(n_1 - n_2)}{n_2}$ and $NA = n_1 (2\Delta)^{0.5}$

Thus $\delta T_s \approx \frac{L n_1 \Delta}{c}$ $\delta T_s \approx \frac{L(NA)^2}{2cn_1}$

For a rectangular input pulse, the RMS pulse broadening due to modal dispersion (step index) at the output of the fibre is:

$$\sigma_s \simeq \frac{L n_1 \Delta}{2\sqrt{3}c}$$

Total dispersion = chromatic dispersion + modal dispersion

$$\sigma_T = (\sigma_c^2 + \sigma_n^2)^{\frac{1}{2}}$$

Bandwidth Distance Product (BDP)

The BDP is the bandwidth of a kilometer of fibre and is a constant for any particular type of fibre.

$$B_{opt} * L = B_T * L \qquad \text{(MHzkm)}$$

For example, A multimode fibre has a BDP of 20 MHz.km, then:-

- 1 km of the fibre would have a bandwidth of 20 MHz
- 2 km of the fibre would have a bandwidth of 10 MHz

Typical B.D.P. for different types of fibres are:

- Multimode 6 - 25 MHz.km
- Single Mode 500 - 1500 MHz.km
- Graded Index 100 - 1000 MHZ.km

Problem

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

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

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

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

(d) the bandwidth–length product corresponding to (c).

Problem

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

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

$$\delta T_s \simeq \frac{L n_1 \Delta}{c} = \frac{6 \times 10^3 \times 1.5 \times 0.01}{2.998 \times 10^8} = 300 \text{ ns}$$

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

$$\sigma_s = \frac{L n_1 \Delta}{2\sqrt{3}c} = \frac{1}{2\sqrt{3}} \frac{6 \times 10^3 \times 1.5 \times 0.01}{2.998 \times 10^8}$$

$$= 86.7 \text{ ns}$$

Problem

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

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

$$B_T(\max) = \frac{1}{2\tau} = \frac{1}{2\delta T_s} = \frac{1}{600 \times 10^{-9}}$$
$$= 1.7 \text{ Mbit s}^{-1}$$

$$B_T(\max) = \frac{0.2}{\sigma_s}$$

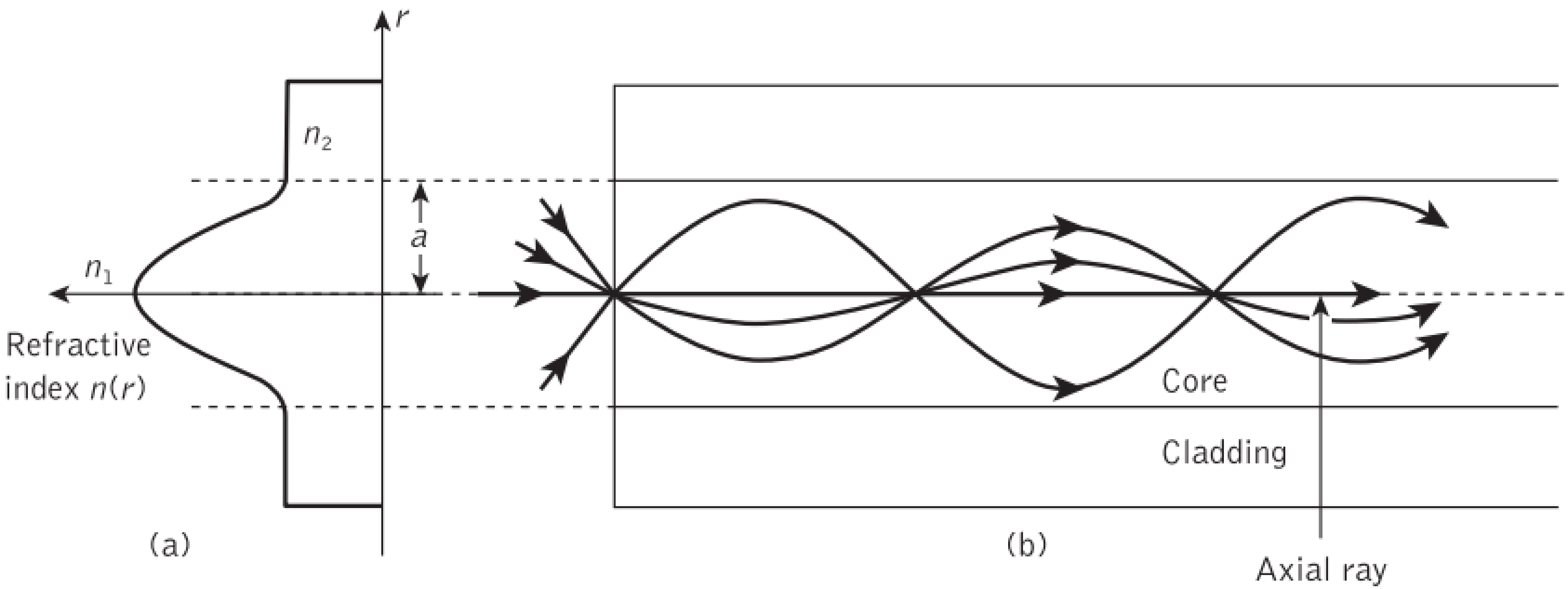
$$= \frac{0.2}{86.7 \times 10^{-9}}$$
$$= 2.3 \text{ Mbit s}^{-1}$$

(d) the bandwidth–length product corresponding to (c).

$$B_{opt} \times L \quad = 2.3 \text{ MHz} \times 6 \text{ km} = 13.8 \text{ MHz km}$$

Modal Dispersion - GIMMF

- Intermodal dispersion in multimode fibers is minimized with the use of graded index fibers.
- The fiber has a parabolic index profile with a maximum at the core axis.

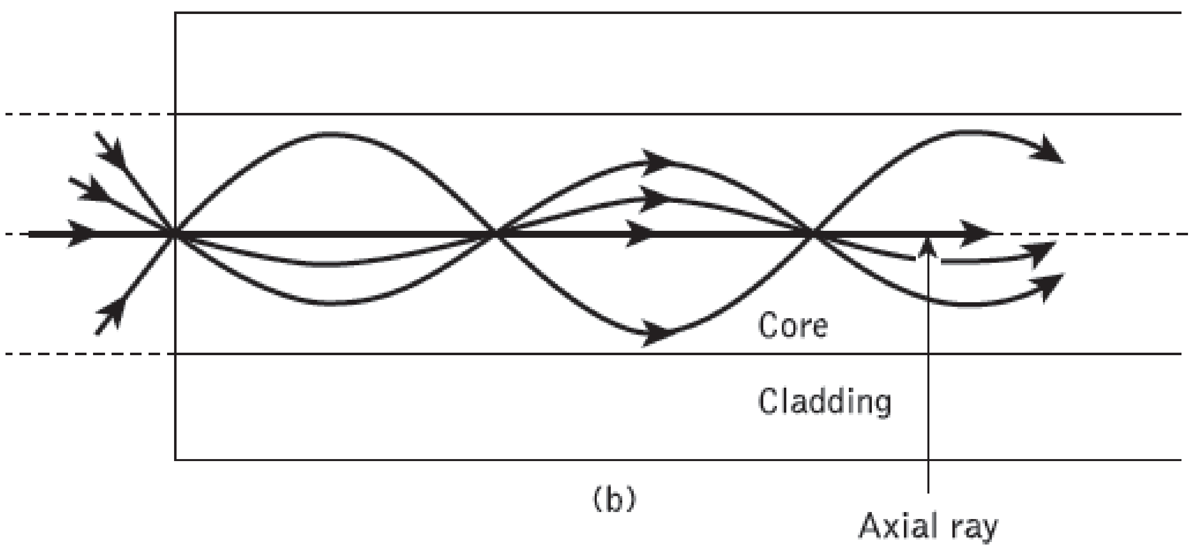


A multimode graded index fiber: (a) parabolic refractive index profile; (b) meridional ray paths within the fiber core

Modal Dispersion - GIMMF

- It may be observed that apart from the axial ray the meridional rays follow sinusoidal trajectories of different path lengths which results from the index grading.

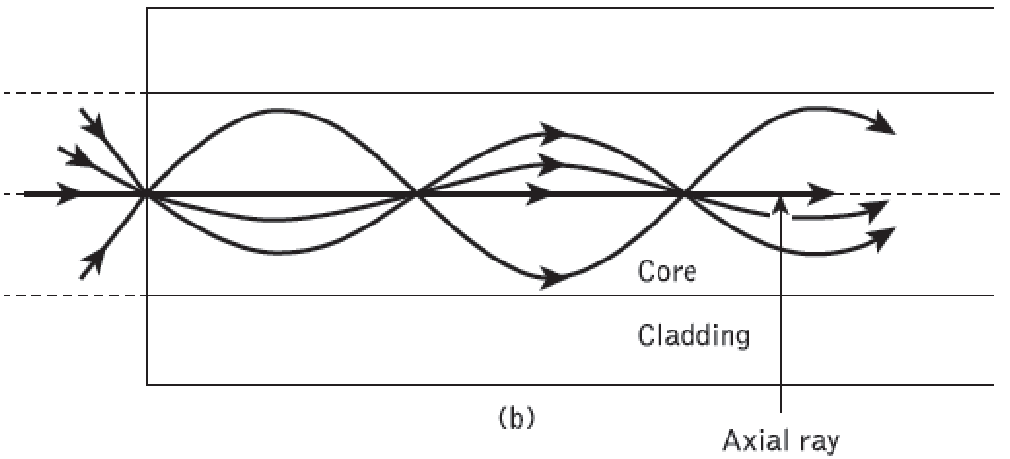
- The longer sinusoidal paths are compensated for by the higher speeds in the lower index medium away from the axis.



(b)

Modal Dispersion - GIMMF

- The ray that travels along the axial ray is exclusively in the high index region at the core axis, and at the lowest speed.
- Thus there is an equalization of the transmission times of the various trajectories and the graded index profile reduces the disparity in the mode transit times.
- Thus the delay difference between the fastest and slowest modes are reduced for graded index fiber.

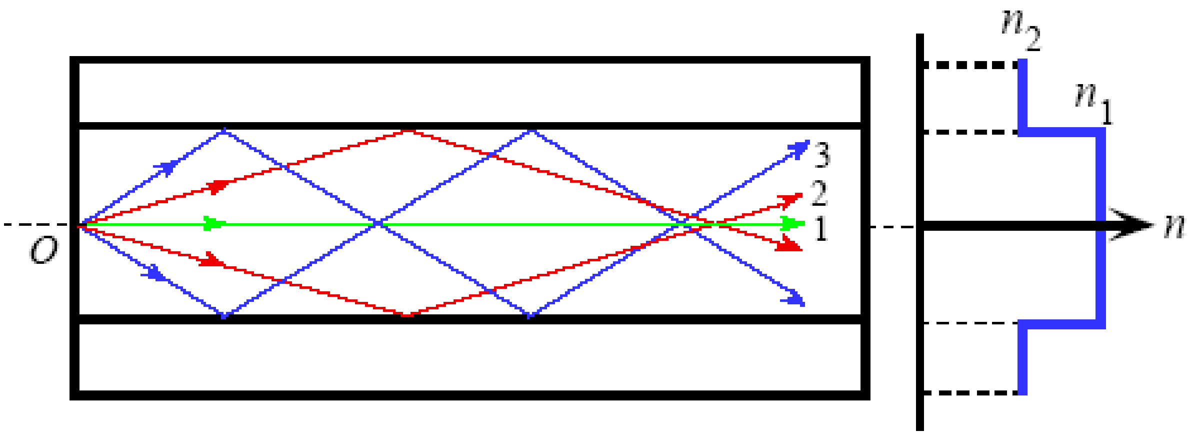


Modal Dispersion - GIMMF

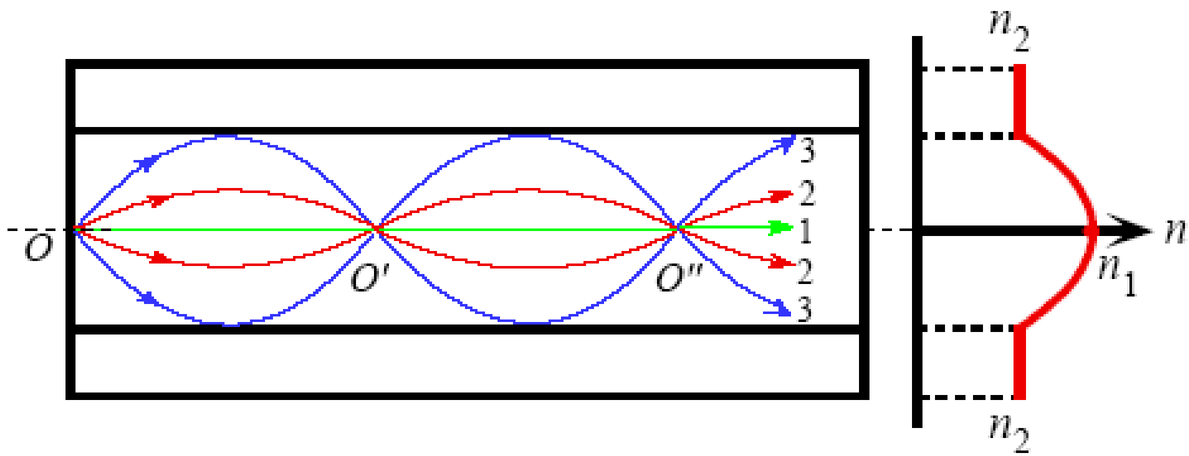
- The delay difference $$\delta T_g \approx \frac{L n_1 \Delta^2}{2c}$$

- the RMS pulse broadening $$\sigma_g = \frac{L n_1 \Delta^2}{20\sqrt{3}c}$$

Step and Graded Index Fibers



(a) Multimode step index fiber. Ray paths are different so that rays arrive at different times.



(b) Graded index fiber. Ray paths are different but so are the velocities along the paths so that all the rays arrive at the same time.

Problem

A 6 km optical link consists of multimode step index fiber with a core refractive index of 1.5 and a relative refractive index difference of 1%. Estimate the rms pulse broadening per kilometre due to intermodal dispersion on the link; Also estimate the rms pulse broadening per kilometre for an optimum near-parabolic profile graded index fiber with the same core axis refractive index and relative refractive index difference and compare it.

Solution:

The rms pulse broadening due to intermodal dispersion on the link

$$\sigma_s = \frac{L n_1 \Delta}{2\sqrt{3}c} = \frac{1}{2\sqrt{3}} \frac{6 \times 10^3 \times 1.5 \times 0.01}{2.998 \times 10^8}$$

$$= 86.7 \text{ ns}$$

The rms pulse broadening per kilometer for the multimode step index fiber is:

$$\frac{\sigma_s(1 \text{ km})}{L} = \frac{86.7}{6} = 14.4 \text{ ns km}^{-1}$$

Problem

A 6 km optical link consists of multimode step index fiber with a core refractive index of 1.5 and a relative refractive index difference of 1%. Estimate the rms pulse broadening per kilometre due to intermodal dispersion on the link; Also estimate the rms pulse broadening per kilometre for an optimum near-parabolic profile graded index fiber with the same core axis refractive index and relative refractive index difference and compare it.

The rms pulse broadening per kilometre for the corresponding graded index fiber is:

$$\sigma_g(1\ \text{km}) = \frac{L n_1 \Delta^2}{20\sqrt{3}c}$$

$$= \frac{10^3 \times 1.5 \times (0.01)^2}{20\sqrt{3} \times 2.998 \times 10^8}$$

$$= 14.4\ \text{ps km}^{-1}$$

Overall fiber dispersion

- The overall dispersion in multimode fibers comprises both chromatic and intermodal terms.
- The total rms pulse broadening σ_T is given by

$$\sigma_T = (\sigma_c^2 + \sigma_n^2)^{\frac{1}{2}}$$

where σ_c is the intramodal or chromatic broadening and σ_n is the intermodal broadening caused by delay differences between the modes (i.e. σ_s for multimode step index fiber and σ_g for multimode graded index fiber). The chromatic term σ_c consists of pulse broadening due to both material and waveguide dispersion. However, since waveguide dispersion is generally negligible compared with material dispersion in multimode fibers, then $\sigma_c \simeq \sigma_m$.

Cutoff wavelength

- It may be noted that single-mode operation only occurs above a theoretical cutoff wavelength λ_c given by

$$\lambda_c = \frac{2\pi a n_1}{V_c}(2\Delta)^{\frac{1}{2}}$$

- where V_c is the cutoff normalized frequency. Hence λ_c is the wavelength above which a particular fiber becomes single-moded

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%

with $V_c = 2.405$ gives:

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

$$= 1.214\ \mu\text{m}$$
$$= 1214\ \text{nm}$$

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

A multimode step index fiber has a numerical aperture of 0.3 and a core refractive index of 1.45. The material dispersion parameter for the fiber is 250 ps nm^{-1} km^{-1} which makes material dispersion the totally dominating chromatic dispersion mechanism. Estimate (a) the total rms pulse broadening per kilometer when the fiber is used with an LED source of rms spectral width 50 nm and (b) the corresponding bandwidth–length product for the fiber

(a) The rms pulse broadening per kilometer due to material dispersion may be obtained as:

$$\sigma_m(1\ \text{km}) \simeq \frac{\sigma_\lambda L \lambda}{c} \left| \frac{d^2 n_1}{d\lambda^2} \right| = \sigma_\lambda L M \quad = 50 \times 1 \times 250\ \text{ps km}^{-1}$$

$$= 12.5\ \text{ns km}^{-1}$$

The rms pulse broadening per kilometer due to intermodal dispersion for the step index fiber is given by

$$\sigma_s(1\ \text{km}) \simeq \frac{L(NA)^2}{4\sqrt{3} n_1 c} \quad = \frac{10^3 \times 0.09}{4\sqrt{3} \times 1.45 \times 2.998 \times 10^8} \quad = 29.9\ \text{ns km}^{-1}$$

A multimode step index fiber has a numerical aperture of 0.3 and a core refractive index of 1.45. The material dispersion parameter for the fiber is 250 ps nm^{-1} km^{-1} which makes material dispersion the totally dominating chromatic dispersion mechanism. Estimate (a) the total rms pulse broadening per kilometer when the fiber is used with an LED source of rms spectral width 50 nm and (b) the corresponding bandwidth–length product for the fiber

The total rms pulse broadening per kilometer may be obtained with $\sigma_c \approx \sigma_m$ as the waveguide dispersion is negligible and $\sigma_n = \sigma_s$ for the multi-mode step index fiber. Hence

$$\sigma_T = (\sigma_m^2 + \sigma_s^2)^{\frac{1}{2}}$$

$$= (12.5^2 + 29.9^2)^{\frac{1}{2}}$$
$$= 32.4 \text{ ns km}^{-1}$$

The bandwidth–length product may be estimated as

$$B_{opt} \times L = \frac{0.2}{\sigma_T}$$

$$= \frac{0.2}{32.4 \times 10^{-9}}$$
$$= 6.2 \text{ MHz km}$$

Polarization mode Dispersion and Nonlinear effects in Optical Fibers

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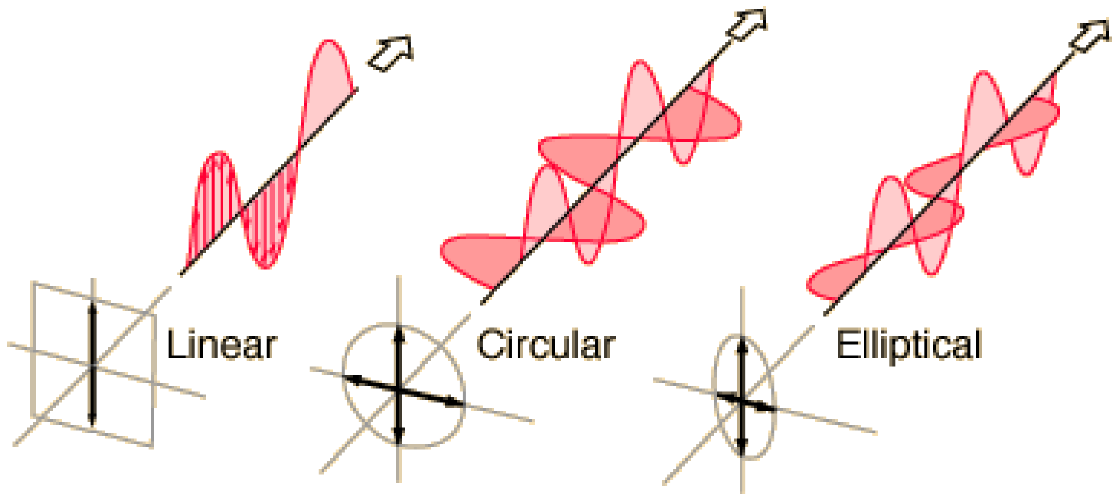
Polarization

- Polarization is a property of certain types of waves that describes the orientation of their oscillations.
- Electromagnetic waves, such as light, and gravitational waves exhibit polarization.
- Acoustic waves (sound waves) in a gas or liquid do not have polarization because the direction of vibration and direction of propagation are the same.
- When light travels in free space, in most cases it propagates as a transverse wave—the polarization is perpendicular to the wave's direction of travel
- In this case, the electric field may be oriented in a single direction (linear polarization), or it may rotate as the wave travels (circular or elliptical polarization

Classification of Polarization

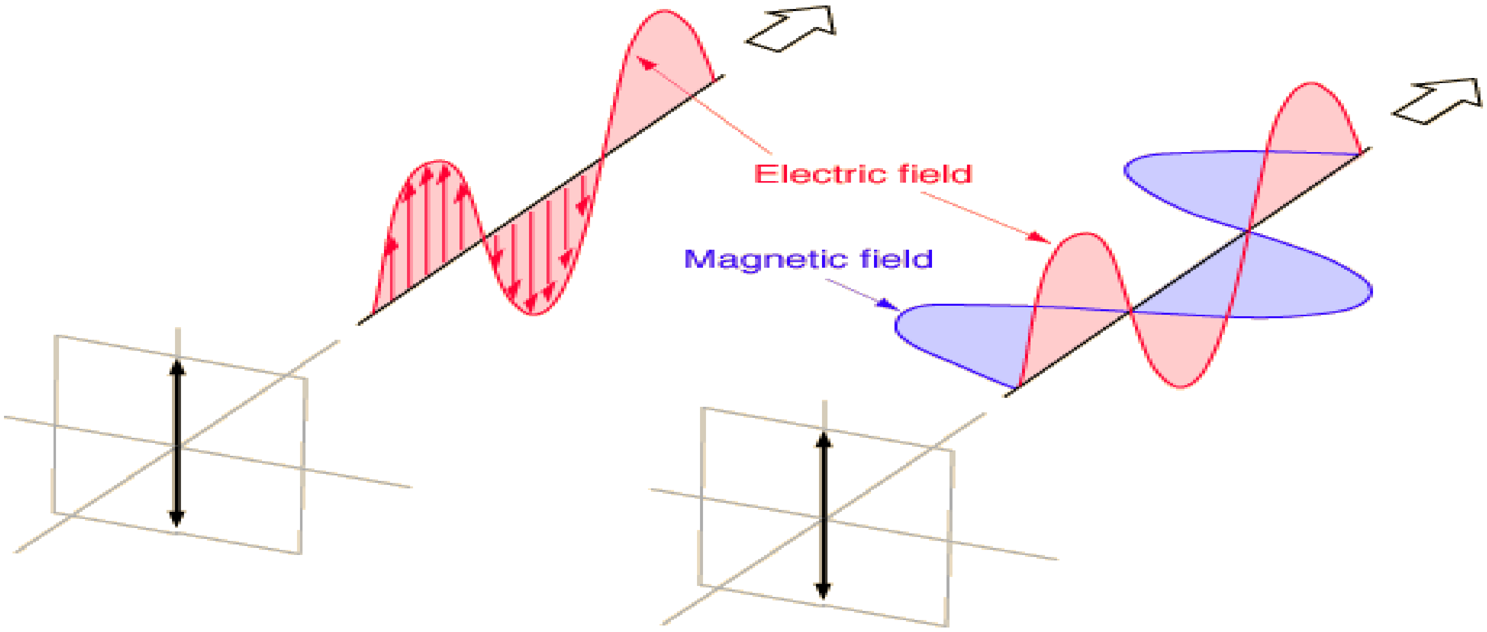


- Light in the form of a plane wave in space is said to be linearly polarized.

- If light is composed of two plane waves of equal amplitude by differing in phase by 90°, then the light is said to be circularly polarized.

- If two plane waves of differing amplitude are related in phase by 90°, or if the relative phase is other than 90° then the light is said to be elliptically polarized.

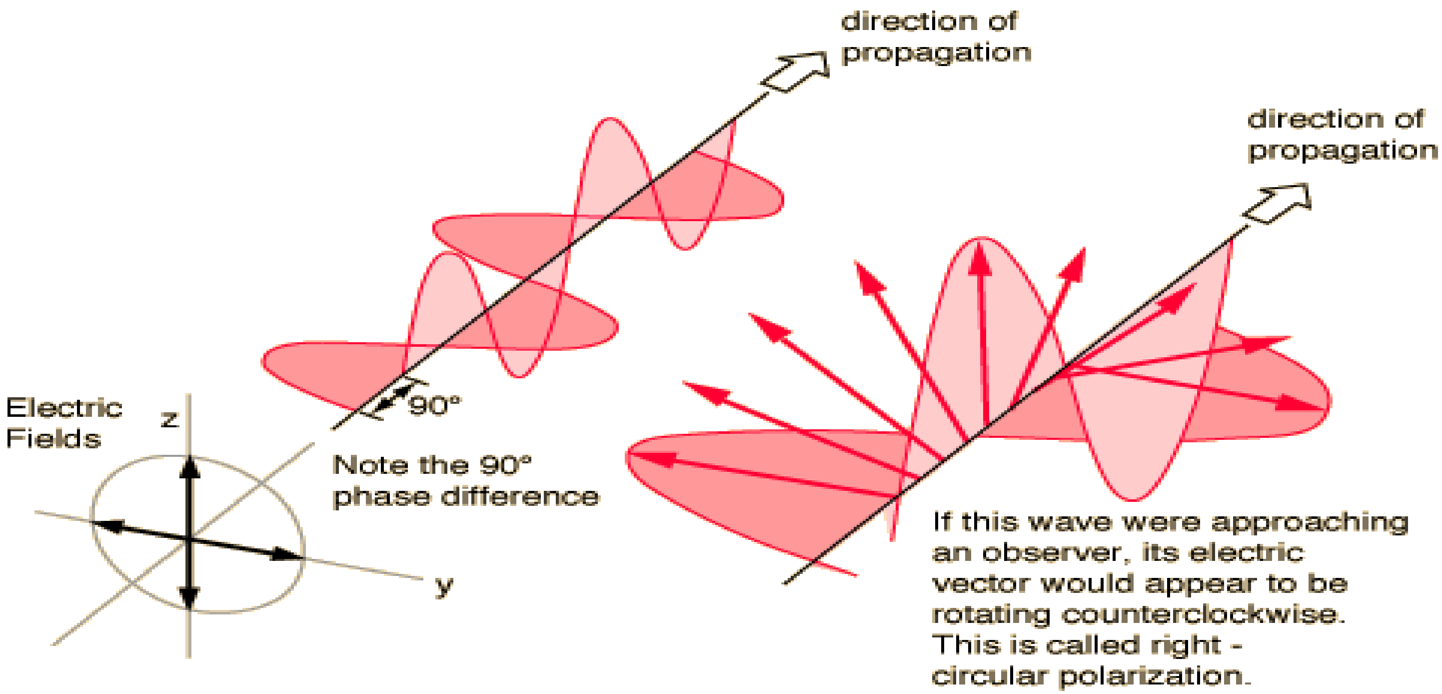
Linear Polarization



▪A plane electromagnetic wave is said to be linearly polarized.

▪The transverse electric field wave is accompanied by a magnetic field wave as illustrated.

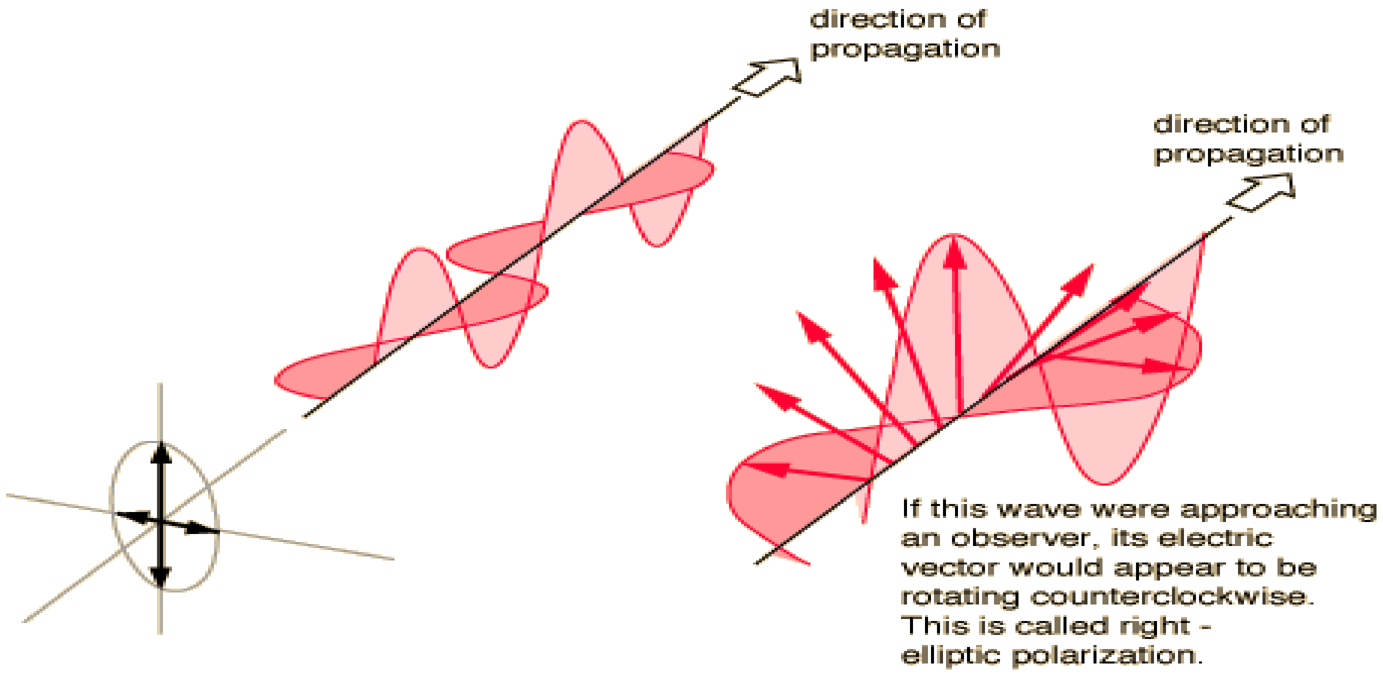
Circular Polarization



- Circularly polarized light consists of two perpendicular electromagnetic plane waves of equal amplitude and 90° difference in phase.

- The light illustrated is right- circularly polarized.

Elliptical Polarization



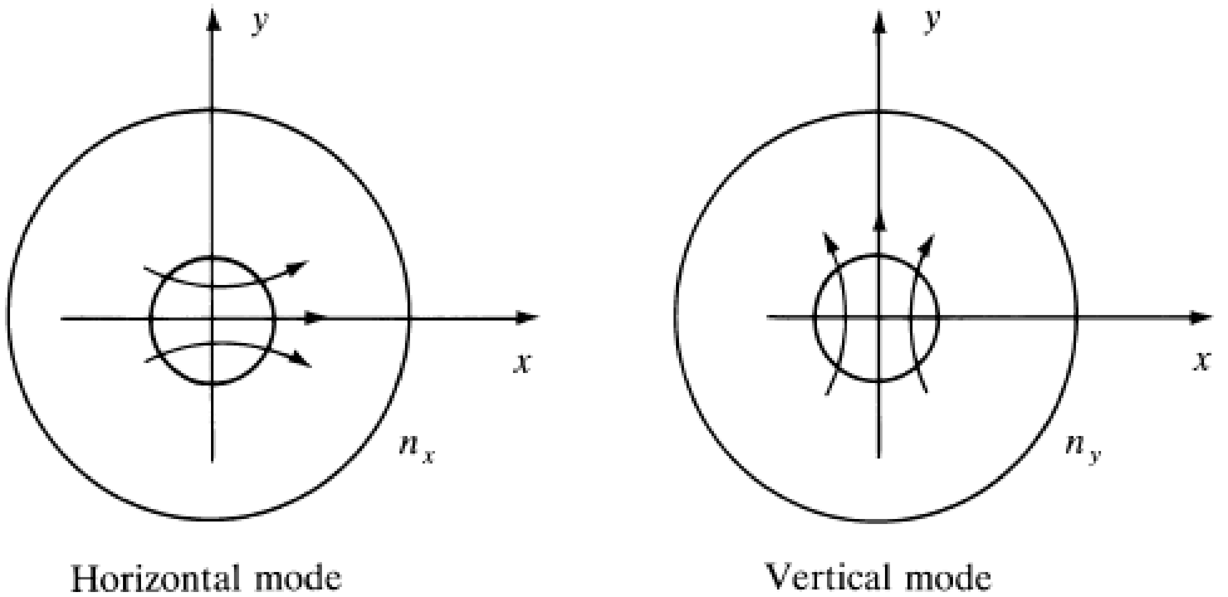
- Elliptically polarized light consists of two perpendicular waves of unequal amplitude which differ in phase by 90°.

- The illustration shows right- elliptically polarized light.

Polarization Mode Dispersion

- Due to differently polarized light traveling at slightly different velocity
- Usually small
- Significant if all other dispersion mechanisms are small

Polarizations of fundamental mode

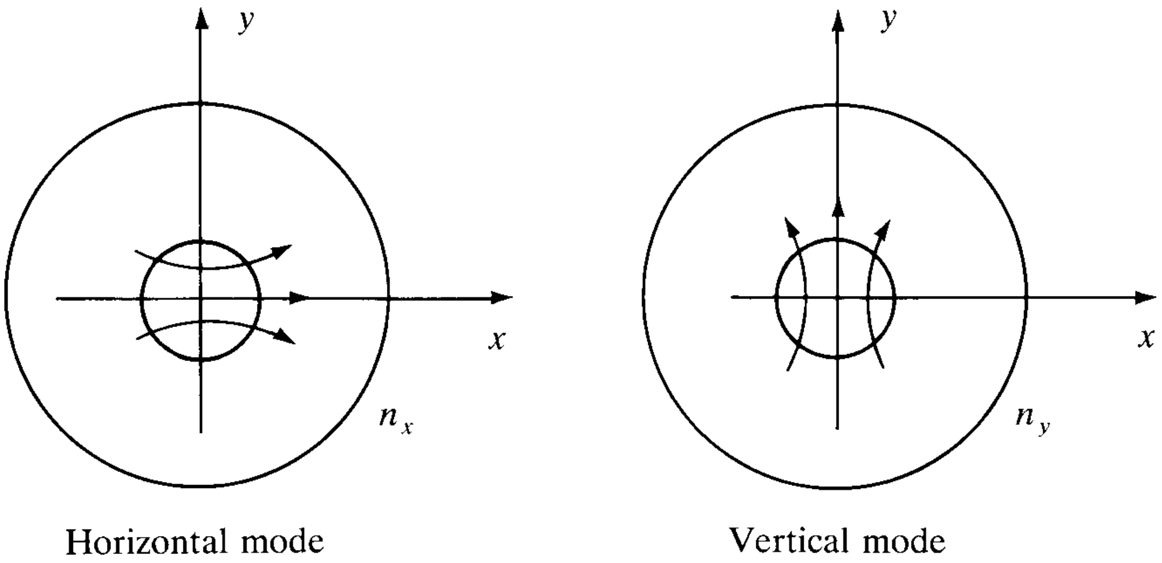


Two polarization states exist in the fundamental mode in a single mode fiber

Birefringence in single-mode fibers

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

$$B_f = n_y - n_x$$



Optical Fiber communications, 3rd ed.,G.Keiser,McGrawHill, 2000

Birefringence in single-mode fibers

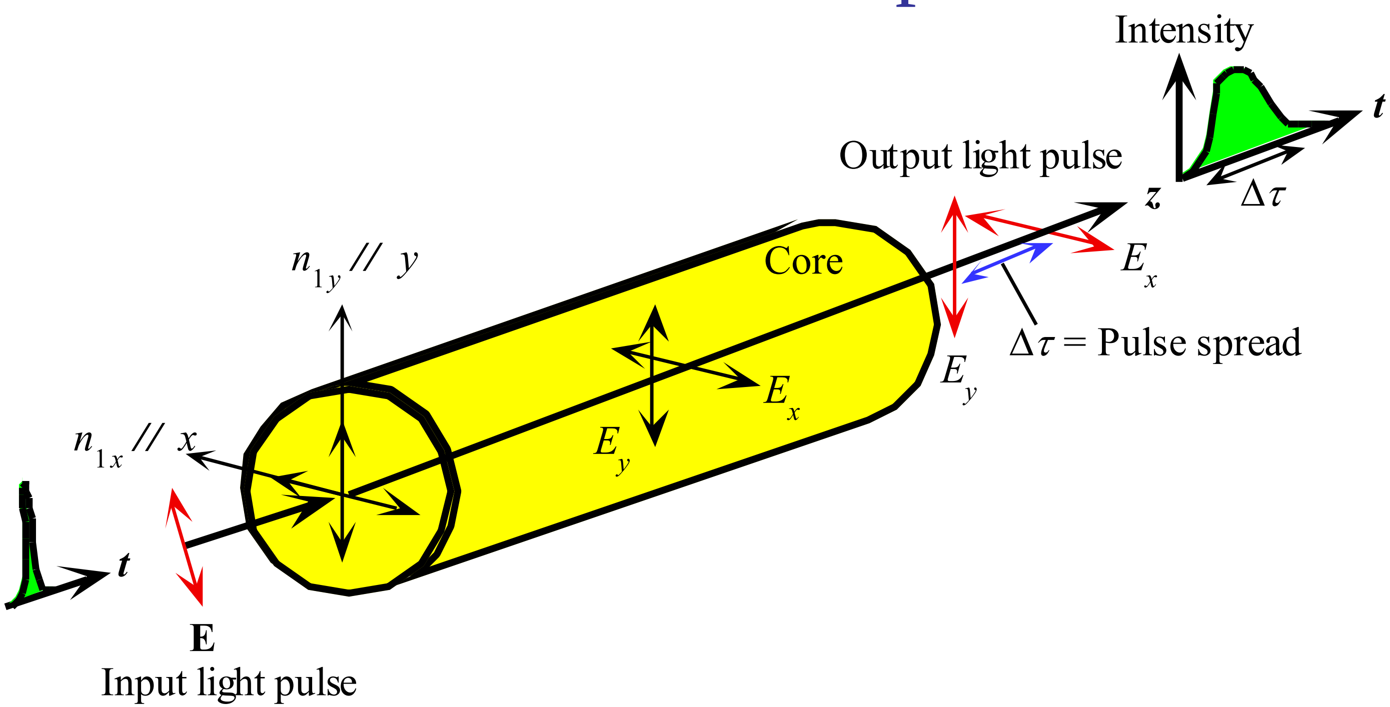
- The effects of fiber birefringence on the polarization states of an optical signal are another source of pulse broadening.

- Results from intrinsic factors such as geometric irregularities of the fiber core or internal stresses on it.

- External factors such as bending, twisting or pinching of the fiber can also lead to birefringence.

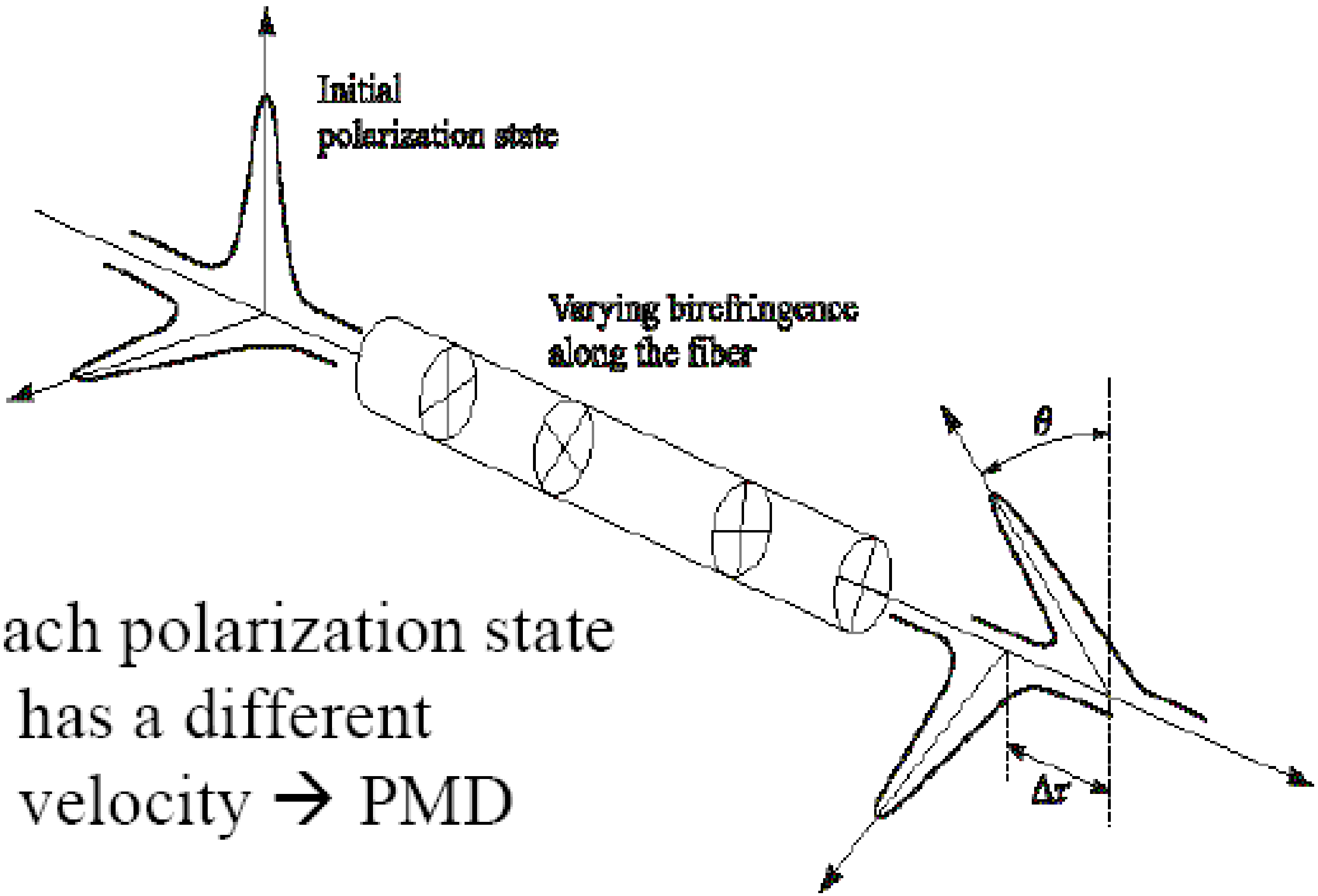
- All these mechanisms exist to some extent in the fiber, there will be a varying birefringence along its length.

Polarization Mode dispersion



Suppose that the core refractive index has different values along two orthogonal directions corresponding to electric field oscillation direction (polarizations). We can take x and y axes along these directions. An input light will travel along the fiber with E_x and E_y polarizations having different group velocities and hence arrive at the output at different times

Polarization Mode Dispersion (PMD)



Each polarization state has a different velocity → PMD

Polarization Mode dispersion

- **Polarization mode dispersion** (PMD) is due to slightly different velocity for each polarization mode .If the group velocities of two orthogonal polarization modes are V_{gx} and V_{gy} then the differential time delay between these two polarization over a distance L is $\Delta\tau_{PMD}$

$$\Delta\tau_{\mathrm{PMD}} = \left| \frac{L}{V_{gx}} - \frac{L}{V_{gy}} \right|$$

- PMD varies randomly along the fiber, since the birefringence effects vary with temperature.
- For long fiber lengths , PMD is characterized in terms of mean value of the differential group delay.
- The rms value of the differential group delay can be approximated as:

$$\Delta\tau_{PMD} = D_{PMD}\sqrt{L}$$

Polarization Mode dispersion

$$\Delta\tau_{PMD} = D_{PMD}\sqrt{L}$$

- $D_{PMD} \rightarrow$ mean value of the polarization mode dispersion parameter.
- Varies from 0.03 to 1.3 ps/√km depending on the cable environment.
- To have a power penalty of less than 1.0 dB, the pulse spreading resulting from polarization mode dispersion must on the average be less than 10 percent of a bit period T_b.

$$\Delta\tau_{PMD} = D_{PMD}\sqrt{L} < 0.1\, T_b$$

Dispersion Calculation

- If t_{mod}, t_{CD}, and t_{PMD} are the modal, chromatic, and polarization mode dispersion times, respectively, then the total dispersion t_T can be calculated by the relationship

$$t_T = \sqrt{(t_{\text{mod}})^2 + (t_{\text{CD}})^2 + (t_{\text{PMD}})^2}$$

- Note that $t_{mod} = 0$ for single-mode fibers.
- The information-carrying capacity over a certain length of fiber then is determined by specifying that the pulse spreading not be more than 10 percent of the pulse width at a designated data rate.

Fiber Beat Length

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

$$L_B = \frac{2\pi}{kB_F} = \frac{\lambda}{B_F}$$

Fiber Beat Length

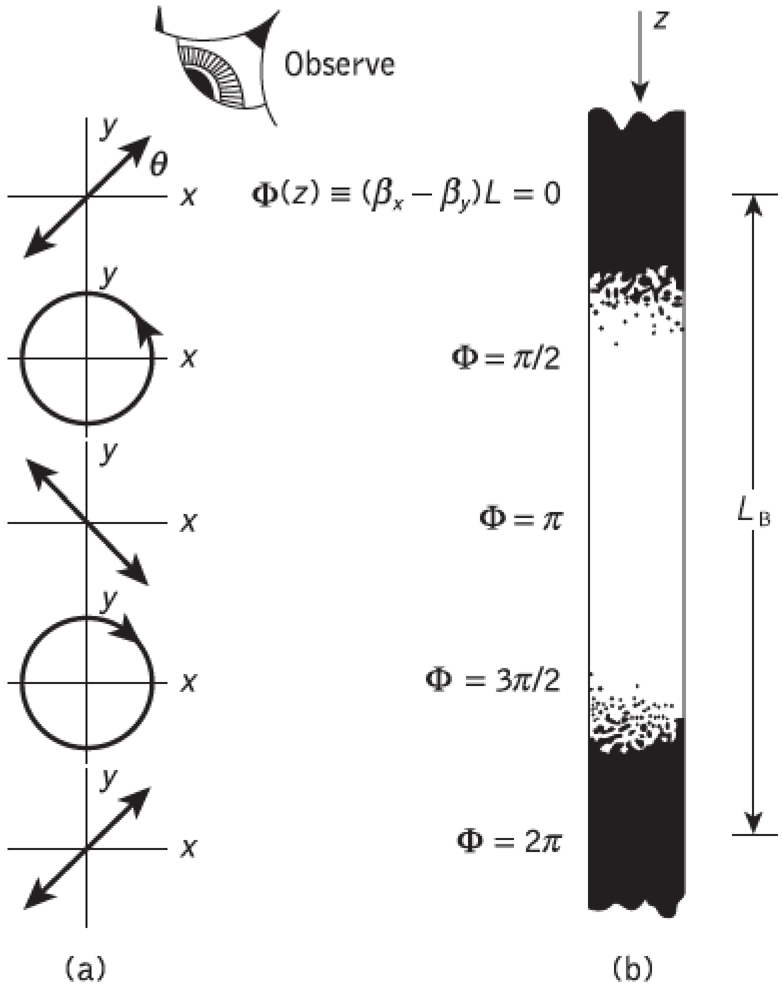


Figure 3.28 An illustration of the beat length in a single-mode optical fiber [Ref. 81]: (a) the polarization states against $\Phi(z)$; (b) the light intensity distribution over the beat length within the fiber

Consider a 100-km long fiber for which $D_{PMD} = 0.5$ ps/$\sqrt{\text{km}}$. What is the maximum possible data rate for an NRZ-encoded signal if the pulse spread can be no more than 10 percent of a pulse width?

the pulse spread over the 100-km distance is $\boldsymbol{\Delta\tau_{PMD} = D_{PMD}\sqrt{L}}$

$$\boldsymbol{\Delta\tau_{PMD} = 5.0 \text{ ps.}}$$

Since this pulse spread can be no more than 10 percent of a pulse width, we have $\boldsymbol{\Delta\tau_{PMD} = 5.0 \text{ ps} \le 0.1T_b}$

Therefore the maximum NRZ bit rate is 1/Tb = 0.1/(5 ps)

= 20 Gb/s.

Consider a single-mode fiber for which D_{CD} = 2 ps/(km nm) and D_{PMD} = 0.1 ps/√km . If a transmission link has a length L = 500 km and uses a laser source with a spectral emission width of Δλ = 0.01 nm , Calculate the total dispersion times and the maximum data rate by assuming t_T can be no more than 10 percent of the pulse width.

we have t_{mod} = 0.

$$t_{\mathrm{CD}} = D_{\mathrm{CD}} \times L \times \Delta\lambda \quad = 10\,\mathrm{ps}$$

$$t_{\mathrm{PMD}} = D_{\mathrm{PMD}} \times \sqrt{L} = 2.24\,\mathrm{ps}$$

$$t_T = \sqrt{(t_{\mathrm{mod}})^2 + (t_{\mathrm{CD}})^2 + (t_{\mathrm{PMD}})^2}$$

$$t_T = \sqrt{(10\,\mathrm{ps})^2 + (2.24\,\mathrm{ps})^2} = 10.2\,\mathrm{ps}$$

Consider a single-mode fiber for which D_{CD} = 2 ps/(km nm) and D_{PMD} = 0.1 ps/$\sqrt{\text{km}}$. If a transmission link has a length L = 500 km and uses a laser source with a spectral emission width of $\Delta\lambda$ = 0.01 nm , Calculate the total dispersion times and the maximum data rate by assuming t_T can be no more than 10 percent of the pulse width.

If t_T can be no more than 10 percent of a pulse width, then the maximum data rate R_{max} that can be sent over this 500-km link is

$$R_{max} = 0.1/t_T$$

R_{max} = 9.8 Gbps (gigabits per second)

Nonlinear Effects in fibers

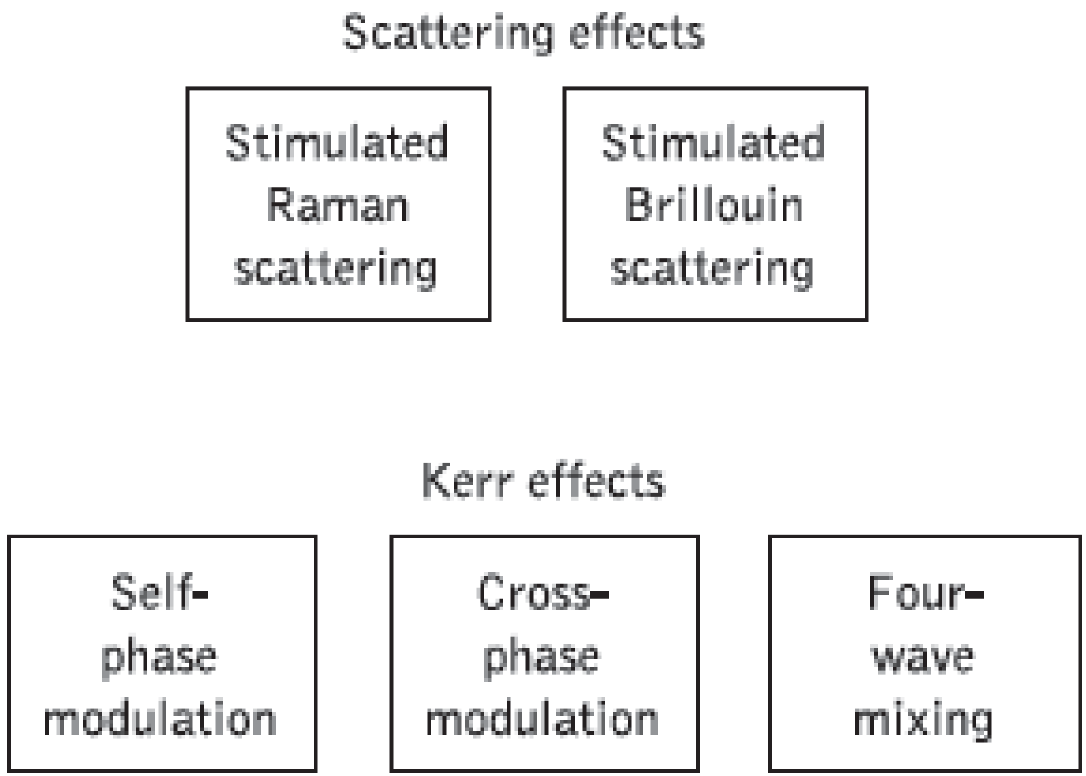
➢The interactions between lightwaves and the material transmitting them, can affect optical signals→ Phenomena is called nonlinear effects in Fibers.

➢Weak at low powers but dominant at high optical intensities.

➢This situation can result either
- ✓**when the power is increased, or**
- ✓ **when it is concentrated in a small area such as the core of a single-mode optical fiber**

➢Two Broad Categories
- ✓**Scattering effects**
- ✓**Kerr effects**

Nonlinear Effects in fibers



Kerr nonlinearities

- Nonlinear effects which can be readily described by the intensity-dependent refractive index of the fiber are commonly referred to as Kerr nonlinearities.

- At low optical intensities the refractive index is constant.

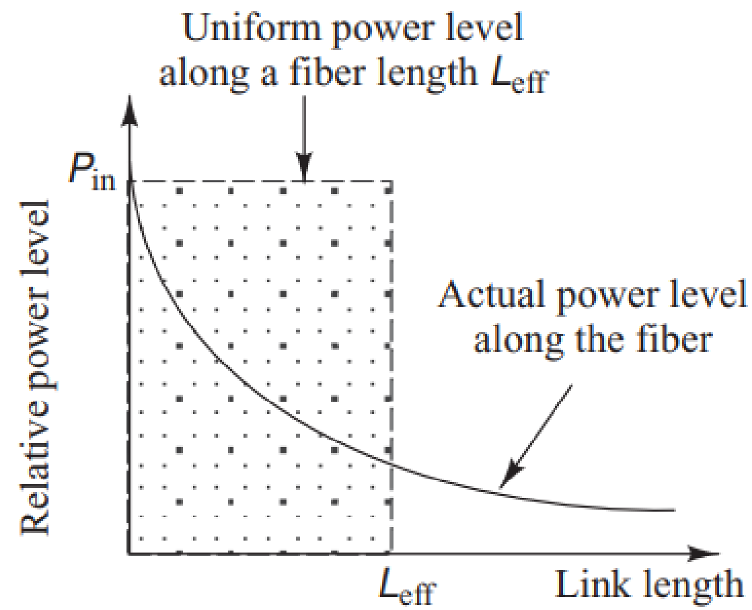
- However, at higher optical intensities the refractive index do not remain linear with the applied field which results in Kerr nonlinear effects.

- SPM and CPM affect only the phase of signals and can cause spectral broadening, which leads to increased dispersion.

Effective Length

- The optical power is constant over a certain fiber length, which is less than or equal to the actual fiber length.
- This effective length Leff, takes into account power absorption along the length of the fiber (i.e., the fact that the optical power decays exponentially with length), is given by

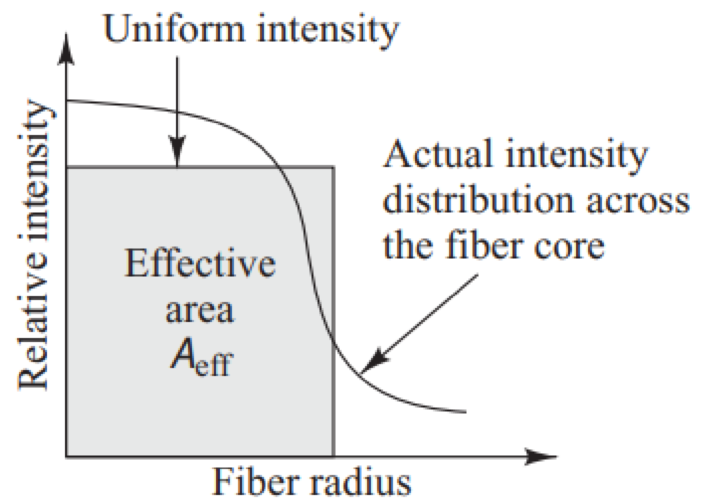
$$L_{\text{eff}} = \frac{1 - e^{-\alpha L}}{\alpha}$$



The effective length is modeled as the transmission length at which the shaded area equals the area under the actual power-distribution curve

Effective Area

- The effects of nonlinearities increase with the light intensity in a fiber.
- For a given optical power, this intensity is inversely proportional to the cross sectional area of the fiber core.
- The effective cross-sectional area Aeff, is modeled as a central area of the fiber core within which the intensity distribution is uniform.



The effective area is modeled as a central area of the fiber core within which the intensity is assumed to be uniform

Self Phase Modulation

- When the intensity of the optical signal propagating through the optical fiber varies, the core refractive index varies.
- As a result, there will be a possible phase shift in the optical pulse within the fiber.
- Moreover, the phase shift would be different at the peak of the optical pulse as compared to the near the leading or trailing edges of the pulse.
- It is quite evident that the spectrum of the optical pulse will be modified. This phenomenon is called self-phase modulation (SPM).
- Due to variation in the phase with time, a time-varying frequency will be created.
- Therefore, we can conclude that the impact of SPM will be broadening of the frequency spectrum of the optical pulse.

Self Phase Modulation

- The refractive index n of many optical materials has a weak dependence on optical intensity I given by

$$n = n_0 + n_2 I = n_0 + n_2 \frac{P}{A_{\text{eff}}}$$

- where n0 is the ordinary refractive index of the material and n2 is the nonlinear index coefficient.
- The nonlinearity in the refractive index is known as the Kerr nonlinearity.
- This nonlinearity produces a carrier-induced phase modulation of the propagating signal, which is called the Kerr effect.
- In single-wavelength links, this gives rise to self-phase modulation (SPM), which converts optical power fluctuations in a propagating lightwave to spurious phase fluctuations in the same wave.

Self Phase Modulation

- The main parameter γ, which indicates the magnitude of the nonlinear effect for SPM, is given by

$$\gamma = \frac{2\pi}{\lambda}\frac{n_2}{A_{\text{eff}}}$$

- Where λ is the free-space wavelength and Aeff is the effective core area.
- the term γ produces a nonlinear phase shift given by

$$\phi_{\text{NL}} = \gamma P_{\text{in}} L_{\text{eff}}$$

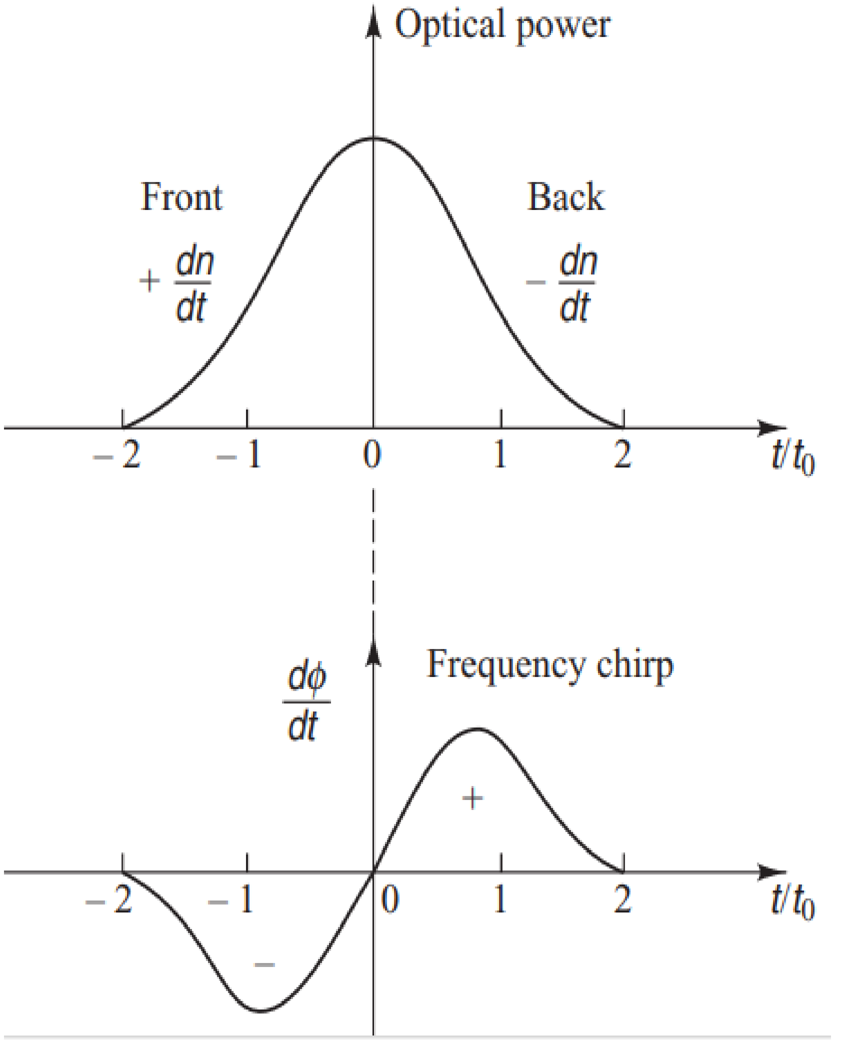
- The frequency shift Δφ arising from SPM is given by

$$\Delta\varphi = \frac{d\varphi}{dt} = \gamma L_{\text{eff}} \frac{dP}{dt}$$

- Here Leff is the effective length and dP/dt is the derivative of the optical pulse power.

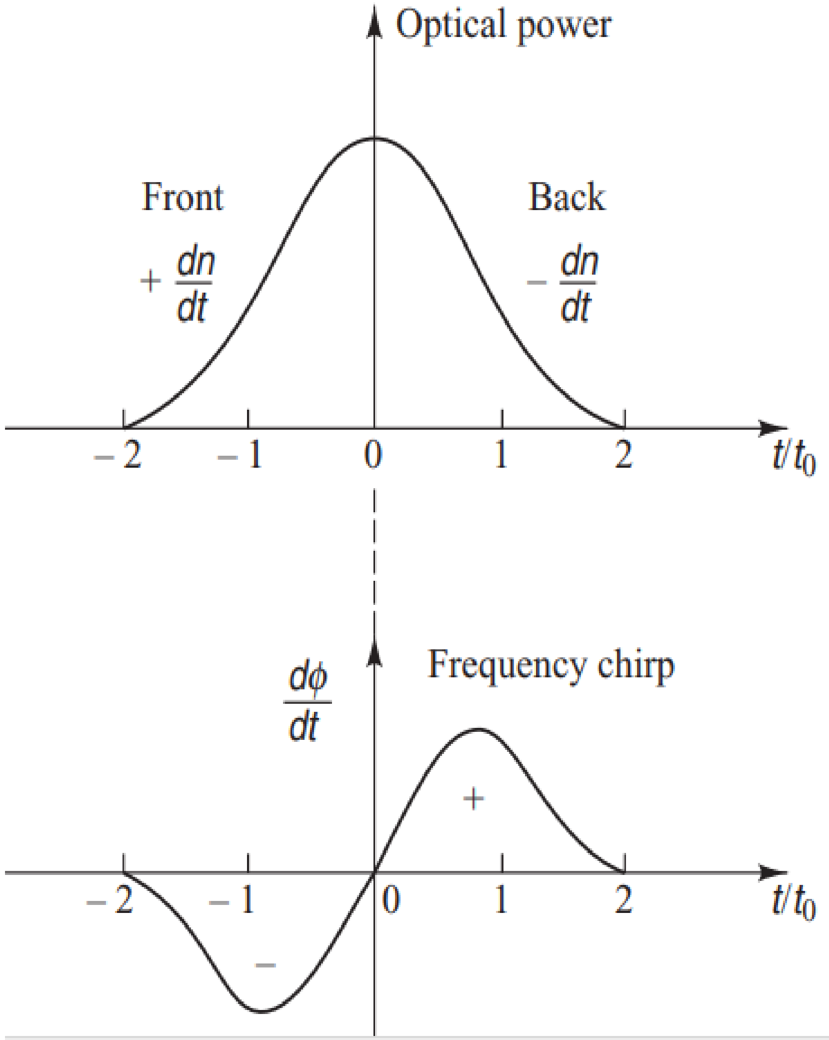
Frequency Chriping

- In a medium having an intensity-dependent refractive index, a time-varying signal intensity will produce a time-varying refractive index.
- Thus the index at the peak of the pulse will be slightly different than the value in the wings of the pulse.
- The leading edge will see a positive dn/dt, whereas the trailing edge will see a negative dn/dt.
- This temporally varying index change results in a temporally varying phase change, shown by dφ/dt



Frequency Chriping

- Since the phase fluctuations are intensity-dependent, different parts of the pulse undergo different phase shifts.
- This leads to what is known as frequency chirping, in that the rising edge of the pulse experiences a red shift in frequency (toward lower frequencies or longer wavelengths)
- whereas the trailing edge of the pulse experiences a blue shift in frequency(toward higher frequencies or shorter wavelengths).
- Since the degree of chirping depends on the transmitted power, SPM effects are more pronounced for higher-intensity pulses.



Calculate the power launched into a 40-km-long single-mode fiber for which the SPM-induced nonlinear phase shift becomes 180°. Assume $\lambda = 1.55\ \mu m$, $A_{eff} = 40\ \mu m^2$, $\alpha = 0.2\ dB/km$, and $n_2 = 2.6 \times 10^{-20}\ m^2/W$.

Given data,

$\lambda = 1.55\ \mu m$

$A_{eff} = 40\ \mu m^2$

$\alpha = 0.2\ dB/km$

$n_2 = 2.6 \times 10^{-20}\ m^2$

$\phi_{NL} = \gamma P_{in} L_{eff}$

$$\gamma = \frac{2\pi n_2}{\lambda A_{eff}}$$

$$= \frac{2\pi \times 2.6 \times 10^{-20}\ m^2}{1.55 \times 10^{-6} \times 40\ \mu m^2}$$

$$\boxed{\gamma = 2.635}$$

Calculate the power launched into a 40-km-long single-mode fiber for which the SPM-induced nonlinear phase shift becomes 180°. Assume $\lambda = 1.55\ \mu m$, $A_{eff} = 40\ \mu m^2$, $\alpha = 0.2\ dB/km$, and $n_2 = 2.6 \times 10^{-20}\ m^2/W$.

$$\boxed{\alpha_{1/km} = \alpha_{dB/km} \cdot \frac{\ln(10)}{10}}$$

$$L_{eff} = \frac{1}{\alpha}\left(1 - e^{-\alpha L}\right)$$

$$= \frac{1}{0.0461}\left(1 - e^{-0.0461 \times 40}\right)$$

$0.2\ dB/km = 0.046/km$

$$= 18.261$$

$$P_{in} = \frac{\phi_{NL}}{\gamma L_{eff}} = \frac{\pi}{2.635 \times 18.261}$$

$$= 65.29\ mW$$

Cross Phase Modulation

- Cross-phase modulation (XPM) appears in WDM systems and has a similar origin as SPM.
- The refractive index nonlinearity converts optical intensity fluctuations in a particular wavelength channel to phase fluctuations in another copropagating channel.
- SPM is always present when XPM occurs.
- Analogous to SPM, for two interacting wavelengths the XPM-induced frequency shift Δφ is given by

$$\Delta\varphi = \frac{d\varphi}{dt} = 2\gamma L_{\text{eff}} \frac{dP}{dt}$$

Four-Wave Mixing(FWM)

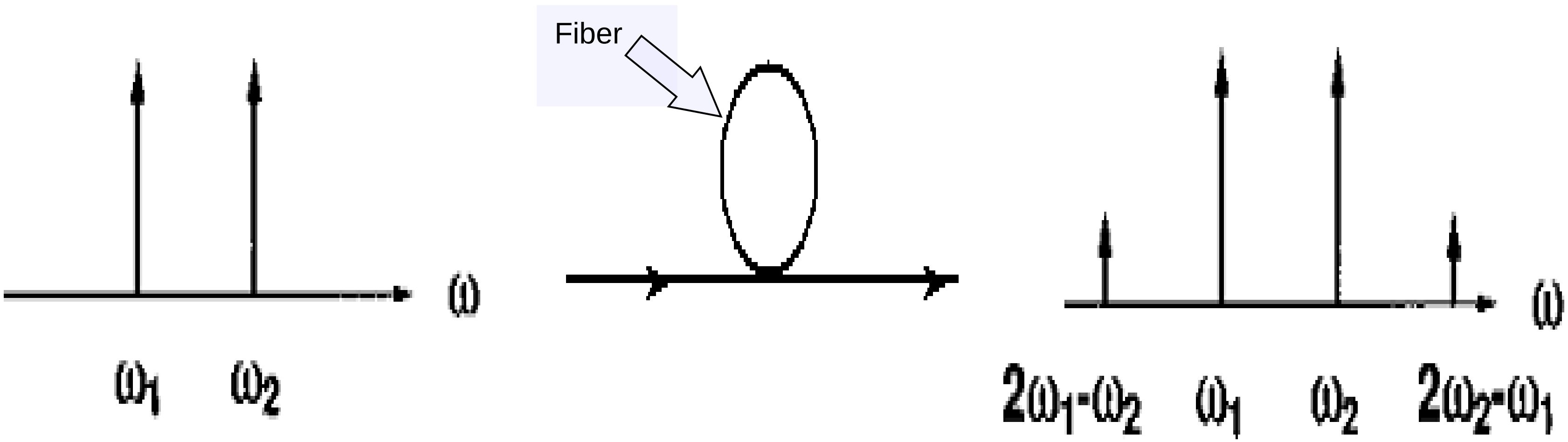
Generates one or more new channels (or harmonics). For instance, when three waves at frequencies f_i, f_j, and f_k traverse a fiber they generate another signal located at

$$\mathbf{f_{ijk}} = \mathbf{f_i} + \mathbf{f_j} - \mathbf{f_k}$$

With i, j Not equal to k

FWM

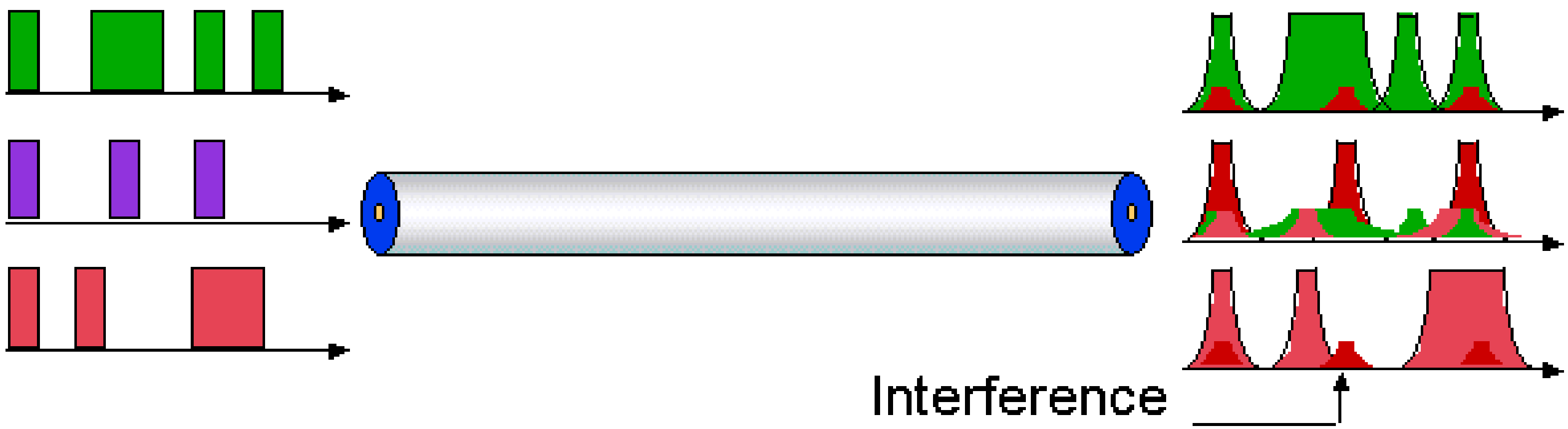
Example : The input is two signals located at ω_1 and ω_2 traverse a fiber of length (L) and the output is four different signals located at ω_1, ω_2, $2\omega_1 - \omega_2$, and $2\omega_2 - \omega_1$.



Effects of Nonlinearities

- A single channel's pulses interact as they travel (Self-Phase)

- Multiple channels interact as they travel (Cross Phase, FWM)



- Degradation scales as (channel power)^2

Four Wave Mixing (FWM)

Effect and consequences

- **The created mixing products interfere with the signal channels causing consequent eye closing and BER degradation.**
- **Decreasing channel spacing and chromatic dispersion will increase FWM.**
- N channels → $N^2(N-1)/2$ side bands are created, causing
  - – Reduction of signals
  - – Interference
  - – Cross talk

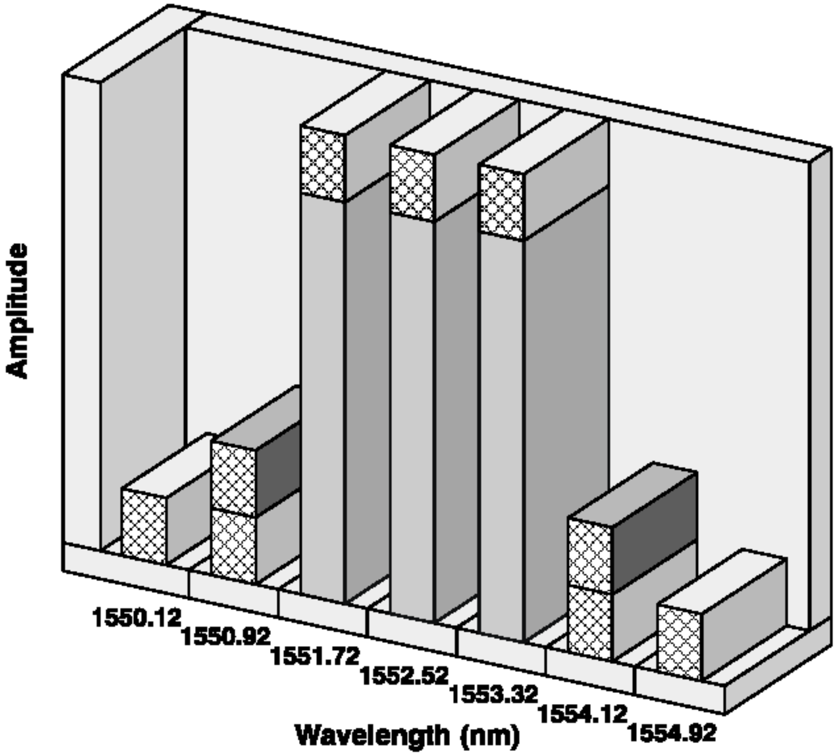
Counteractions

- **Avoid use of ITU-T G.653 (DSF) fiber, Use of ITU-T G.652 (SMF) fiber and ITU-T G.655 (NZDSF) fiber**
- **Unequal channel spacing will cause the mixing products to be created at different frequencies which do not interfere with the signal channels**

Four Wave Mixing

- Consider a simple three wavelength ($\lambda 1$, $\lambda 2$ & $\lambda 3$)
- Let's assume that the input wavelengths are λl = 1551.72 nm, $\lambda 2$ = 1552.52 nm & $\lambda 3$ = 1553.32 nm. The interfering wavelengths that are of most concern in our hypothetical three wavelength system are:

  - □ $\lambda 1 + \lambda 2 - \lambda 3$ = 1550.92 nm
  - □ $\lambda 1 - \lambda 2 + \lambda 3$ = 1552.52 nm
  - □ $\lambda 2 + \lambda 3 . \lambda 1$ = 1554.12 nm
  - – $2\lambda 1 - \lambda 2$ = 1550.92 nm
  - – $2\lambda 1 - \lambda 3$ = 1550.12 nm
  - – $2\lambda 2 - \lambda 1$ = 1553.32 nm
  - – $2\lambda 2 - \lambda 3$ = 1551.72 nm
  - – $2\lambda 3 - \lambda 1$ = 1554.92 nm
  - – $2\lambda 3 - \lambda 2$ = 1554.12 nm



SOURCES: LED STRUCTURES

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FIBER OPTIC SOURCES

Two basic light sources are used for fiber optics:

- ✓ Laser diodes (LD)
- ✓ Light-emitting diodes(LED).

- Fiber optic sources must operate in the low-loss transmission windows of glass fiber.
- LEDs are typically used at the 850-nm and 1310-nm transmission wavelengths, whereas lasers are primarily used at 1310 nm and 1550 nm.

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

SEMICONDUCTOR LIGHT-EMITTING DIODES

- **Semiconductor LEDs emit incoherent light.**
- **Spontaneous emission of light in semiconductor LEDs produces light waves that lack a fixed-phase relationship.**
- **Light waves that lack a fixed-phase relationship are referred to as incoherent light.**

SEMICONDUCTOR LIGHT-EMITTING DIODES Cont…

- **The use of LEDs in single mode systems is severely limited because they emit unfocused incoherent light.**
- **Even LEDs developed for single mode systems are unable to launch sufficient optical power into single mode fibers for many applications.**
- **LEDs are the preferred optical source for multimode systems because they can launch sufficient power at a lower cost than semiconductor LDs.**

Types of LED

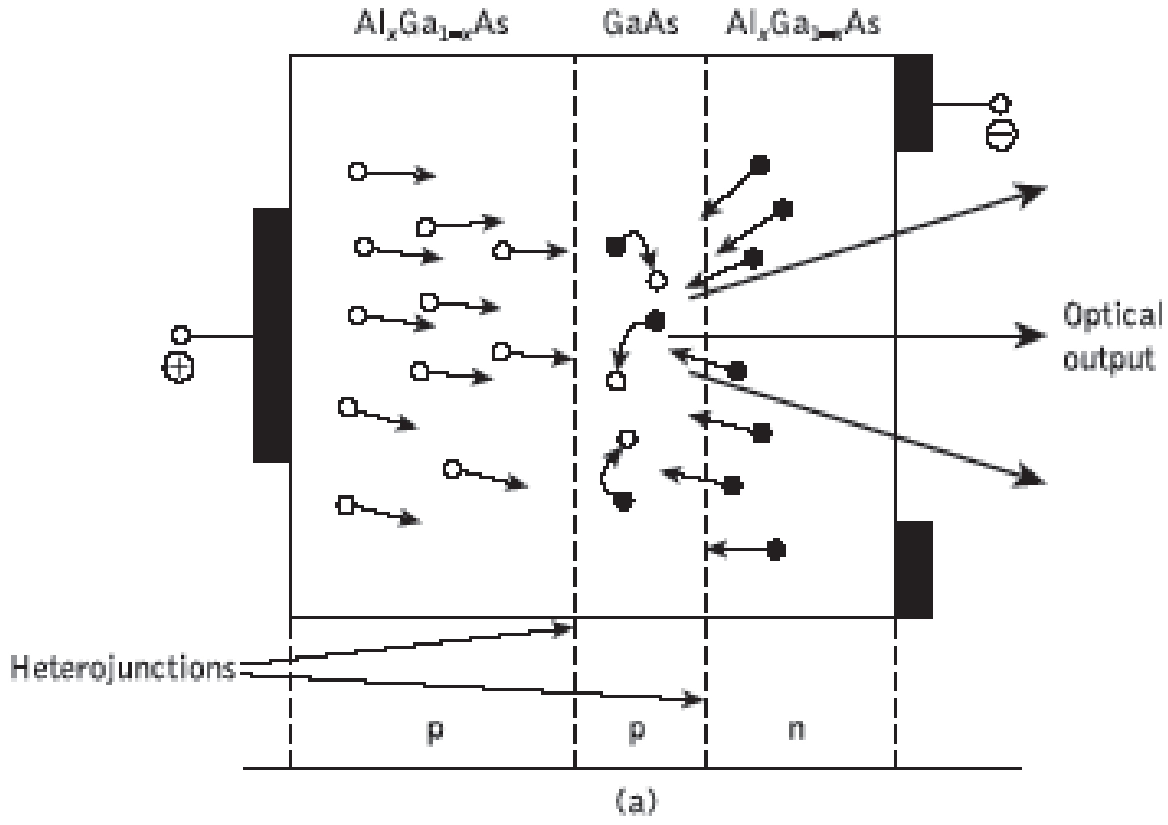
- Heterojunction LED
- Planar LED
- Dome LED
- Surface-emitting LED (SLED),
- Edge-emitting LED (ELED), and
- Super luminescent LED (SLD)

Homo- and Hetro-Junction

- **Homojunction** = a p-n junction made out of two differently doped semiconductors that are of the same material (i.e having the same band gap).
- **Heterojunction** = junction formed between two different band gaps semiconductors.
- **Heterostructure device** = semiconductor device structure that has junctions between different bandgap materials.

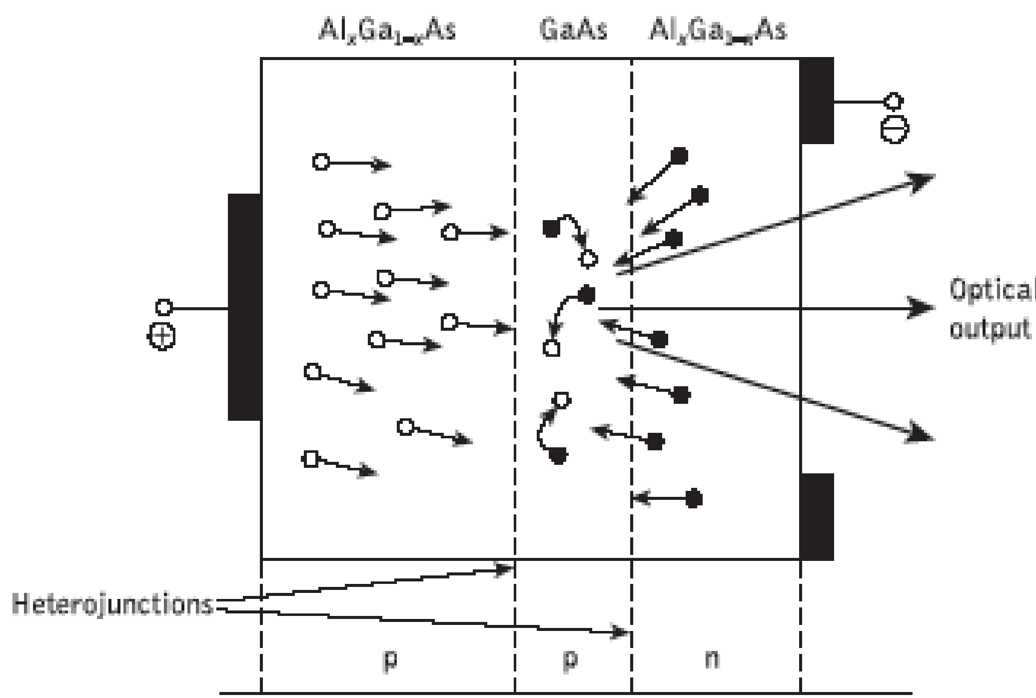
DOUBLE Heterojunction LED

- Consists of a p type GaAs layer sandwiched between a p type AlGaAs and a n type AlGaAs layer.
- When Forward biasing is applied electrons from the n type layer are injected through the p-n junction into the p type GaAs layer where they become minority carriers .



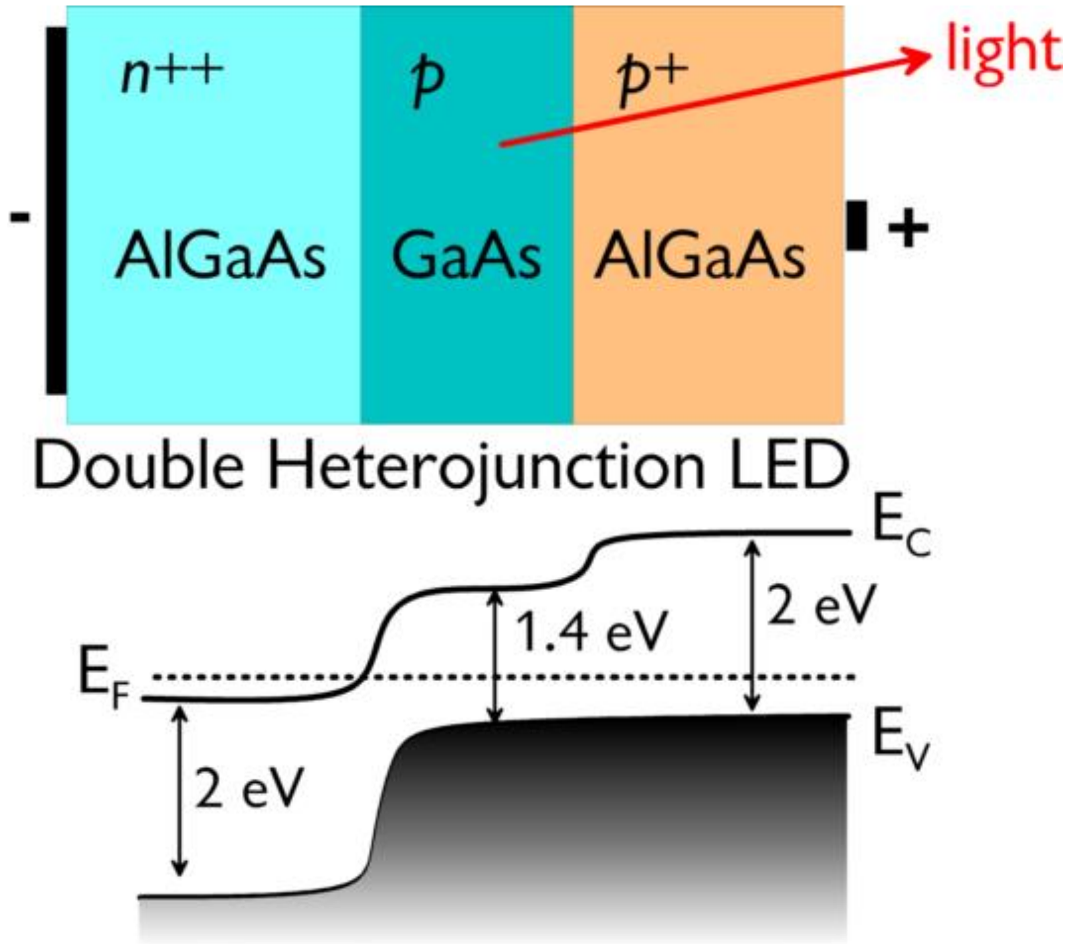
DOUBLE Heterojunction LED

- These minority carriers diffuse away from the junction, recombining with majority carriers (holes).
- Photons are produced with energy corresponding to the bandgap energy of the p type GaAs layer.
- The injected electrons are inhibited from diffusing into the p type AlGaAs layer because of the potential barrier presented by the p-p heterojunction.



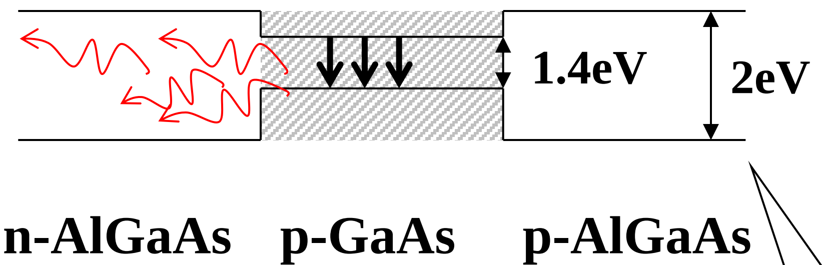
(a)

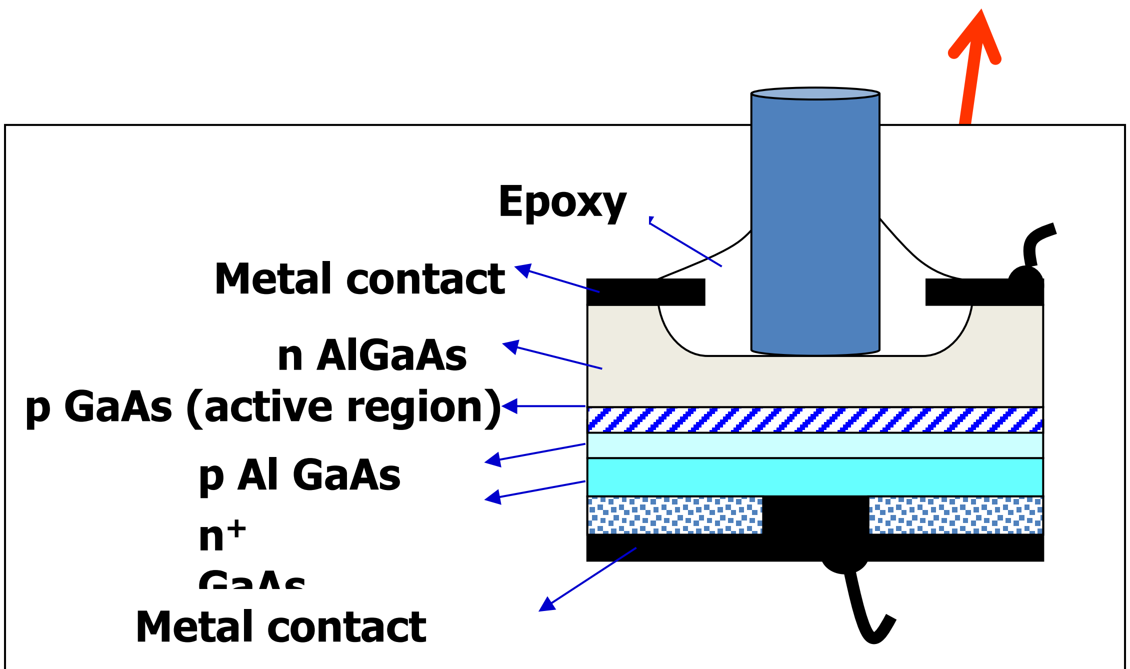
Double Heterojunction LED



Reabsorption Problem

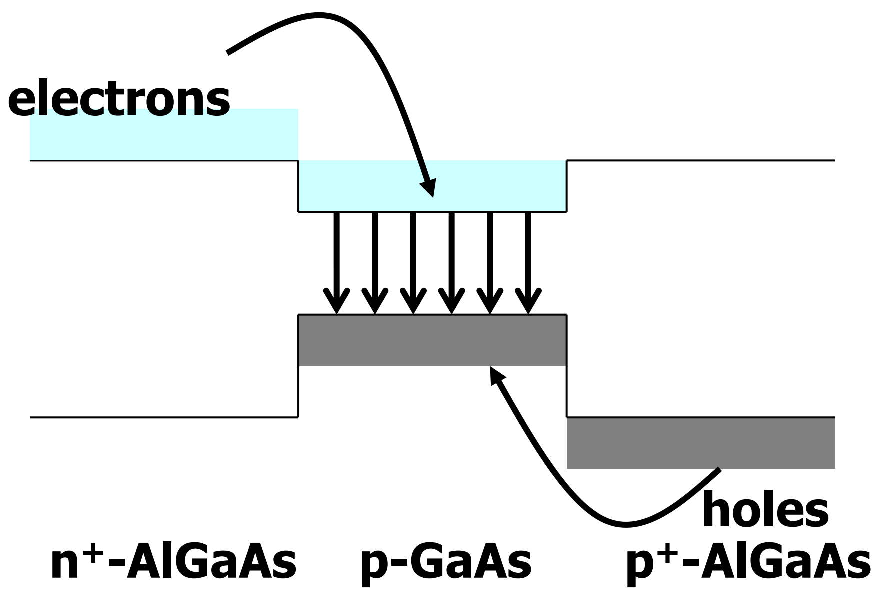
In order to prevent reabsorption, the upper layer (one that is above the active region) needs to have higher band gap therefore the emitted photons will not be absorbed by the upper layer .





Active region – Photons will not be absorbed by the n-AlGaAs since the band gap is much higher than GaAs

Carrier confinement



- Simplified band diagram of the 'sandwich' top show carrier confinement.
- Drastically reduce nonradiative recombination at the surface states.

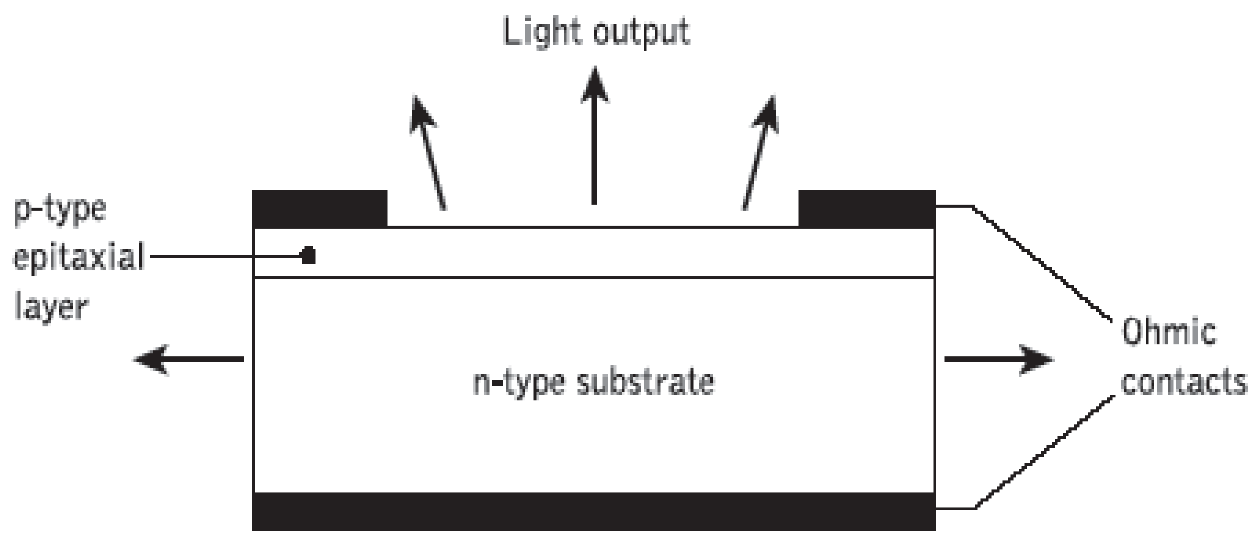
Double Heterostructure

- Provides good internal quantum efficiency and high radiance emission.

- The double heterostructure is therefore used to provide the most efficient incoherent sources for optical fiber communication.

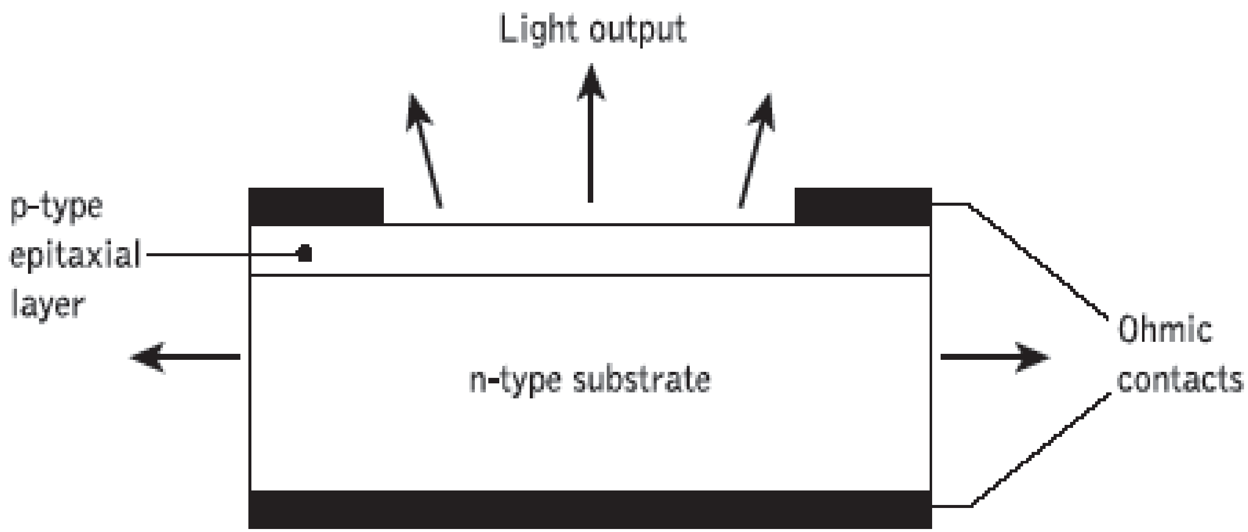
Planar LED

- Simplest of the structures that are available.
- Fabricated by either liquid or vapour-phase epitaxial process over the whole surface of a GaAs substrate.
- Involves a p type diffusion into the n type substrate in order to create the junction.



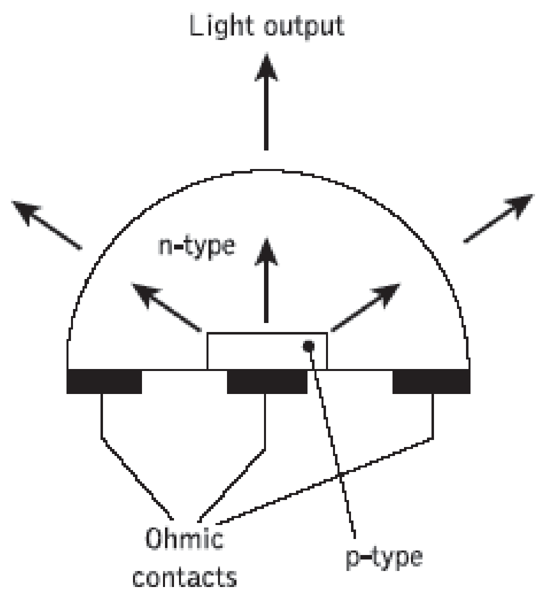
Planar LED

- Forward current flow through the junction gives spontaneous emission and the device emits light from all surfaces.
- Only a limited amount of light escapes the structure due to total internal reflection.



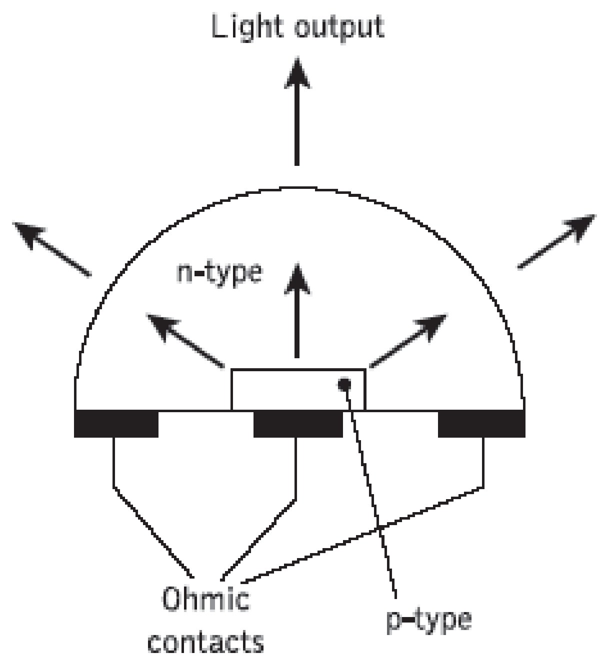
Dome LED

- A hemisphere of n type GaAs is formed around a diffused p type region.
- The diameter of the dome is chosen to maximize the amount of internal emission reaching the surface within the critical angle of the GaAs-air interface.

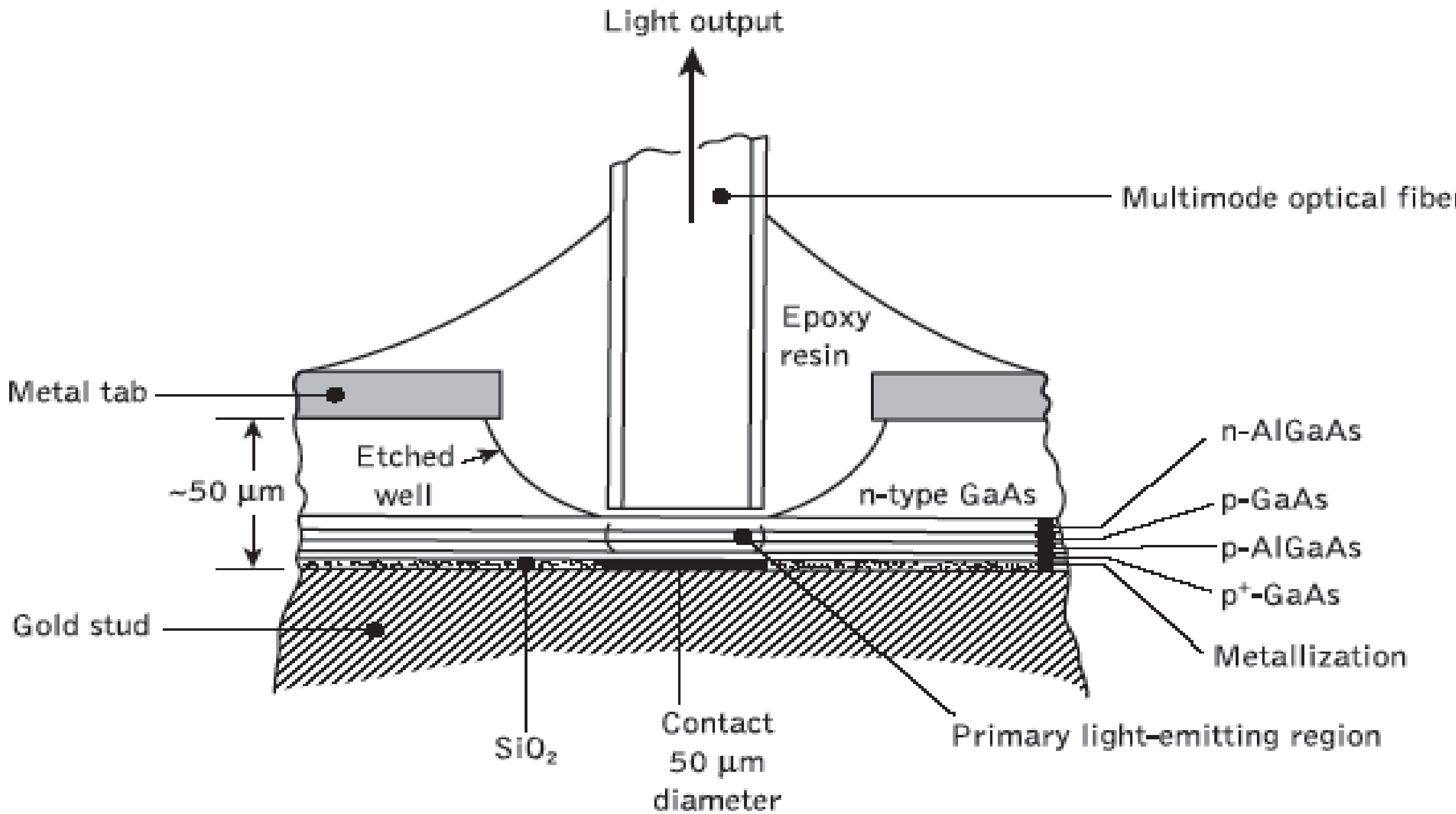


Dome LED

- Has a higher external power efficiency than the planar LED.
- Dome must be far larger than the active recombination area, which gives a greater effective emission area.



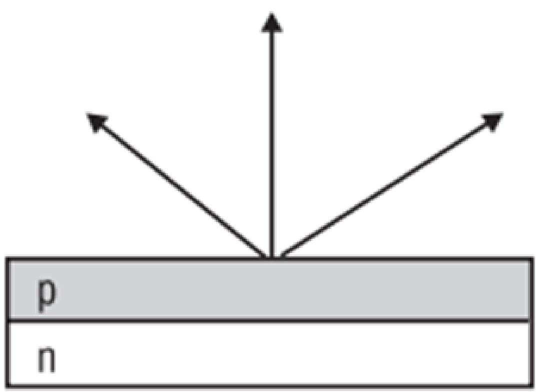
Surface Emitting LED



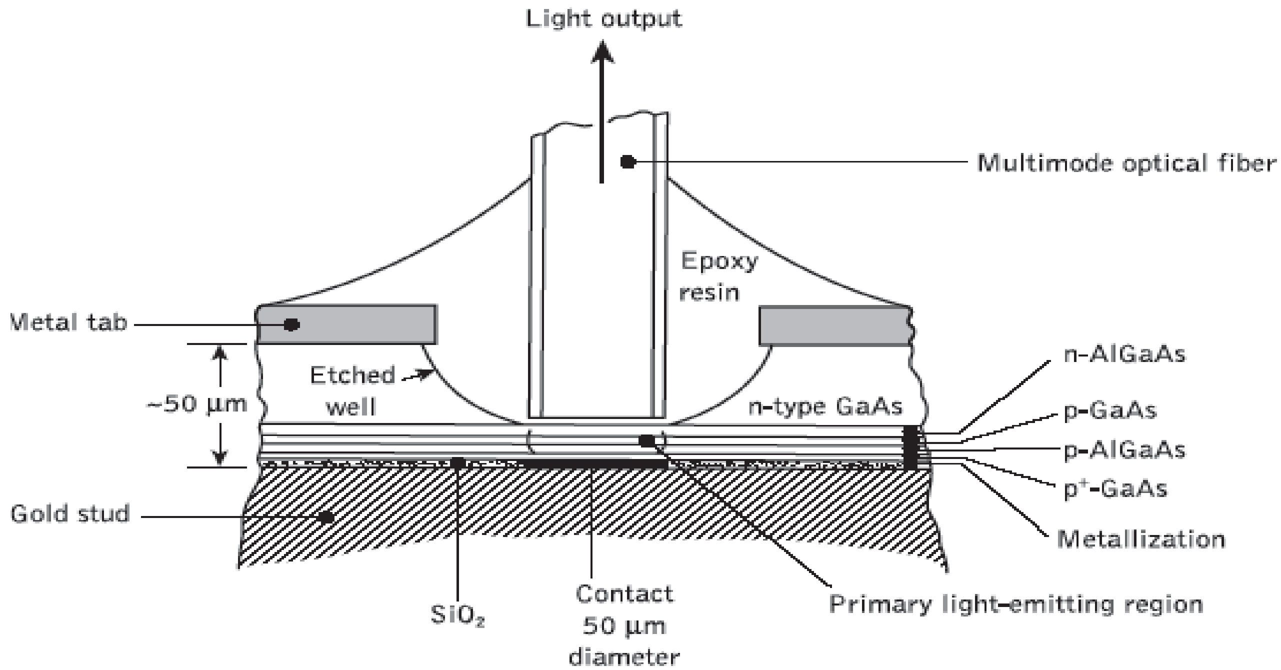
The structure of an AlGaAs DH surface-emitting LED (Burrus type).

Surface Emitting LED

- Also called front emitter LED's.
- Structured to obtain high radiance and efficient coupling of the emitted light into a fiber.
- It is essentially a double heterostructure device.
- The bottom P- GaAs and top n- GaAs are included for the realization of the low resistance ohmic contacts.
- To avoid reabsorption of the emitted radiation in the top n-GaAs layer , a deep well is etched to reach the top n-AlGaAs layer.

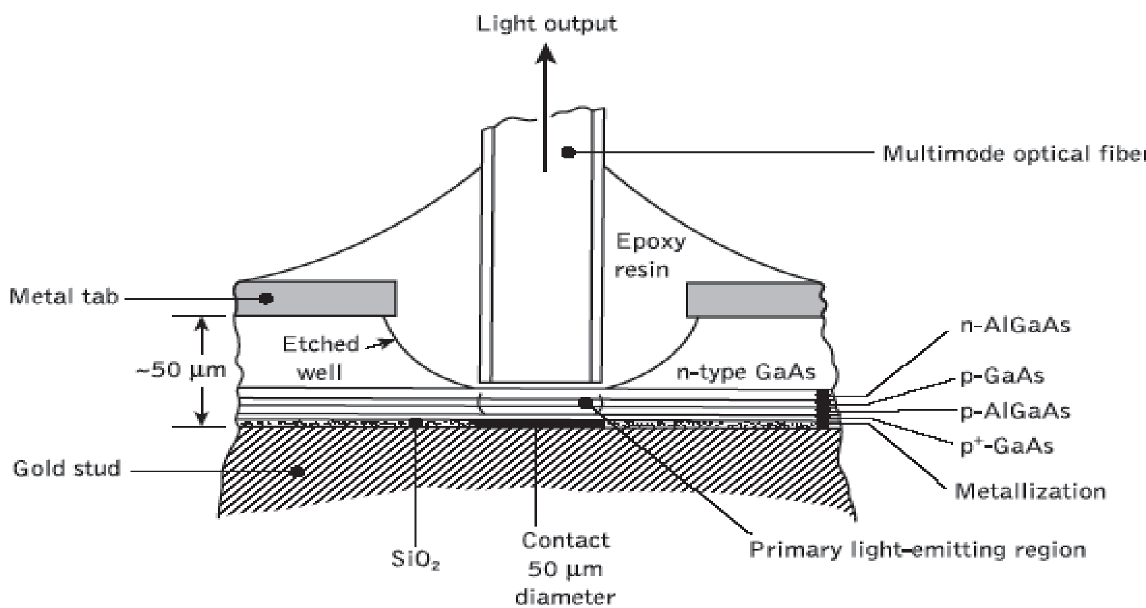


Surface emitting



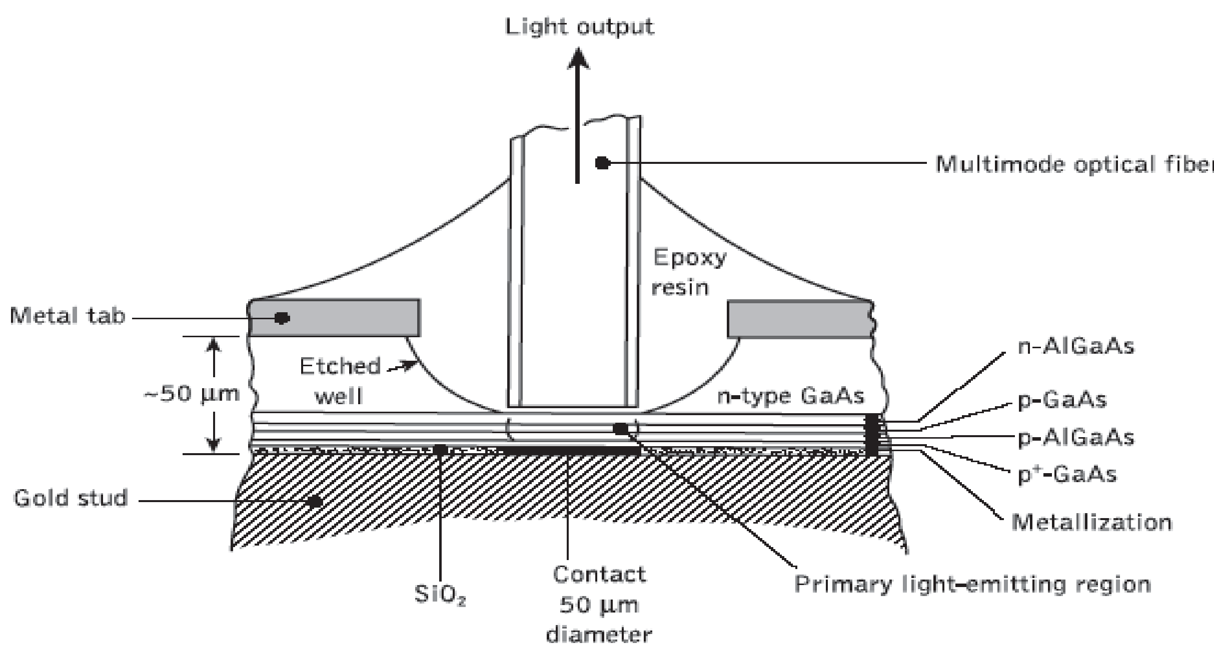
Surface Emitting LED

- Can be done by a selective etchant that etches GaAs but not AlGaAs.
- The well is also used to support the fiber, which is butt-coupled to the device inorder to accept the emitted light.
- The plane of the active light-emitting region is oriented perpendicularly to the axis of the fiber.
- The thin SiO2 layer at the back isolates the contact layer from the gold heat sink.
- Photons are generated in the thin p-GaAs region and emission from the top surface is ensured by the heterostructure and reflection from the back crystal face.



Surface Emitting LED

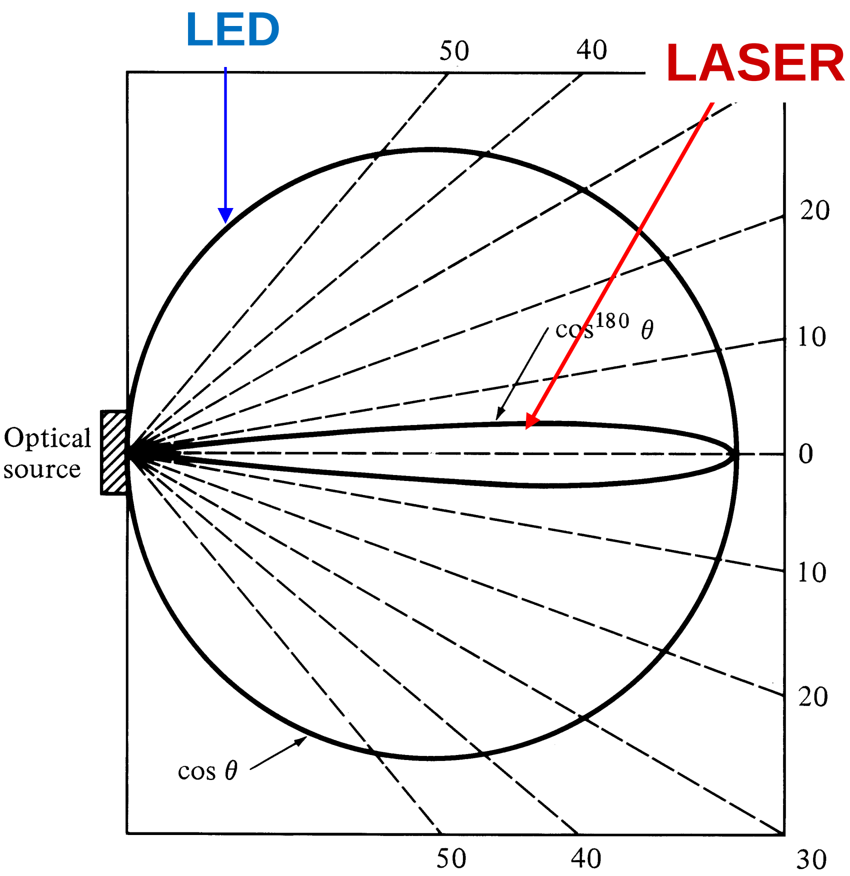
- Thus the forward radiance of these devices is very high.
- The fiber is properly aligned to optimize coupling of the emitted radiation.
- But, there is some loss due to the Lambertian distribution of the radiation intensity and the coupling efficiency is typically 1-2 %.



Lambertian pattern

- In this pattern the source is equally bright when viewed from any direction, but the power diminishes as cos θ .

- Thus the power is down to 50 percent of its peak when θ=60°, so that half power beam width is 120°



Surface Emitting LED

- The power coupled $\mathbf{P_c}$ into a multimode step index fiber may be estimated from the relationship

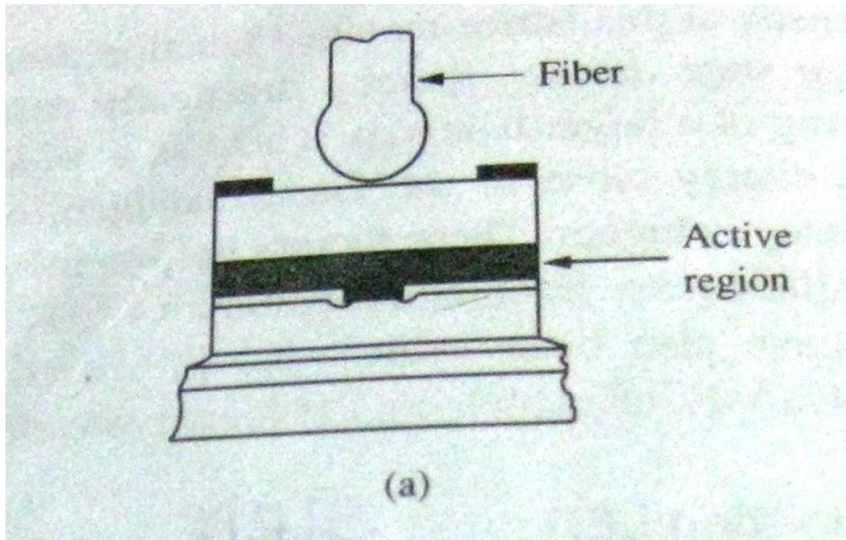
$$P_c = \pi (1 - r) A R_D (NA)^2$$

- where $\mathbf{r}$→ is the Fresnel reflection coefficient at the fiber surface,
- **A** →is the smaller of the fiber core cross-section or the emission area of the source and
- $\mathbf{R_D}$→ is the radiance of the source.
- **NA**→ Numerical Aperture

Surface Emitting LED

- Other lens coupling used to improve the coupling efficiency are
  - Spherical ended fiber-coupled device
  - Microlens coupling
  - Integrated semiconductor lens structure

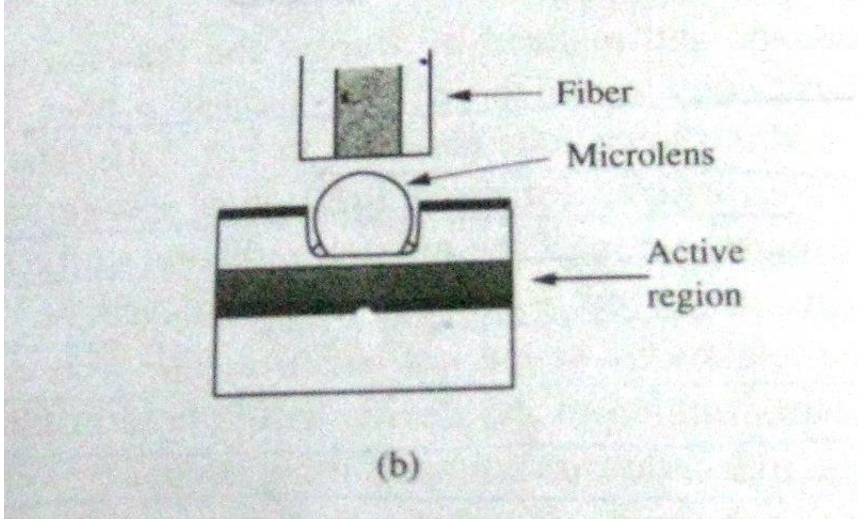
Surface Emitting LED



Spherical ended fiber-coupled device

- **Figure shows the end of the fiber that is polished into a spherical lens.**
- **This collects and collimates the divergent radiation from the LED.**

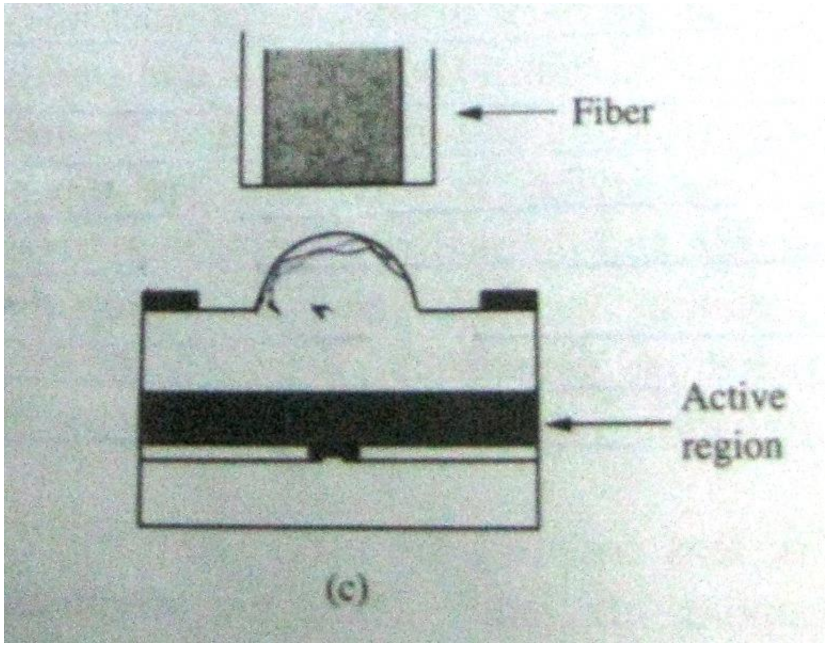
Surface Emitting LED



Microlens coupling

- **A glass microlens is inserted between the device and the fiber which collects and collimates the divergent radiation from the LED.**

Surface Emitting LED



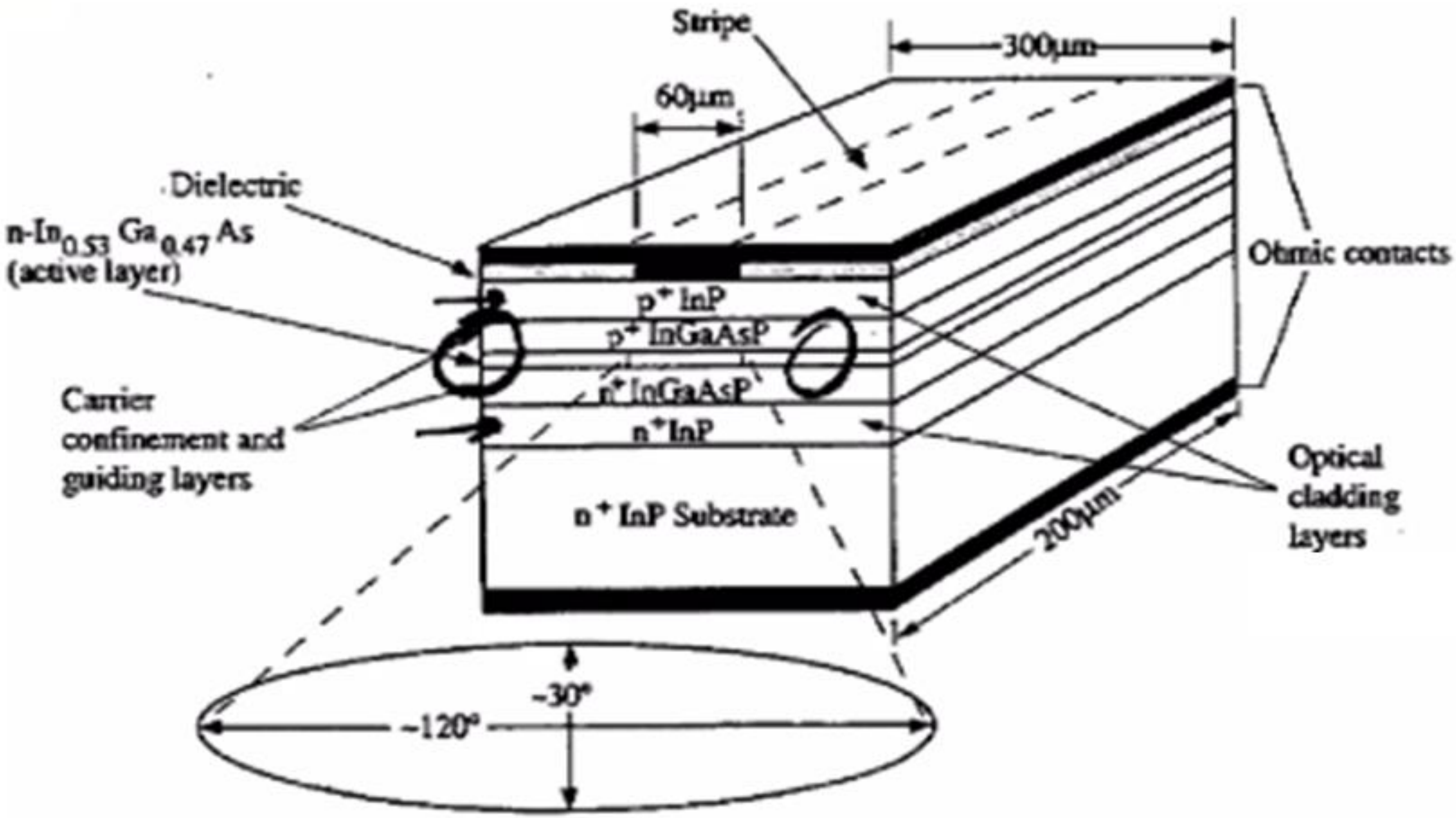
Integrated semiconductor lens structure

- **An integrated structure is obtained by etching and polishing the top surface layer of the LED into a spherical lens which collects and collimates the divergent radiation from the LED.**
- **Difficult to implement.**

Surface Emitting LED-Applications

- Important for large-volume and low cost applications.
- Short-distance chip-to-chip communications where surface-emitting sources are essential.
- Optical computing applications.
- With the different techniques of lens coupling, coupling efficiencies of 5%-15% have been achieved.

Guided wave or Edge-emitting LED

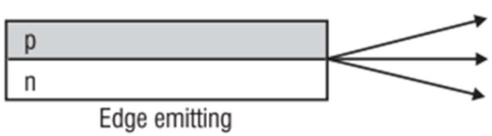


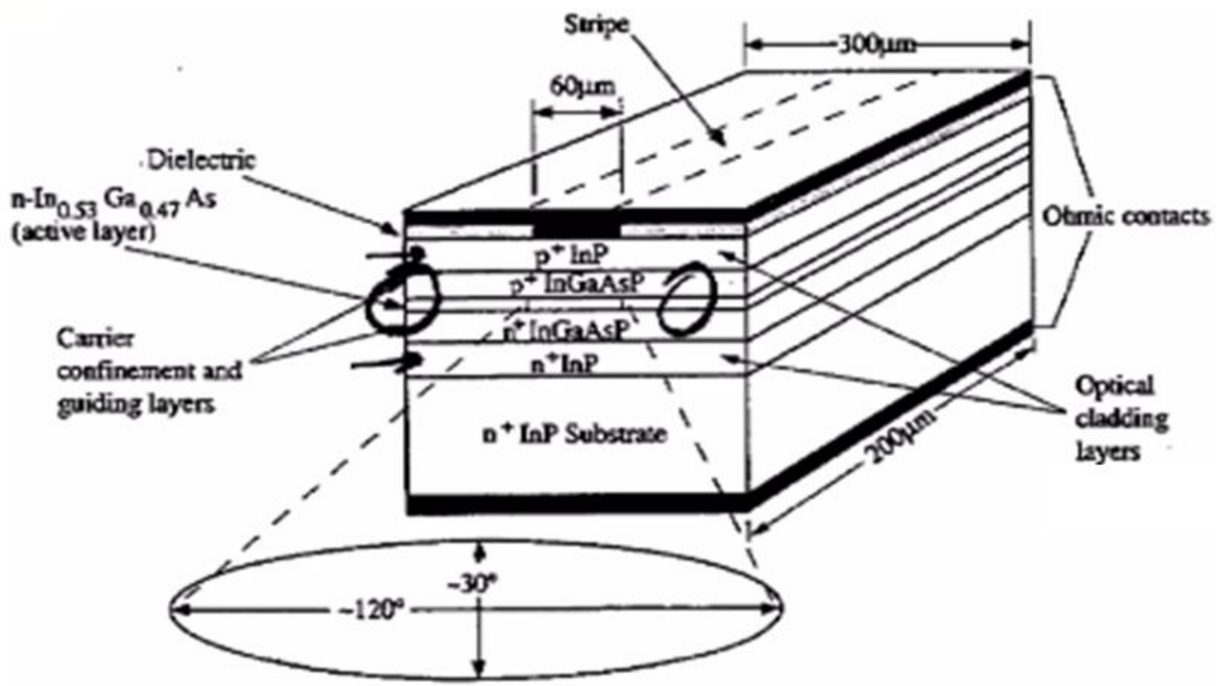
Guided wave or Edge-emitting LED

➢In optical communication where tight coupling of the emitted light to a fiber or waveguide is required, a more collimated light emission is desirable.

➢The active layer is usually lightly doped or undoped and a very large population of carriers for recombination is created in this region by forward-bias injection.

➢The two InGaAsP layers on both sides serve as carrier confinement layers.





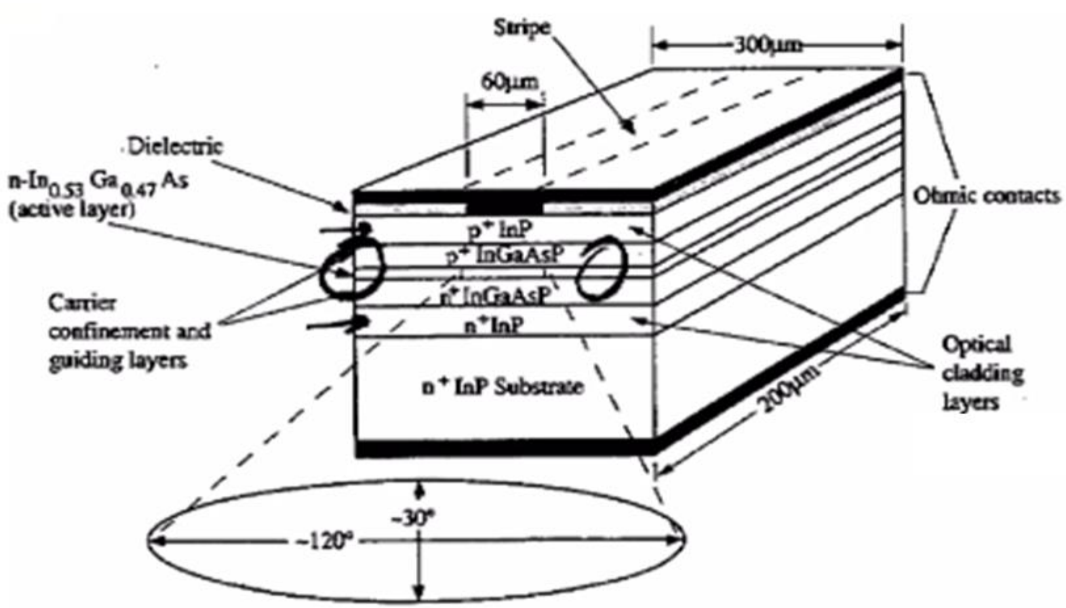
Guided wave or Edge-emitting LED

- The outside InP layers serve as the cladding layers.

- This structure forms a waveguide channel that directs the optical radiation toward the fiber core.

- Thus the wide bandgap layers serve the dual purpose of optical and carrier confinement.

- The photons are generated in the very thin active region and spread into the guiding layers, without reabsorption because of their larger bandgaps.



Guided wave or Edge-emitting LED

➢The stripe geometry , made by selective metallization on the top surface improves the injection efficiency.

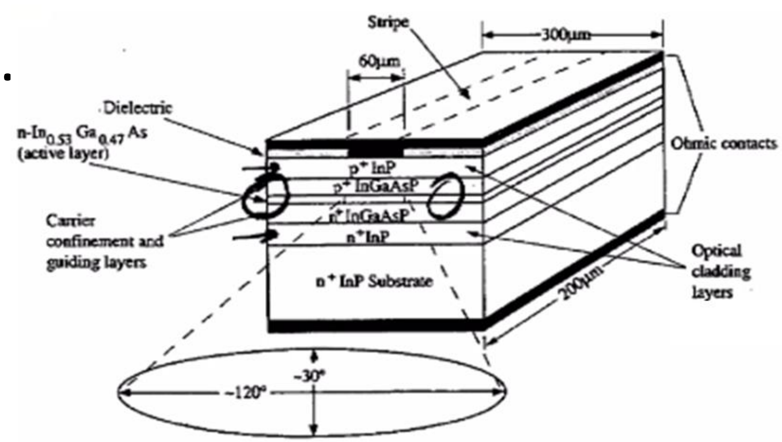
➢Most of the light is made to come out of one edge of the structure, by putting an reflective coating at the nonemitting end and an antireflective coating at the emitting end.

➢The emission pattern of the edge emitter is more directional than the surface emitter.

➢In the plane

➢parallel to the junction , HPBW=120 º.

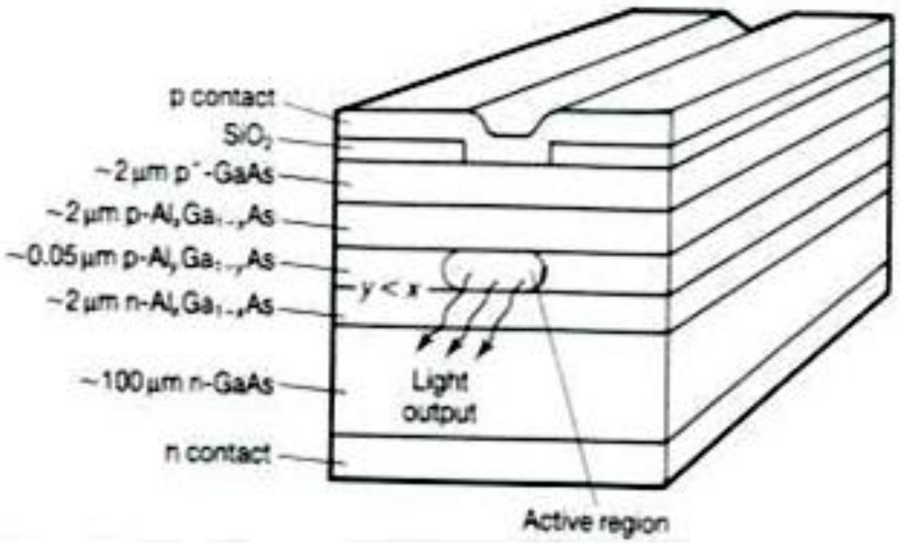
➢perpendicular to the junction , HPBW=30 º.



Double-Heterojunction (DH) LED
--- Edge-emitting type

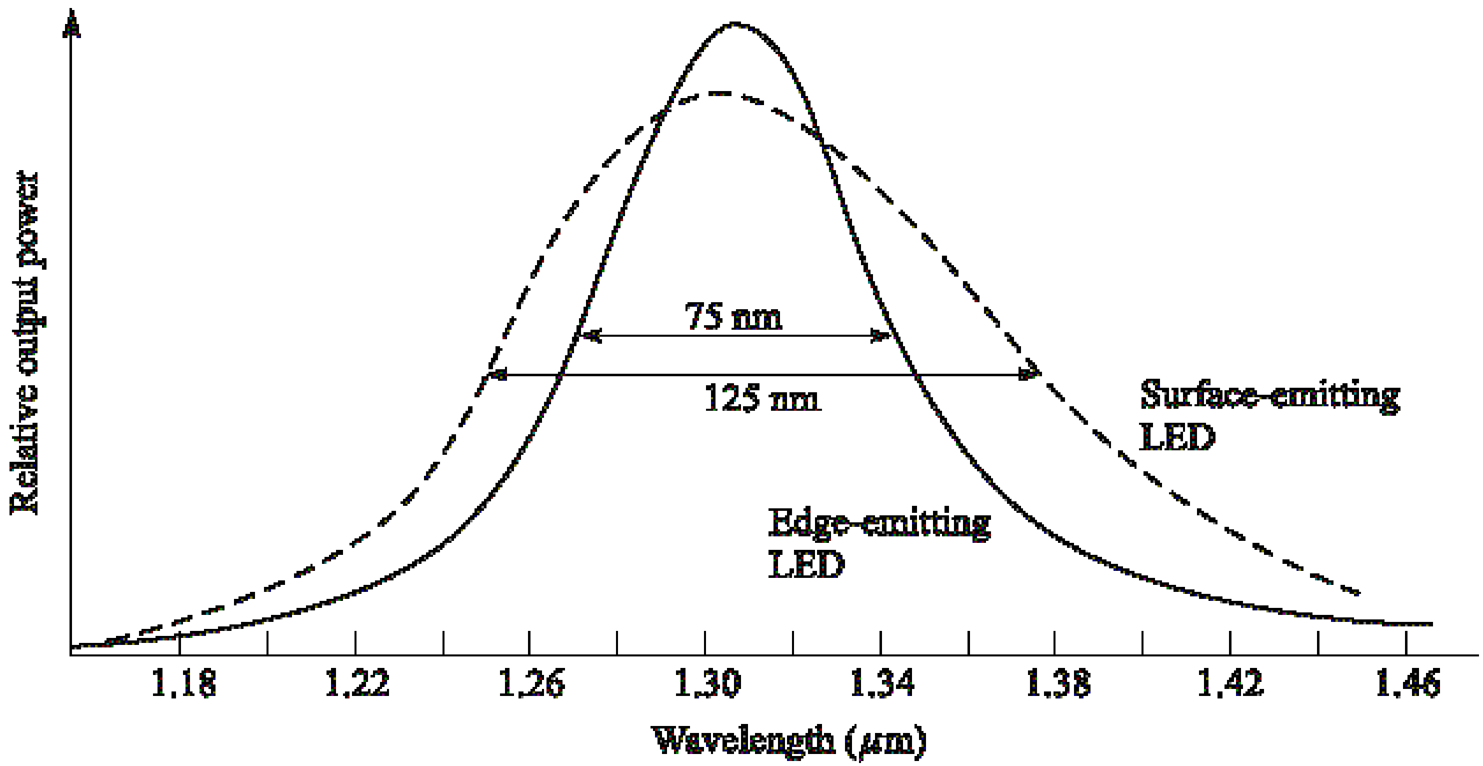
- ***Carrier and optical confinement***
  - In an edge-emitting LED, the wide gap cladding layers confine not only the electrons and holes to the active layer, but also cause the emitted photons to travel along the LED axis and emerge from from the edge of the device

- ***Improved coupling efficiency***
  - Due to the superior collimation of the edge-emitting LED (~30° width perpendicular to the layer and ~120° parallel to the layer), the coupling efficiency to a fiber is greatly improved.



➢ **The larger operating current density in a smaller structure can cause heat-sinking problems.**

Spectral width of LED types



LED performance differences (1)

- LED performance differences help link designers to decide which device is appropriate for the intended application.
- For short-distance (0 to 3 km), low-data-rate fiber optic systems, SLEDs are the preferred optical source.
- Typically, SLEDs operate efficiently for bit rates up to 250 Megabits per second (Mb/s).
- Because SLEDs emit light over a wide area (wide far-field angle), they are almost exclusively used in multimode systems.

LED performance differences (2)

- **For medium-distance, medium-data-rate systems, ELEDs are preferred.**

- **ELEDs may be modulated at rates up to 400 Mb/s. ELEDs may be used for both single mode and multimode fiber systems.**

- **Both SLDs and ELEDs are used in long-distance, high-data-rate systems when they are designed to operate in the superluminescence mode.**

- **SLDs may be modulated at bit rates of over 400 Mb/s.**

Superluminescent LED'S

- Another device geometry which is providing significant benefits over both SLEDs and ELEDs for communication applications is the superluminescent diode or SLD.

- This device type offers advantages of:
- (a) a high output power;
- (b) a directional output beam; and
- (c) a narrow spectral linewidth
- all of which prove useful for coupling significant optical power levels into optical fiber (in particular to single-mode fiber)
- the superradiant emission process within the SLD tends to increase the device modulation bandwidth over that of more conventional LEDs.

Superluminescent LED'S

Drawback

- **Nonlinear output characteristic and the increased temperature dependence of the output power .**

- It should be noted that the output of the SLD is spectrally broad (i.e. 20 to 150 nm) and therefore when these devices exhibit sufficient output signal power they can be used as broadband optical power sources .

- Commercially available SLDs can operate within a broad range of wavelengths from either 1.16 to 1.33 μm or 1.52 to 1.57 μm .

- In addition, these devices exhibit an output signal power around four to five times higher than a conventional ELED with optical output power of 8 mW being reported .

A DH surface emitter which has an emission area diameter of 50 μm is butt jointed to an 80 μm core step index fiber with a numerical aperture of 0.15. The device has a radiance of 30 W sr−1 cm−2 at a constant operating drive current. Estimate the optical power coupled into the fiber if it is assumed that the Fresnel reflection coefficient at the index matched fiber surface is 0.01.

The optical power coupled into the fiber Pc is given by

$$P_c = \pi(1 - r)AR_D(NA)^2$$

In this case A represents the emission area of the source. Hence:

$$A = \pi(25 \times 10^{-4})^2 \qquad = 1.96 \times 10^{-5}\ \text{cm}^2$$

Thus:

$$P_c = \pi(1 - 0.01)1.96 \times 10^{-5} \times 30 \times (0.15)^2$$

$$= 41.1\ \mu\text{W}$$

so around 41 μW of optical power is coupled into the step index fiber

LED Power and Efficiency

Prof. Dr.G. Aarthi

Associate Professor

SENSE,VIT,Vellore

LED power and efficiency

- The absence of optical amplification through stimulated emission in the LED tends to limit the internal quantum efficiency .
- Reliance on spontaneous emission allows nonradiative recombination to take place within the structure due to crystalline imperfections and impurities giving, at best, an internal quantum efficiency of 50% for simple homojunction devices.
- However, as with injection lasers, double-heterojunction (DH) structures have been implemented which recombination lifetime measurements give internal quantum efficiencies of 60 to 80%.

LED power and efficiency

- The power generated internally by an LED may be determined by consideration of the excess electrons and holes in the *p- and n-type material respectively (i.e. the minority* carriers)

- The excess density of electrons Δ*n and holes Δp is equal since the* injected carriers are created and recombined in pairs such that charge neutrality is maintained.

- In extrinsic materials one carrier type will have a much higher concentration than the other and hence in the *p-type region, for example, the hole* concentration will be much greater than the electron concentration.

LED power and efficiency

- In the **steady state the total number of carrier recombinations per second or the recombination rate r_t** *will be:*

$$r_t = r_r + r_{nr} \quad (\mathrm{m}^{-3})$$

- where r_r *is the radiative recombination rate per unit volume and*
- r_{nr} *is the nonradiative* recombination rate per unit volume
- when the **forward-biased current into the device is *i, then the total number of recombinations per second R_t*** *becomes:*

$$R_t = \frac{i}{e}$$

LED Internal quantum efficiency

- The LED internal quantum efficiency η_{int}, can be defined as the ratio of the radiative recombination rate to the total recombination rate,

$$\eta_{\text{int}} = \frac{r_{\text{r}}}{r_{\text{t}}} = \frac{r_{\text{r}}}{r_{\text{r}} + r_{\text{nr}}}$$

$$= \frac{R_{\text{r}}}{R_{\text{t}}}$$

- where R_r *is the total number of radiative recombinations per second.*
- *Therefore*

$$R_{\text{r}} = R_{\text{t}}\,\eta_{\text{int}}$$

$$R_{\text{r}} = \eta_{\text{int}}\frac{i}{e}$$

LED Internal Power

- Since R_r *is also equivalent to the total number of photons generated per second and* each photon has an energy equal to *hf joules, then the optical power generated i*nternally by the LED, $\boldsymbol{P_{int}}$ *is:*

$$P_{\text{int}} = \eta_{\text{int}} \frac{i}{e} hf \quad \text{(W)}$$

- In terms of wavelength

$$P_{\text{int}} = \eta_{\text{int}} \frac{hci}{e\lambda} \quad \text{(W)}$$

- Above equations display a linear relationship between the optical power generated in the LED and the drive current into the device.

LED Internal Quantum Efficiecny

- For the exponential decay of excess carriers
- the radiative minority carrier lifetime is $\tau_r = \Delta n / r_r$ *and*
- *the nonradiative minority carrier lifetime is* $\tau_{nr} = \Delta n / r_{nr}$

$$\eta_{\text{int}} = \frac{r_{\text{r}}}{r_{\text{t}}} = \frac{r_{\text{r}}}{r_{\text{r}} + r_{\text{nr}}}$$

$$\eta_{\text{int}} = \frac{1}{1 + (r_{\text{nr}}/r_{\text{t}})} = \frac{1}{1 + (\tau_{\text{r}}/\tau_{\text{nr}})}$$

$$\frac{1}{\tau} = \frac{1}{\tau_{\text{r}}} + \frac{1}{\tau_{\text{nr}}} \qquad \eta_{\text{int}} = \frac{\tau}{\tau_{\text{r}}}$$

External Power Efficiency

- The external power efficiency η_{ep} is defined as the ratio of the optical power emitted externally P_e *to the electric power provided* to the device P

$$\eta_{ep} \simeq \frac{P_e}{P} \times 100\%$$

$$P_e = \frac{P_{int} F n^2}{4 n_x^2}$$

- where P_{int} *is the power generated internally*
- *F is the transmission factor of the* semiconductor–external interface.
- **n** is the refractive index of outside medium(low)where the optical power is emitted.
- n_x is the refractive index of the LED material.

The radiative and nonradiative recombination lifetimes of the minority carriers in the active region of a double-heterojunction LED are 60 ns and 100 ns respectively. Determine the total carrier recombination lifetime and the power internally generated within the device when the peak emission wavelength is 0.87 μm at a drive current of 40 mA.

The total carrier recombination lifetime is given by

$$\frac{1}{\tau} = \frac{1}{\tau_r} + \frac{1}{\tau_{nr}} \qquad \tau = \frac{\tau_r \tau_{nr}}{\tau_r + \tau_{nr}} = \frac{60 \times 100 \text{ ns}}{60 + 100} = 37.5 \text{ ns}$$

To calculate the power internally generated it is necessary to obtain the internal quantum efficiency of the device.

$$\eta_{int} = \frac{\tau}{\tau_r} = \frac{37.5}{60} = 0.625$$

$$P_{int} = \eta_{int} \frac{hci}{e\lambda} = \frac{0.625 \times 6.626 \times 10^{-34} \times 2.998 \times 10^{8} \times 40 \times 10^{-3}}{1.602 \times 10^{-19} \times 0.87 \times 10^{-6}} = 35.6 \text{ mW}$$

The LED which has an internal quantum efficiency of 62.5% generates 35.6 mW of optical power, internally.

A planar LED is fabricated from gallium arsenide which has a refractive index of 3.6. (a) Calculate the optical power emitted into air as a percentage of the internal optical power for the device when the transmission factor at the crystal–air interface is 0.68. (b) When the optical power generated internally is 50% of the electric power supplied, determine the external power efficiency.

(a) The optical power emitted is given by

$$P_e \simeq \frac{P_{int} F n^2}{4 n_x^2}$$

in which the refractive index n for air is 1

$$P_e \simeq \frac{P_{int} F n^2}{4 n_x^2} = \frac{P_{int} 0.68 \times 1}{4(3.6)^2} = 0.013 P_{int}$$

Hence the power emitted is only 1.3% of the optical power generated internally.

A planar LED is fabricated from gallium arsenide which has a refractive index of 3.6. (a) Calculate the optical power emitted into air as a percentage of the internal optical power for the device when the transmission factor at the crystal–air interface is 0.68. (b) When the optical power generated internally is 50% of the electric power supplied, determine the external power efficiency.

(b)The external power efficiency is given by

$$\eta_{ep} = \frac{P_e}{P} \times 100 \quad = 0.013\,\frac{P_{int}}{P} \times 100$$

Also, the optical power generated internally Pint = 0.5P. Hence:

$$\eta_{ep} = \frac{0.013 P_{int}}{2 P_{int}} \times 100 \quad = 0.65\%$$

The light output from the GaAs LED of the previous example is coupled into a step index fiber with a numerical aperture of 0.2, a core refractive index of 1.4 and a diameter larger than the diameter of the device. Estimate:

(a) The coupling efficiency into the fiber when the LED is in close proximity to the fiber core.

(b) The optical loss in decibels, relative to the power emitted from the LED, when coupling the light output into the fiber.

(c) The loss relative to the internally generated optical power in the device when coupling the light output into the fiber when there is a small air gap between the LED and the fiber core

(a) the coupling efficiency is given by:

$$\eta_c = (NA)^2 \quad = (0.2)^2 = 0.04$$

Thus about 4% of the externally emitted optical power is coupled into the fiber.

The light output from the GaAs LED of the previous example is coupled into a step index fiber with a numerical aperture of 0.2, a core refractive index of 1.4 and a diameter larger than the diameter of the device. Estimate:

(a) The coupling efficiency into the fiber when the LED is in close proximity to the fiber core.

(b) The optical loss in decibels, relative to the power emitted from the LED, when coupling the light output into the fiber.

(c) The loss relative to the internally generated optical power in the device when coupling the light output into the fiber when there is a small air gap between the LED and the fiber core

(b) Let the optical power coupled into the fiber be P_c. Then the optical loss in decibels relative to P_e when coupling the light output into the fiber is

$$\text{Loss} = -10 \log_{10} \frac{P_c}{P_e} \quad = -10 \log_{10} \eta_c$$

$$\text{Loss} = -10 \log_{10} 0.04$$

$$= 14.0 \text{ dB}$$

The light output from the GaAs LED of the previous example is coupled into a step index fiber with a numerical aperture of 0.2, a core refractive index of 1.4 and a diameter larger than the diameter of the device. Estimate:

(a) The coupling efficiency into the fiber when the LED is in close proximity to the fiber core.

(b) The optical loss in decibels, relative to the power emitted from the LED, when coupling the light output into the fiber.

(c) The loss relative to the internally generated optical power in the device when coupling the light output into the fiber when there is a small air gap between the LED and the fiber core

(c) When the LED is emitting into air,

$$P_e = 0.013 P_{int}$$

Assuming a very small air gap , then from (a) the power coupled into the fiber is:

$$P_c = 0.04 P_e \quad = 0.04 \times 0.013 P_{int}$$

$$= 5.2 \times 10^{-4} P_{int}$$

Hence in this case only about 0.05% of the internal optical power is coupled into the fiber.

The light output from the GaAs LED of the previous example is coupled into a step index fiber with a numerical aperture of 0.2, a core refractive index of 1.4 and a diameter larger than the diameter of the device. Estimate:

(a) The coupling efficiency into the fiber when the LED is in close proximity to the fiber core.

(b) The optical loss in decibels, relative to the power emitted from the LED, when coupling the light output into the fiber.

(c) The loss relative to the internally generated optical power in the device when coupling the light output into the fiber when there is a small air gap between the LED and the fiber core

The loss in decibels relative to P_{int} is:

$$\text{Loss} = -10 \log_{10} \frac{P_c}{P_{int}} \qquad = -10 \log_{10} 5.2 \times 10^{-4} \qquad = 32.8 \text{ dB}$$

A lens-coupled surface-emitting LED launches 190 μW of optical power into a multi-mode step index fiber when a forward current of 25 mA is flowing through the device. Determine the overall power conversion efficiency when the corresponding forward voltage across the diode is 1.5 V

The overall power conversion efficiency

$$\eta_{pc} = \frac{P_c}{P} = \frac{190 \times 10^{-6}}{25 \times 10^{-3} \times 1.5} = 5.1 \times 10^{-3}$$

Hence the overall power conversion efficiency is 0.5%

LED Frequency Response and Modulation Bandwidth

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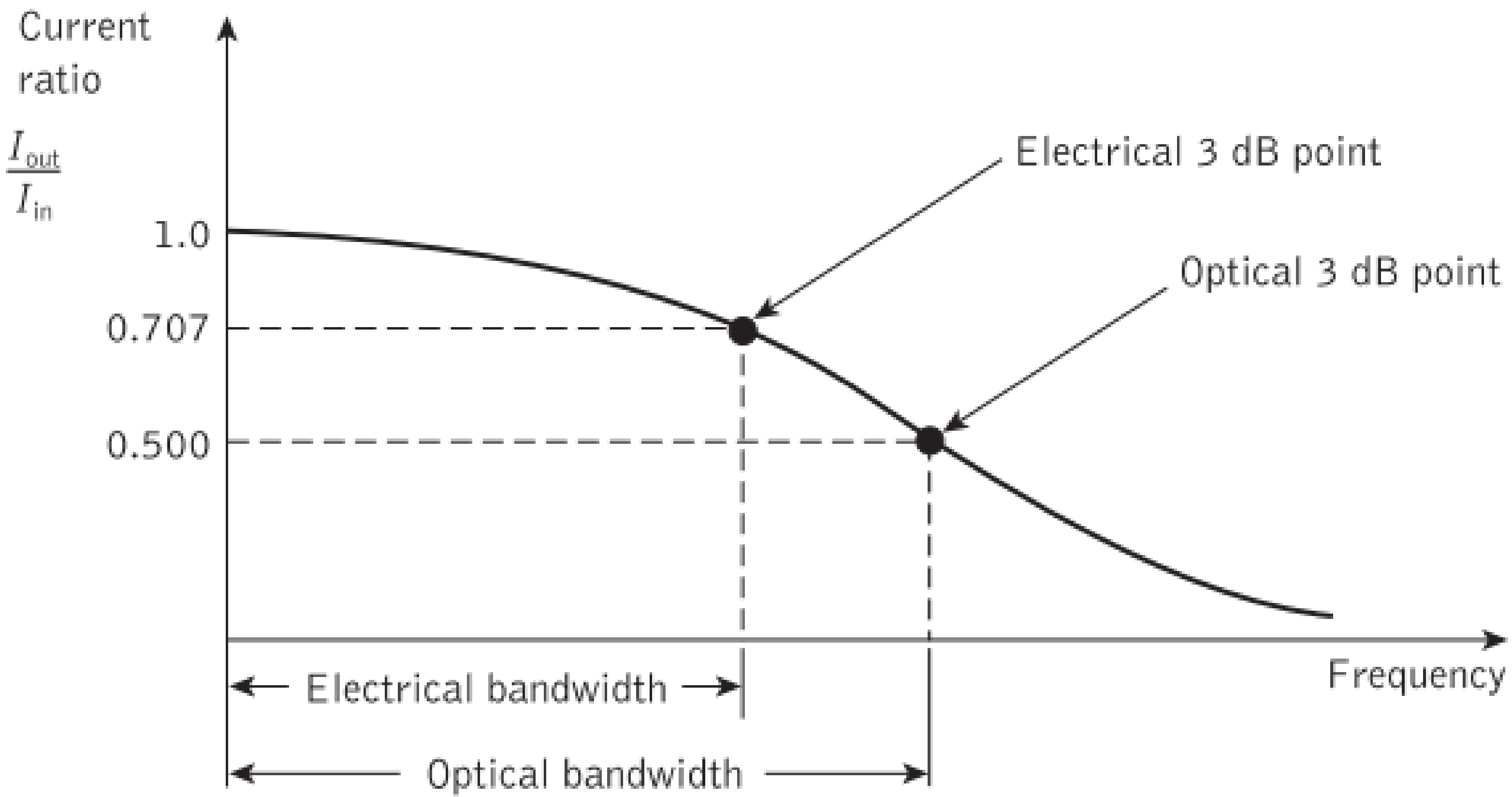
SENSE,VIT,Vellore

Frequency response & Modulation bandwidth



The frequency response for an optical fiber system showing electrical and optical bandwidths.

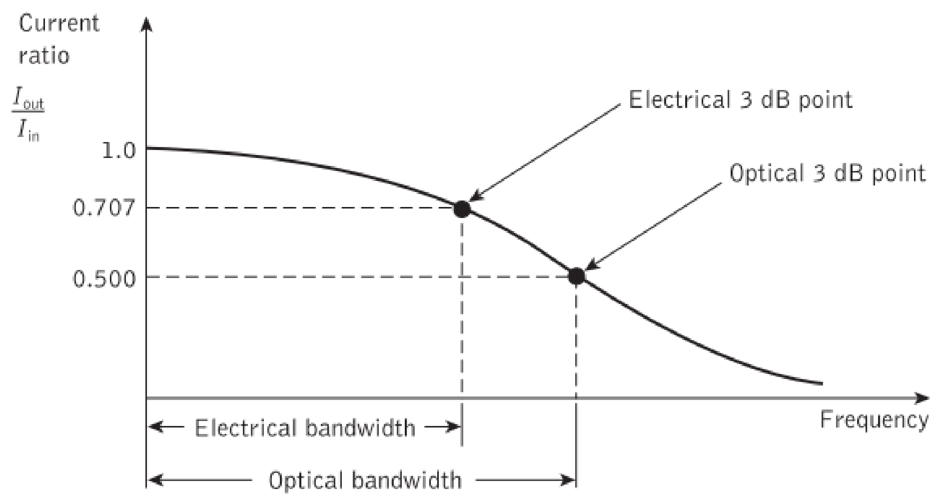
Frequency response & Modulation bandwidth

➢ The modulation bandwidth in optical communications may be defined in either electrical or optical terms.

➢**Electrical Bandwidth:**

Frequency at which the electrical signal power has dropped to half its constant value due to the modulated portion of the optical signal.

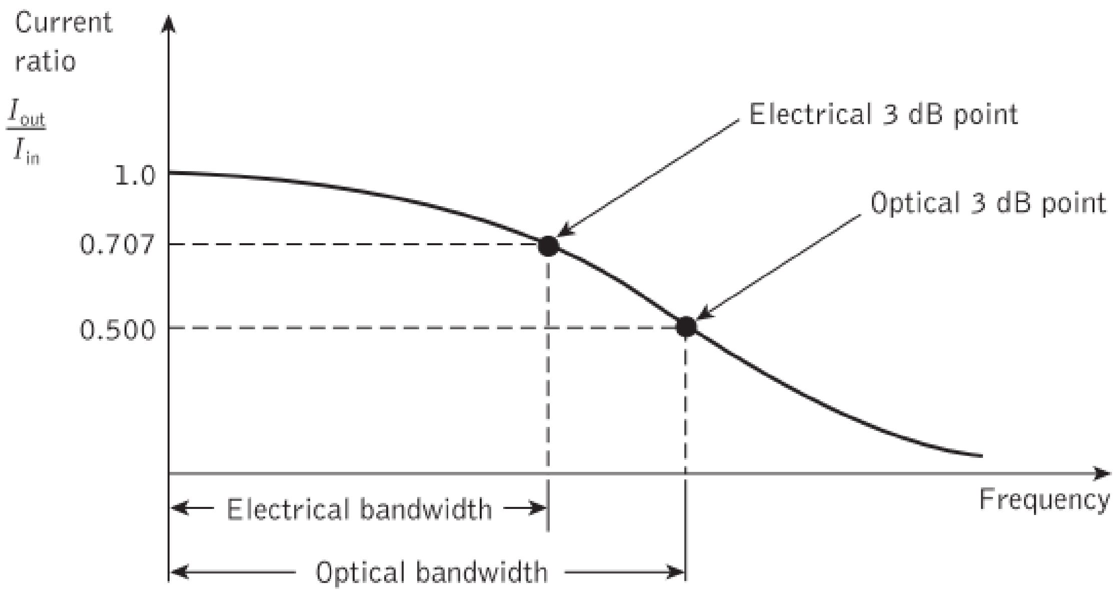
This corresponds to the electrical 3 dB point or the frequency at which the output electric power is reduced by 3 dB with respect to the input electric power.



Frequency response & Modulation bandwidth

➢ The modulation bandwidth in optical communications may be defined in either electrical or optical terms.

➢**Optical Bandwidth:**
Frequency at which the optical signal power has dropped to half its constant value.



Frequency response & Modulation bandwidth

Electrical bandwidth:

The ratio of the electric output power to the electric input power in decibels RE_{dB} *is given by:*

$$RE_{dB} = 10 \log_{10} \frac{\text{electric power out (at the detector)}}{\text{electric power in (at the source)}}$$

$$= 10 \log_{10} \frac{I_{out}^2 R_{out}}{I_{in}^2 R_{in}}$$

$$\propto 10 \log_{10} \left[\frac{I_{out}}{I_{in}}\right]^2$$

The electrical 3 dB points occur when the ratio of electric powers shown above is $\frac{1}{2}$. Hence it follows that this must occur when:

$$\left[\frac{I_{out}}{I_{in}}\right]^2 = \frac{1}{2} \quad \text{or} \quad \frac{I_{out}}{I_{in}} = \frac{1}{\sqrt{2}}$$

Thus in the electrical regime the bandwidth may be defined by the frequency when the output current has dropped to 1/√2 or 0.707 of the input current to the system.

Frequency response & Modulation bandwidth

Optical bandwidth:

The ratio of the optical output power to the optical input power in decibels *RO_{dB} is given by:*

$$RO_{\mathrm{dB}} = 10\log_{10}\frac{\text{optical power out (received at detector)}}{\text{optical power in (transmitted at source)}}$$

$$\propto 10\log_{10}\frac{I_{\mathrm{out}}}{I_{\mathrm{in}}}$$

(due to the linear light/current relationships of the source and detector). Hence the optical 3 dB points occur when the ratio of the currents is equal to 1 /2, and:

$$\frac{I_{\mathrm{out}}}{I_{\mathrm{in}}} = \frac{1}{2}$$

Therefore in the optical regime the bandwidth is defined by the frequencies at which the output current has dropped to 1 /2 or 0.5 of the input current to the system. This corresponds to an electric power attenuation of 6 dB.

Frequency response & Modulation bandwidth

- **The optical bandwidth is significantly greater than the electrical bandwidth.**

- **The optical bandwidth is a factor of √2 greater than the electrical bandwidth.**

The modulation bandwidth of LED's is determined by three factors.

a) **The doping level in the active layer**
b) **The radiative lifetime of the injected carriers.**
c) **The parasitic capacitance and resistance in the circuit.**

Frequency response & Modulation bandwidth

Assuming negligible parasitic capacitance, the speed at which an LED can be directly current modulated is fundamentally limited by the recombination lifetime of the carriers, where the optical output power $P_e(\omega)$ *of the device (with constant peak current) and angular* modulation frequency ω is given by

$$\frac{P_e(\omega)}{P_{dc}} = \frac{1}{[1 + (\omega\tau_i)^2]^{\frac{1}{2}}}$$

where τ_i is the injected (minority) carrier lifetime in the recombination region and P_{dc} is the d.c. optical output power for the same drive current.

The minority carrier recombination lifetime for an LED is 5 ns. When a constant d.c. drive current is applied to the device the optical output power is 300 μW. Determine the optical output power when the device is modulated with an rms drive current corresponding to the d.c. drive current at frequencies of (a) 20 MHz; (b) 100 MHz. It may be assumed that parasitic capacitance is negligible. Further, determine the 3 dB optical bandwidth for the device and estimate the 3 dB electrical bandwidth assuming a Gaussian response.

(a) the optical output power at 20 MHz is

$$P_e(20\text{ MHz}) = \frac{P_{dc}}{[1 + (\omega\tau_i)^2]^{\frac{1}{2}}} \qquad = \frac{300 \times 10^{-6}}{[1 + (2\pi \times 20 \times 10^6 \times 5 \times 10^{-9})^2]^{\frac{1}{2}}}$$

$$= \frac{300 \times 10^{-6}}{[1.39]^{\frac{1}{2}}} \qquad = 254.2\ \mu\text{W}$$

The minority carrier recombination lifetime for an LED is 5 ns. When a constant d.c. drive current is applied to the device the optical output power is 300 μW. Determine the optical output power when the device is modulated with an rms drive current corresponding to the d.c. drive current at frequencies of (a) 20 MHz; (b) 100 MHz. It may be assumed that parasitic capacitance is negligible. Further, determine the 3 dB optical bandwidth for the device and estimate the 3 dB electrical bandwidth assuming a Gaussian response.

(b) the optical output power at 100 MHz is

$$P_e(100\ \text{MHz}) = \frac{300 \times 10^{-6}}{[1 + (2\pi \times 100 \times 10^6 \times 5 \times 10^{-9})^2]^{\frac{1}{2}}}$$

$$= \frac{300 \times 10^{-6}}{[10.87]^{\frac{1}{2}}}$$

$$= 90.9\ \mu\text{W}$$

The minority carrier recombination lifetime for an LED is 5 ns. When a constant d.c. drive current is applied to the device the optical output power is 300 μW. Determine the optical output power when the device is modulated with an rms drive current corresponding to the d.c. drive current at frequencies of (a) 20 MHz; (b) 100 MHz. It may be assumed that parasitic capacitance is negligible. Further, determine the 3 dB optical bandwidth for the device and estimate the 3 dB electrical bandwidth assuming a Gaussian response.

This example illustrates the reduction in the LED optical output power as the device is driven at higher modulating frequencies. It is therefore apparent that there is a somewhat limited bandwidth over which the device may be usefully utilized.

To determine the optical 3 dB bandwidth, the high-frequency 3 dB point occurs when

$$P_e(\omega)/P_{dc} = \tfrac{1}{2}$$

$$P_e(\omega)/P_{dc} = \tfrac{1}{2}$$

$$\frac{1}{[1 + (\omega\tau_i)^2]^{\frac{1}{2}}} = \frac{1}{2}$$

and $1 + (\omega\tau_i)^2 = 4$. Therefore $\omega\tau_i = \sqrt{3}$, and:

$$f = \frac{\sqrt{3}}{2\pi\tau} \qquad = \frac{\sqrt{3}}{\pi \times 10^{-8}} = 55.1 \text{ MHz}$$

Thus the 3 dB optical bandwidth B_{opt} is 55.1 MHz.

Assuming a Gaussian frequency response, the 3 dB electrical bandwidth B will be

$$B = \frac{55.1}{\sqrt{2}} \qquad = 39.0 \text{ MHz}$$

Thus the corresponding electrical bandwidth is 39 MHz.

Semiconductor LASER

Prof.Dr.G.Aarthi,
Associate Professor,
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Recap

- What is the word LASER stands for?

- ❖ Light amplification by Stimulated Emission of Radiation

- What is Population Inversion?

Laser Fundamentals

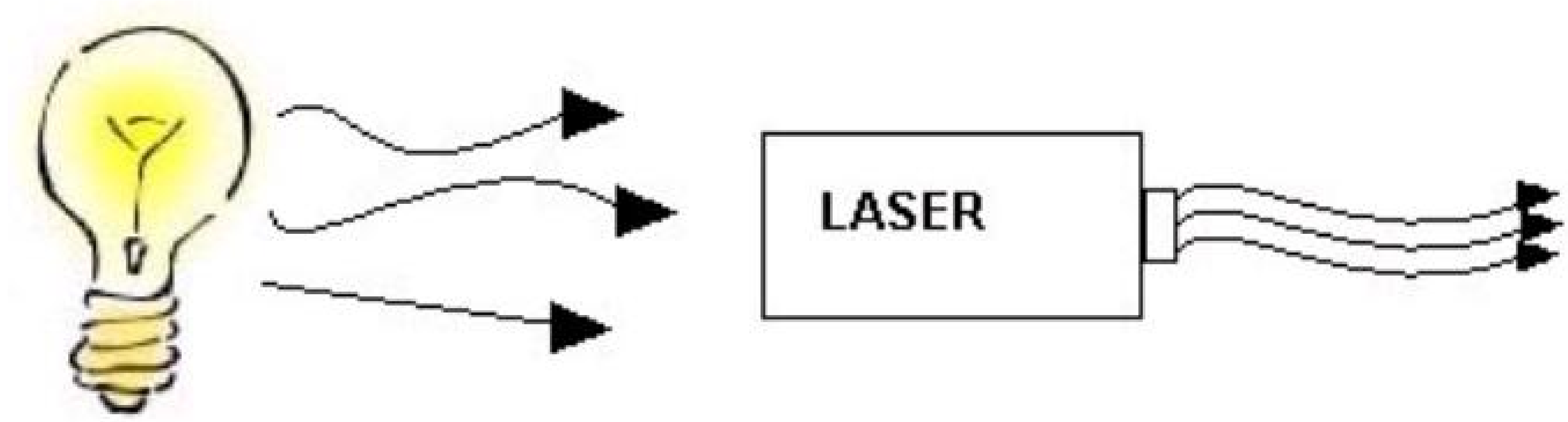
- The light emitted from a laser is **monochromatic**, that is, it is of one color/wavelength. In contrast, ordinary white light is a combination of many colors (or wavelengths) of light.

- Lasers emit light that is highly **directional**, that is, laser light is emitted as a relatively narrow beam in a specific direction. Ordinary light, such as from a light bulb, is emitted in many directions away from the source.

- The light from a laser is said to be **coherent**, which means that the wavelengths of the laser light are in phase in space and time. Ordinary light can be a mixture of many wavelengths.

These three properties of laser light are what can make it more hazardous than ordinary light. Laser light can deposit a lot of energy within a small area.

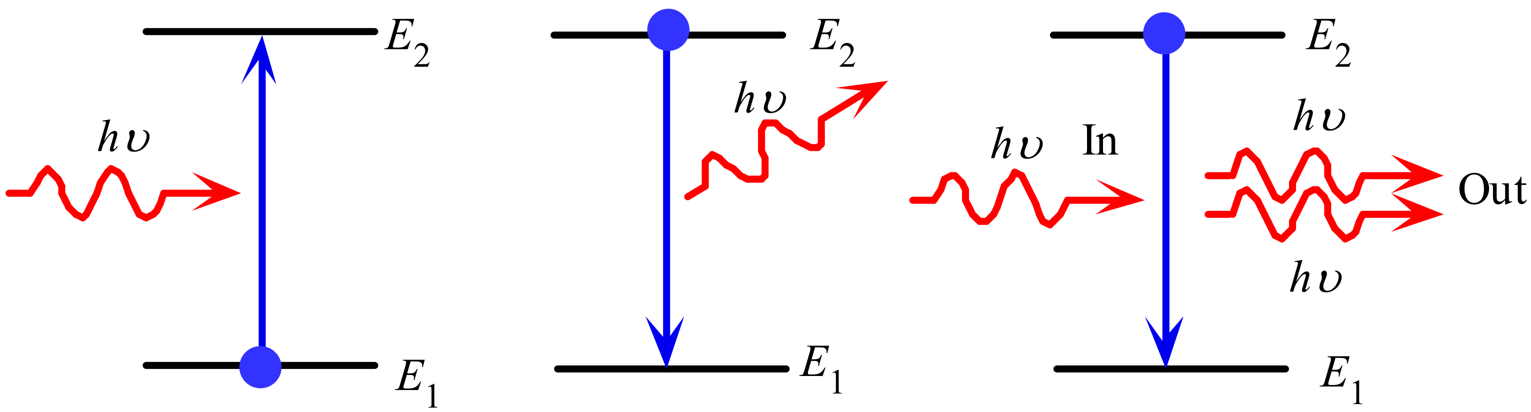
Incandescent vs. Laser Light



1. Many wavelengths
2. Multidirectional
3. Incoherent

1. Monochromatic
2. Directional
3. Coherent

Stimulated Emission

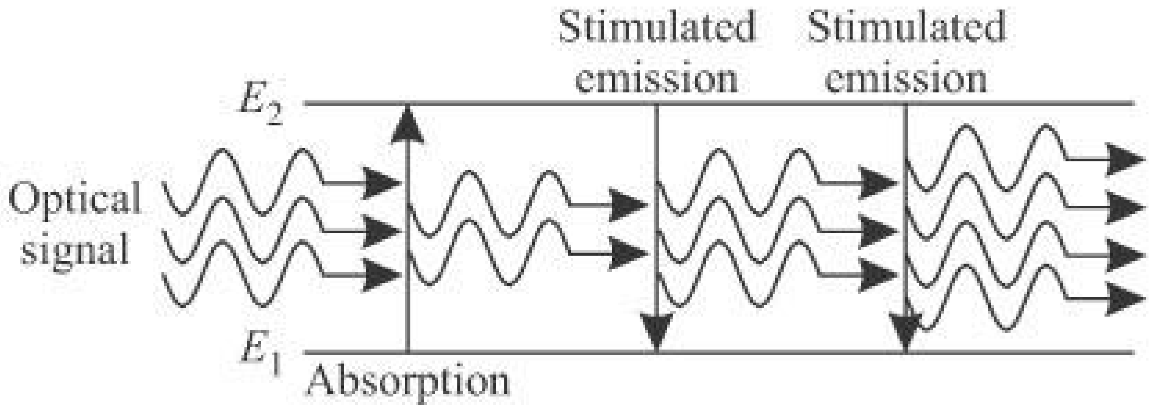


(a) Absorption (b) Spontaneous emission (c) Stimulated emission

- ❑In stimulated emission, an incoming photon with energy hυ stimulates the emission process by inducing electrons in E_2 to transit down to E_1.
- ❑While moving down to E_1, photon of the same energy hυ will be emitted
- ❑Resulting in 2 photons coming out of the system
- ❑Photons are amplified – one incoming photon resulting in two photons coming out.

Principles: Stimulated Emission

- Transitions between discrete energy levels of atoms accompanied by *absorption* or *emission* of photons
- $E_2 \rightarrow E_1$ can be stimulated by an optical signal
- Resulting photon has *same energy, direction of propagation, phase, and polarization* (*coherent!*)
- If stimulated emission dominates absorption, then we have amplification of signal
- Need to create a "*population inversion*" ($N_2 > N_1$) through a *pumping* process

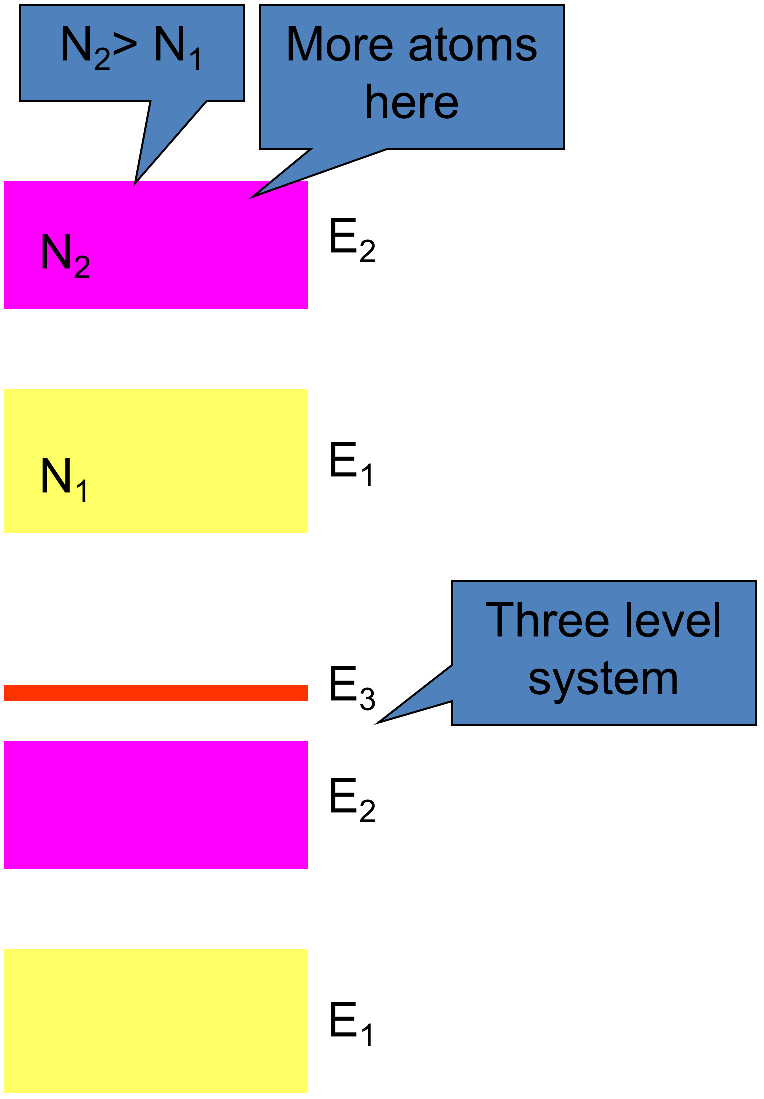


Spontaneous Emission

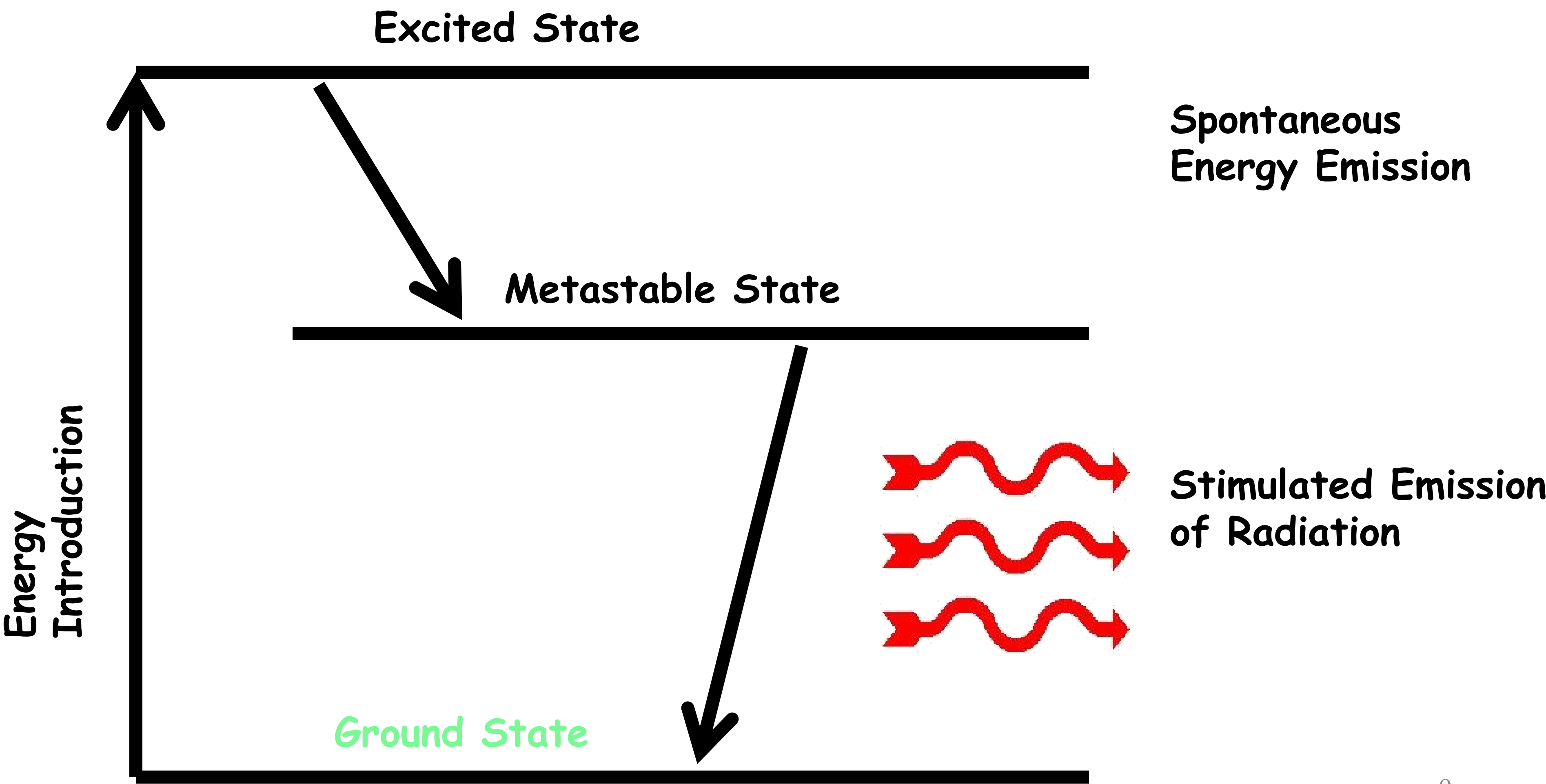
- $E_2 \rightarrow E_1$ transitions can be spontaneous (I.e. *independent* of external radiation)
  - The photons are emitted in random directions, polarizations and phase (I.e. incoherent)!
- *Spontaneous emission rate* is a characteristic of the system
  - Amplification of such incoherent radiation happens along with that of incident radiation
  - The amplified spontaneous emission (ASE): appears as noise
  - ASE could saturate the amplifier in certain cases!

Population Inversion

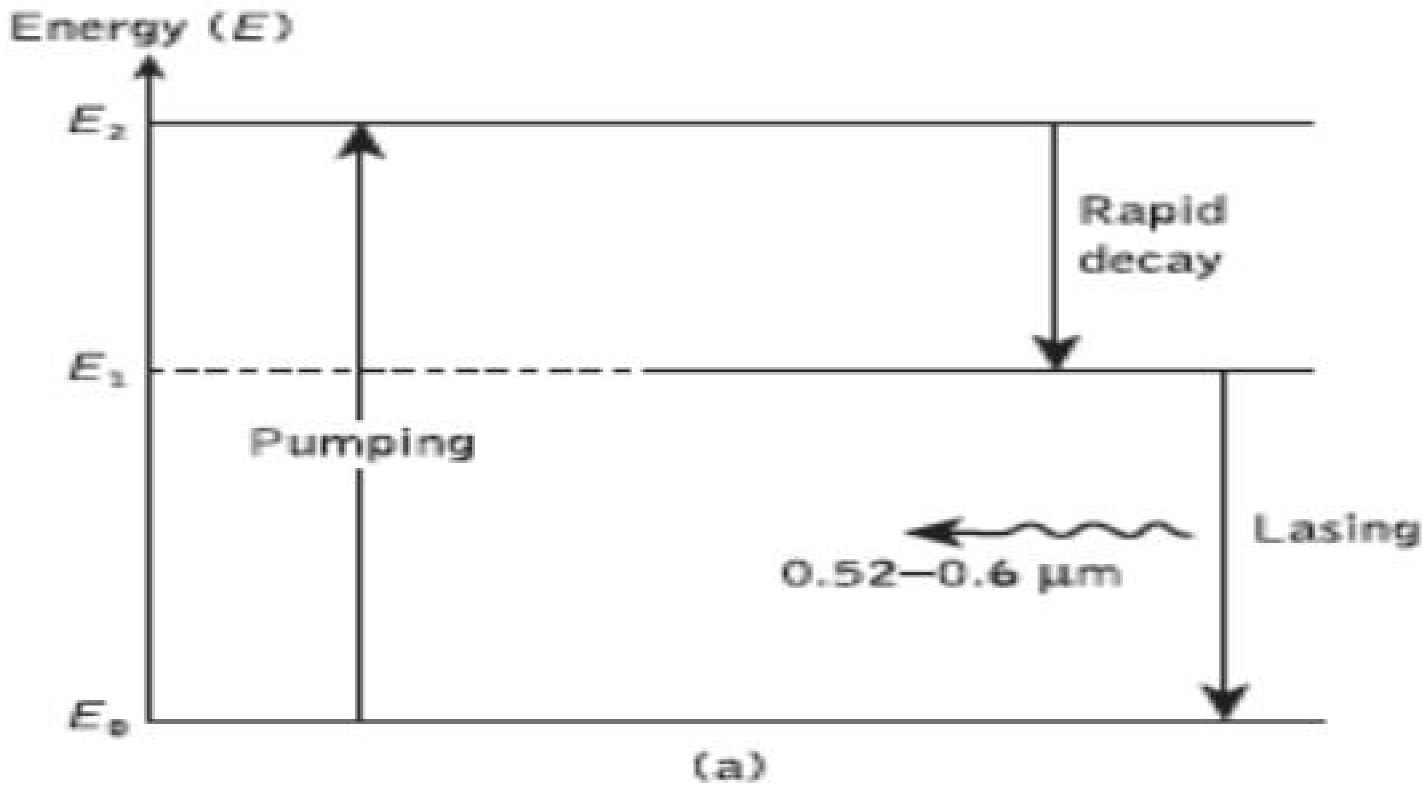
- ✓ Non equilibrium distribution of atoms among the various energy level atomic system
- ✓ To induce more atoms in E_2, i.e. to **<u>create population inversion</u>**, a large amount of energy is required to excite atoms to E_2
- ✓ The excitation process of atoms so $N_2 > N_1$ is called **<u>pumping</u>**
- ✓ It is difficult to attain pumping when using two-level-system.
- ✓ Require 3-level system instead



Lasing Action Diagram

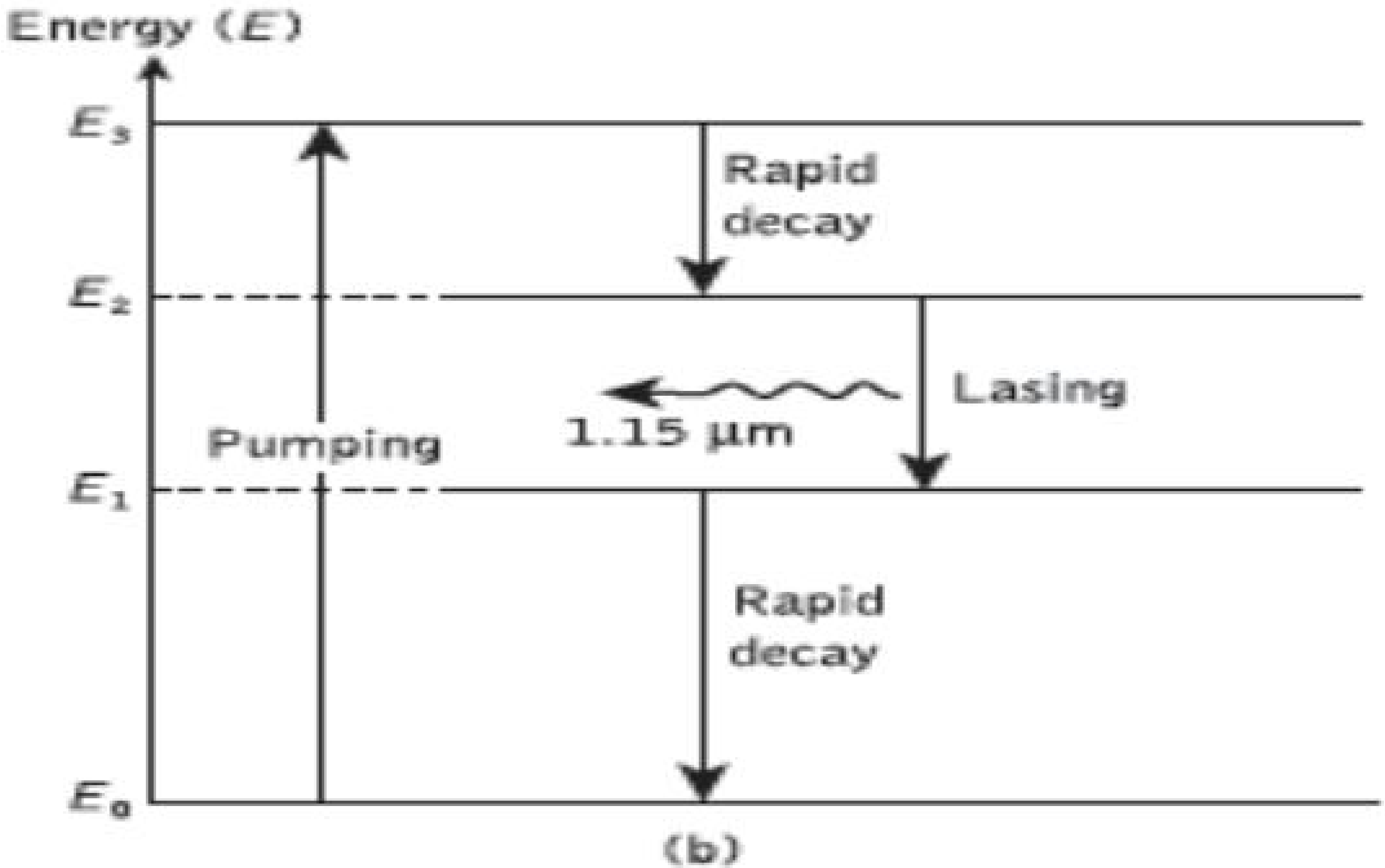


3-level pumping



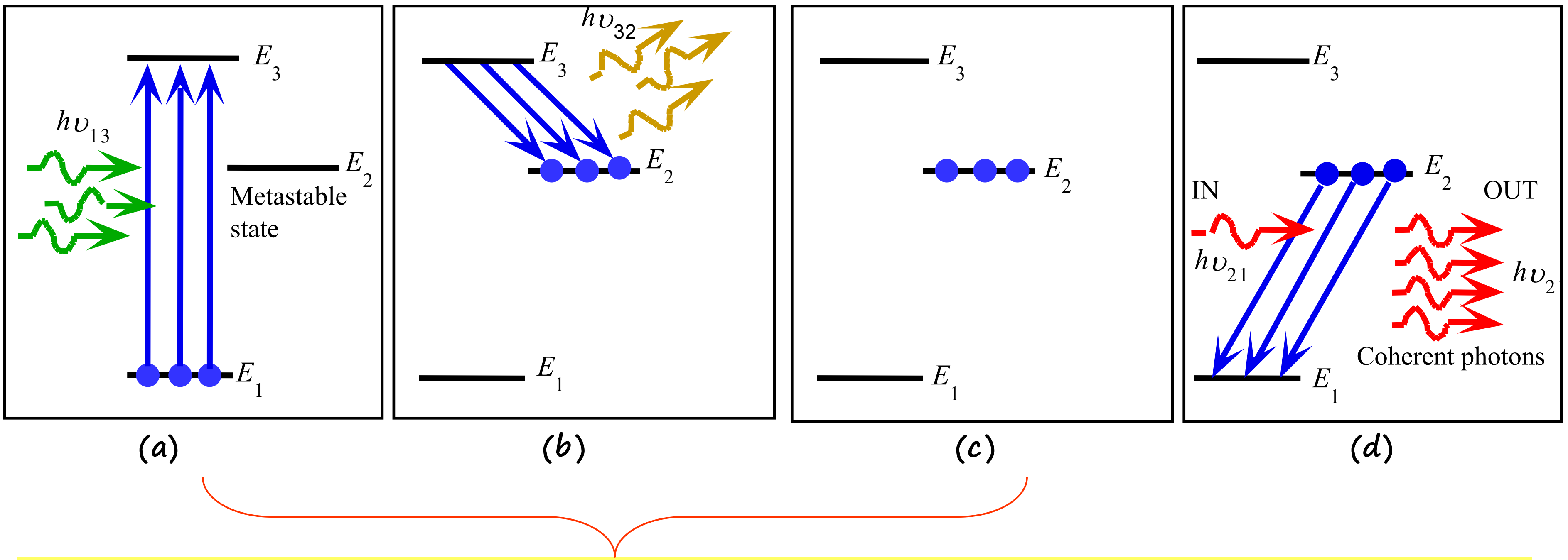
(a) Three-level system -ruby(crystal) Laser

4-level pumping



(b) Four-level system -He-Ne(gas) Laser

Principles of Laser



- In actual case, excite atoms from E_1 to E_3.
- Exciting atoms from E_1 to E_3 → optical pumping
- Atoms from E_3 decays rapidly to E_2 emitting $h\upsilon_3$
- If E_2 is a **long lived state**, atoms from E_2 will not decay to E_1 rapidly
- Condition where there are a lot of atoms in E_2 →population inversion achieved! i.e. between E_2 and E_1.

Coherent Photons Production (explanation of (d))

- When one atom in E_2 decays spontaneously, a random photon resulted which will induce stimulated photon from the neighbouring atoms

- The photons from the neighbouring atoms will stimulate their neighbours and form avalanche of photons.

- Large collection of coherent photons resulted.

Optical feedback and oscillation

✓Light amplification in the laser occurs when a photon colliding with an atom in the excited energy state causes the stimulated emission of a second photon and then both these photons release two more.

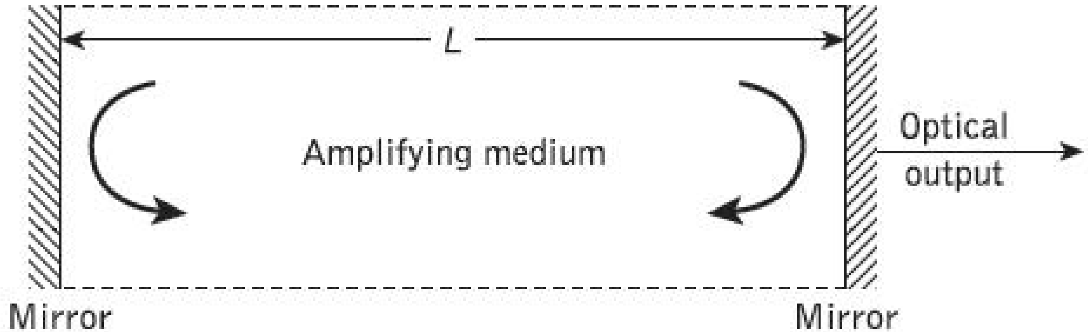
✓Continuation of this process effectively creates avalanche multiplication, and when the electromagnetic waves associated with these photons are in phase, amplified coherent emission is obtained.

Optical feedback and oscillation

✓To achieve this laser action it is necessary to contain photons within the laser medium and maintain the conditions for coherence.

✓This is accomplished by placing or forming mirrors (plane or curved) at either end of the amplifying medium.

✓The optical cavity formed is more analogous to an oscillator than an amplifier as it provides positive feedback of the photons by reflection at the mirrors at either end of the cavity.



The basic laser structure incorporating plane mirrors

Optical feedback and oscillation

✓Hence the optical signal is fed back many times while receiving amplification as it passes through the medium.

✓ The structure therefore acts as a Fabry–Pérot resonator.

✓ Although the amplification of the signal from a single pass through the medium is quite small, after multiple passes the net gain can be large.

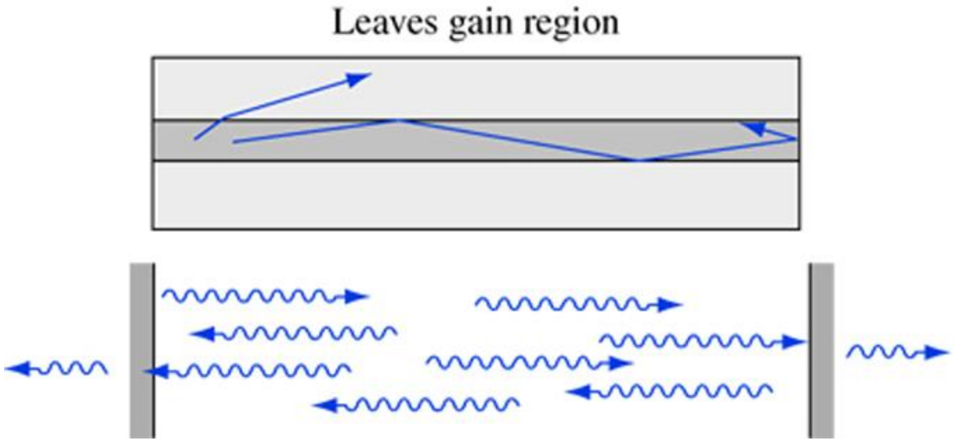
✓Furthermore, if one mirror is made partially transmitting, useful radiation may escape from the cavity.

For Successful Lasing Action:

1. Optical Gain (not absorb)
   - Achieved by population inversion

2. Optical Feedback
   - Achieved by device configuration
   - Needed to increase the total optical amplification by making photons pass through the gain region multiple times
   - Insert 2 mirrors at each end of laser
   - This is termed as an oscillator cavity or Fabry Perot cavity
   - Mirrors are partly transmitted and party reflected

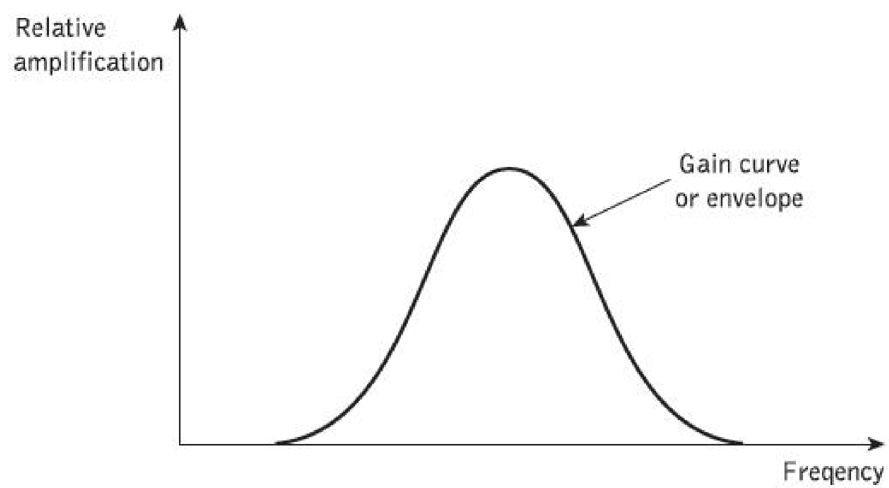
Reflection of Photons Back and Forth, Higher Gain



Fabry-Parrot Cavity

Laser Diode (optical cavity)

- Oscillations occur in the laser cavity over a small range of frequencies where the cavity gain is sufficient to overcome the losses.
- Other oscillation frequencies within the spectral band result from frequency variations due to thermal motion of atoms and atomic collisions.
- Hence amplification within the laser medium results in a broadened gain curve over a finite spectral width.



The relative amplification in the laser amplifying medium showing the broadened laser transition line or gain curve

Laser Diode (optical cavity)

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

$$L = q \times \frac{\lambda}{2n} \quad where: q \text{ is an integer}$$

n is the refractive index of the amplifying medium

λ is the emission wavelength

Laser Diode (optical cavity)

- The emission frequencies f is defined by,

- When L is along the long $f = \frac{qc}{2nL}$ is of the structure, the frequencies are known as longitudina odes.

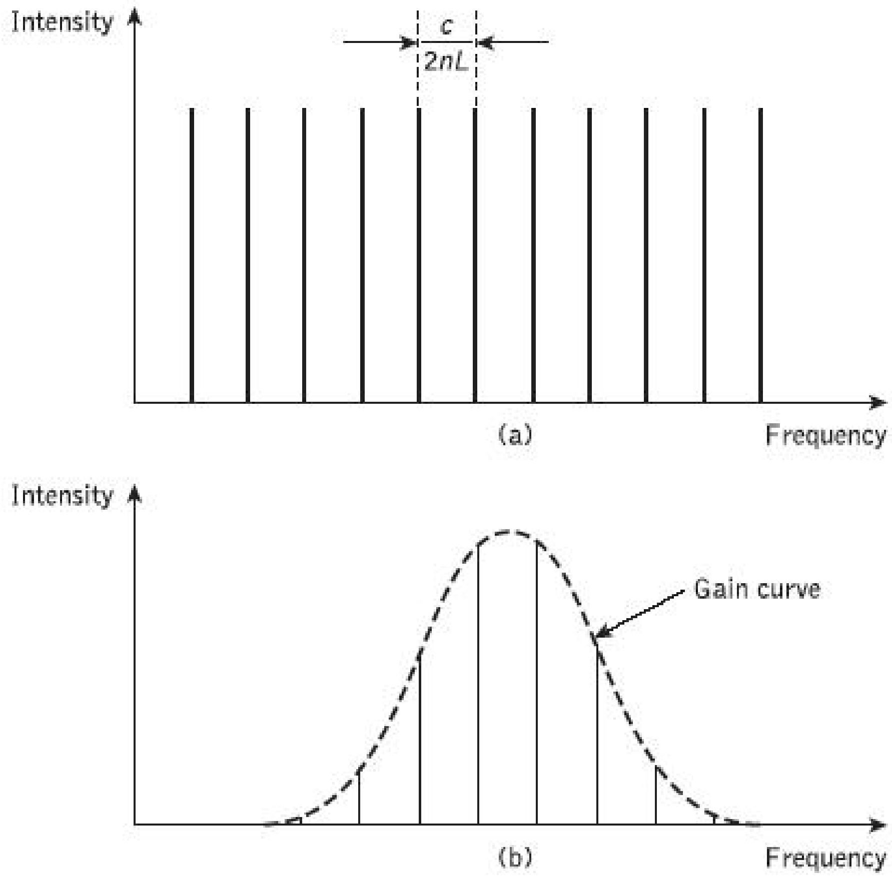
- A longitudinal mode of a beam of EM radiation is a particular field pattern measured in the plane of propagation direction of the beam.

- These modes are separated by a frequency interval $\delta f = \frac{c}{2nL}$

- This can be related to the wavelength spacing through the relationship

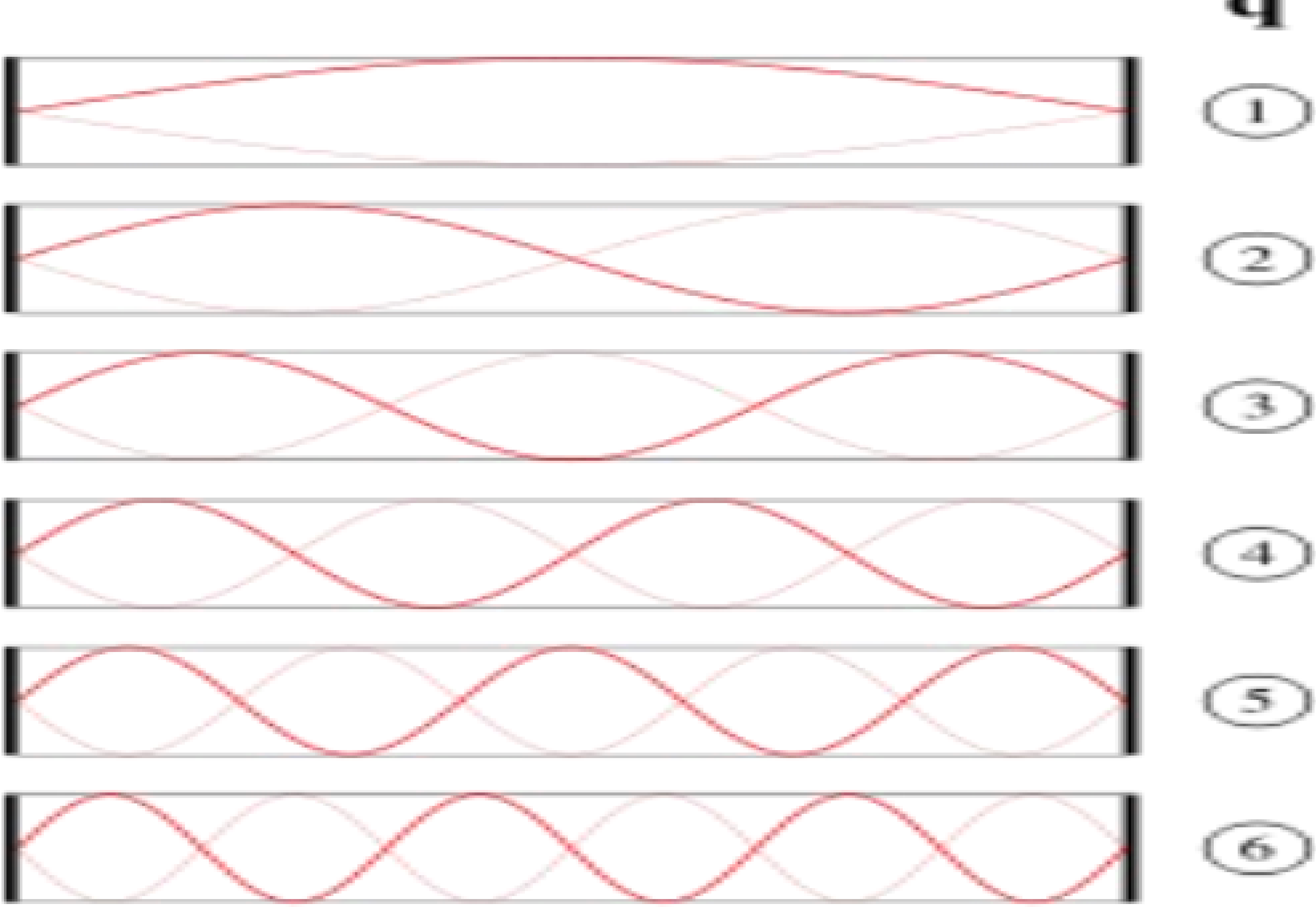
$$\Delta\lambda = \frac{\lambda^2}{2Ln}$$

- The laser emission will only include the longitudinal modes contained within the spectral width of the gain curve.

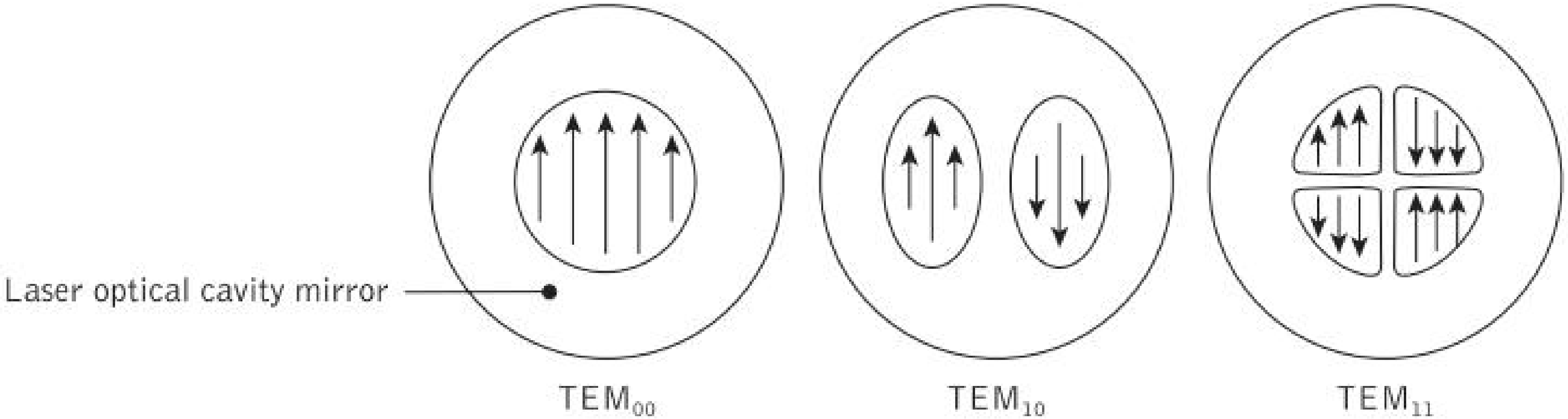


(a) The modes in the laser cavity. (b) The longitudinal modes in the laser output

The first six longitudinal modes of a plane-parallel cavity.



The lower order transverse modes of a laser



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.

The number of longitudinal modes supported within the structure may be obtained from

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

The frequency separation of the modes is

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

Threshold condition for Laser Oscillation

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Threshold condition for Laser Oscillation

1. **The steady state condition for laser oscillation is**
   - Achieved when gain in the amplifying medium exactly balances the total losses.(by population inversion)

2. **For initiated and sustained laser oscillations**
   - A minimum or threshold gain within the amplifying medium must be attained.
   - This threshold gain may be determined by considering the energy of a light beam as it passes through.

Threshold condition for Laser Oscillation

All the losses except due to transmission through the mirrors may be included in the single loss coefficient per unit length

$\bar{\alpha}\ \text{cm}^{-1}$

$$\text{Fractional loss} = r_1 r_2 \exp(-2\bar{\alpha}L)$$

r1 and r2 → reflectivities of the two mirrors
L → Length of the amplifying medium

$$\text{Fractional gain} = \exp(2\bar{g}L)$$

$\bar{g}\ \text{cm}^{-1}$ →gain coefficient per unit length produced by stimulated emission

Hence

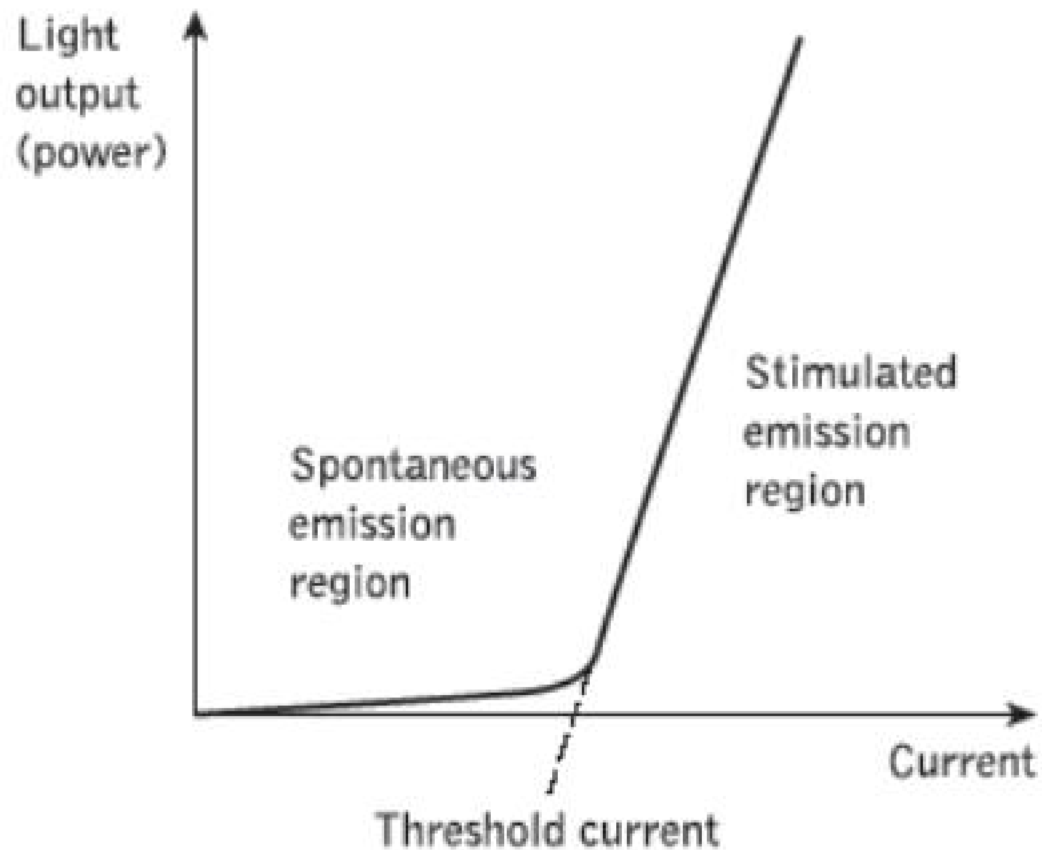
$$\exp(2\bar{g}L) \times r_1 r_2 \exp(-2\bar{\alpha}L) = 1$$

$$r_1 r_2 \exp[2(\bar{g} - \bar{\alpha})L] = 1$$

The threshold gain per unit length is obtained by rearranging the above expression

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

Second term represents transmission loss through the mirrors



The ideal light output against current characteristic for an injection laser

The threshold current density for stimulated emission is related to the threshold gain coefficient for the laser cavity as

$$\bar{g}_{th} = \bar{\beta} J_{th}$$

where the gain factor $\bar{\beta}$ is a constant appropriate to specific devices.

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

The mirror reflectivities **r1** and **r2** may be calculated using Fresnel reflection relationship.

The threshold current I_{th} is given by:

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

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

The threshold gain per unit length where r1 = r2 = r is given by

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

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

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

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.

The reflectivity for normal incidence of a plane wave on the GaAs–air interface may be obtained from

$$r_1 = r_2 = r = \left(\frac{n-1}{n+1}\right)^2 \quad = \left(\frac{3.6-1}{3.6+1}\right)^2 \simeq 0.32$$

The threshold current density may be obtained from

$$J_{\text{th}} = \frac{1}{\bar{\beta}}\left[\bar{\alpha} + \frac{1}{L}\ln\frac{1}{r}\right] \quad = \frac{1}{21 \times 10^{-3}}\left[10 + \frac{1}{250 \times 10^{-4}}\ln\frac{1}{0.32}\right] \quad = 2.65 \times 10^3 \text{ A cm}^{-2}$$

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.

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.

Efficiency

- **Differential Quantum efficiency** η_D - Ratio of increase in the photon output rate for a given increase in the number of injected electrons.

$$\eta_D = \frac{dP_e/hf}{dI/e} \simeq \frac{dP_e}{dI(E_g)}$$

$P_e \rightarrow$ optical power emitted from the device
$I \rightarrow$ current, $e \rightarrow$ charge on the electron
$hf \rightarrow$ photon energy
$E_g \rightarrow$ bandgap energy expressed in eV.

- For CW semiconductor laser usually has values in the range 40 to 60 %.
- **Internal Quantum efficiency** η_i

$$\eta_i = \frac{\text{number of photons produced in the laser cavity}}{\text{number of injected electrons}}$$

- Ranges between 50 to 100%.

$$\eta_D = \eta_i \left[\frac{1}{1 + (2\bar{\alpha}L/\ln(1/r_1 r_2))} \right]$$

Efficiency

- **Total efficiency η_T**

$$\eta_T = \frac{\text{total number of output photons}}{\text{total number of injected electrons}}$$

$$= \frac{P_e/hf}{I/e} \simeq \frac{P_e}{IE_g}$$

$$\eta_T \simeq \eta_D \left(1 - \frac{I_{th}}{I}\right)$$

The external power efficiency of the device (or device efficiency) η_{ep} in converting electrical input to optical output is given by:

$$\eta_{ep} = \frac{P_e}{P} \times 100 = \frac{P_e}{IV} \times 100\%$$

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

External Quantum Efficiency

- The external differential quantum efficiency

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

η_i is the internal quantum efficiency, $\eta_i = 0.6 – 0.7$ at room temperature

Problem

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:

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

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

Photo detectors

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Optical Receivers

- Optical receivers convert optical signal (light) to electrical signal (current/voltage)
  - Hence referred 'O/E Converter'
- Photodetector is the fundamental element of optical receiver, followed by amplifiers and signal conditioning circuitry
- There are several photodetector types:
  - Photodiodes, Phototransistors, Photon multipliers, Photo-resistors etc.

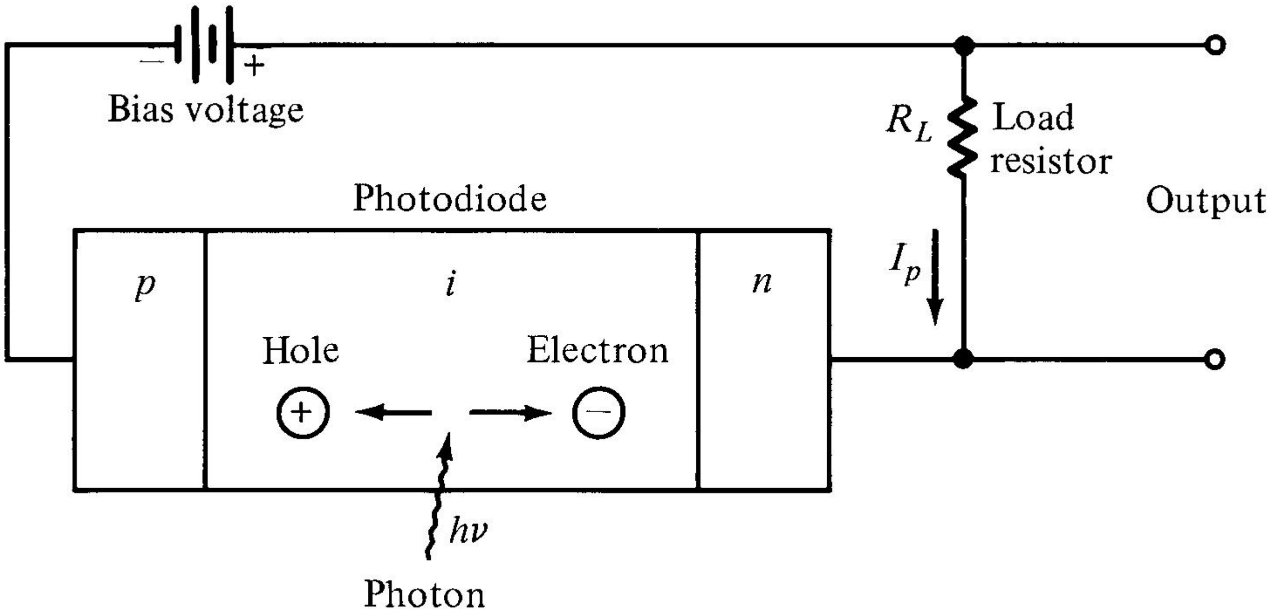
Photodetector Requirements

- High sensitivity (responsivity) at the desired wavelength and low responsivity elsewhere → high wavelength selectivity
- Low noise and reasonable cost
- Fast response time → high bandwidth
- Insensitive to temperature variations
- Compatible physical dimensions
- Long operating life

Photodiodes

- Due to above requirements, only *photodiodes* are used as photo detectors in optical communication systems
- Positive-Intrinsic-Negative (*pin*) photodiode
  - No internal gain
- Avalanche Photo Diode (*APD*)
  - An internal gain of *M* due to self multiplication
- Photodiodes are *reverse biased* for normal operation

Basic *pin* photodiode circuit

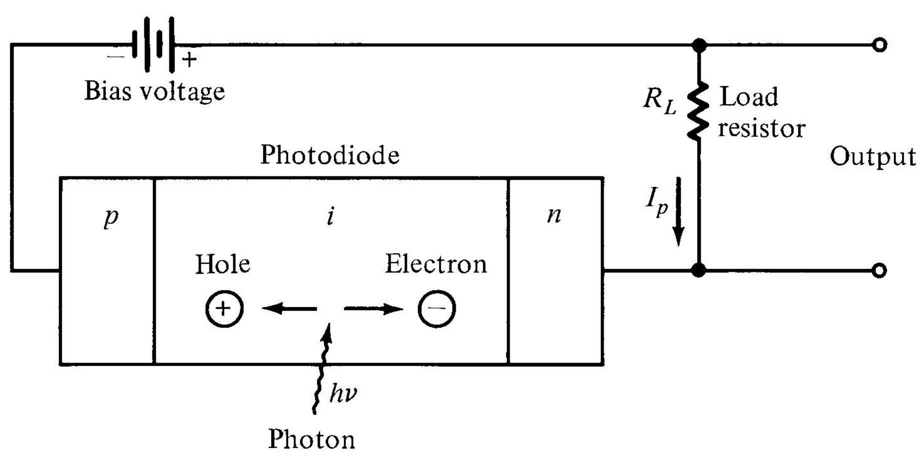


- Incident photons trigger a *photocurrent* I_p in the external circuitry by pumping energy

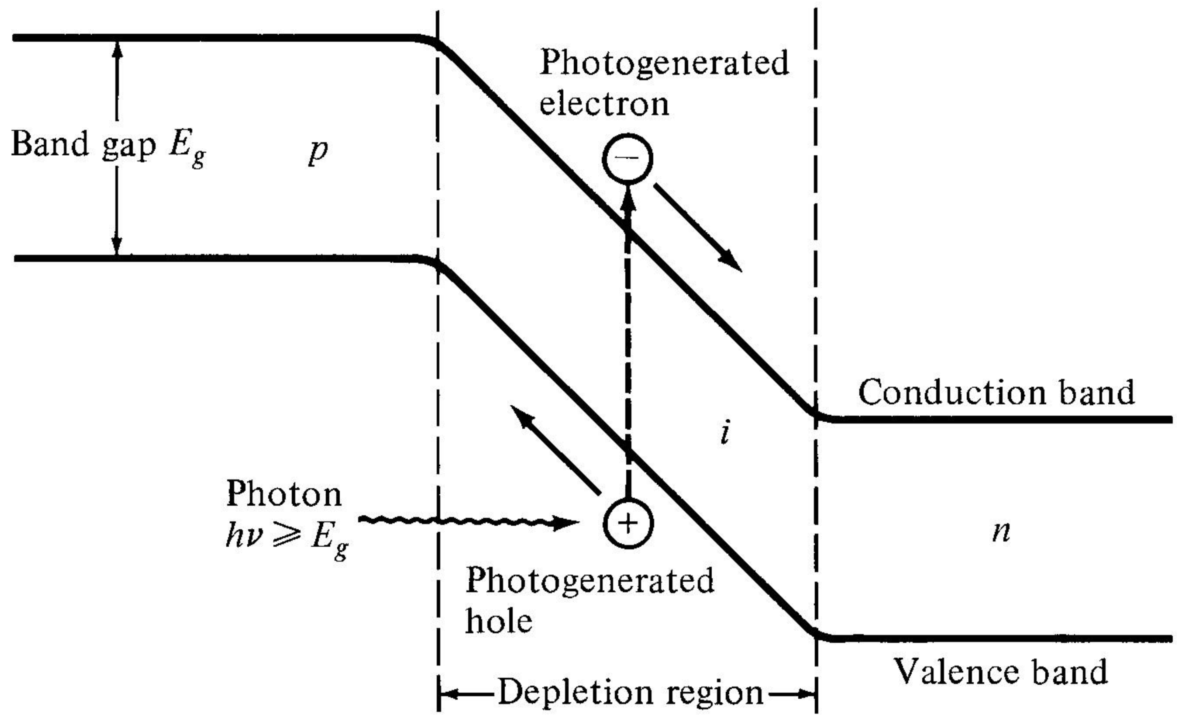
Photocurrent ∝ Incident Optical Power

PIN Photodiode

- It is a junction diode in which an undoped intrinsic (*i*) region is inserted between relatively thin p region and relatively thick n region.
- Diode is reverse biased so that the entire i- region is depleted and has a strong electric field.
- Light absorbed in intrinsic region produce free electron hole pairs, provided that photon energy is high enough.
- These carriers which are responsible for photocurrent are swept across the region with high velocity and are collected across the reverse –biased junction.
- This gives rise to a current flow in the external circuit called the photocurrent.



pin energy-band diagram



$$\lambda_c = \frac{hc}{E_g}$$

A particular semiconductor material can be used only over a limited wavelength range

pin energy-band diagram

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

Cut off wavelength depends on the bandgap energy

Cut off wavelength for Si is about 1.06 µm and for Ge it is 1.6 µm. For longer wavelengths the photon energy is not sufficient to excite an electron from the valence band to the conduction band.

Materials of construction

- The material used to make a photodiode is critical to defining its properties, because only **photons** with sufficient energy to excite **electrons** across the material's **bandgap** will produce significant photocurrents.
- Materials commonly used to produce photodiodes include:

Material	Wavelength range (nm) (for good sensitivity)
Silicon	190–1100
Germanium	400–1700
Indium gallium arsenide	800–2600
InGaAsP	<1000-3500

Quantum Efficiency(η)

Quantum Efficiency (η) = number of e-h pairs generated / number of incident photons

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

Ip→ average photocurrent produced by a steady-state average optical power Po incident on the photodetector

q →is the charge of the electron

hv→ photon energy

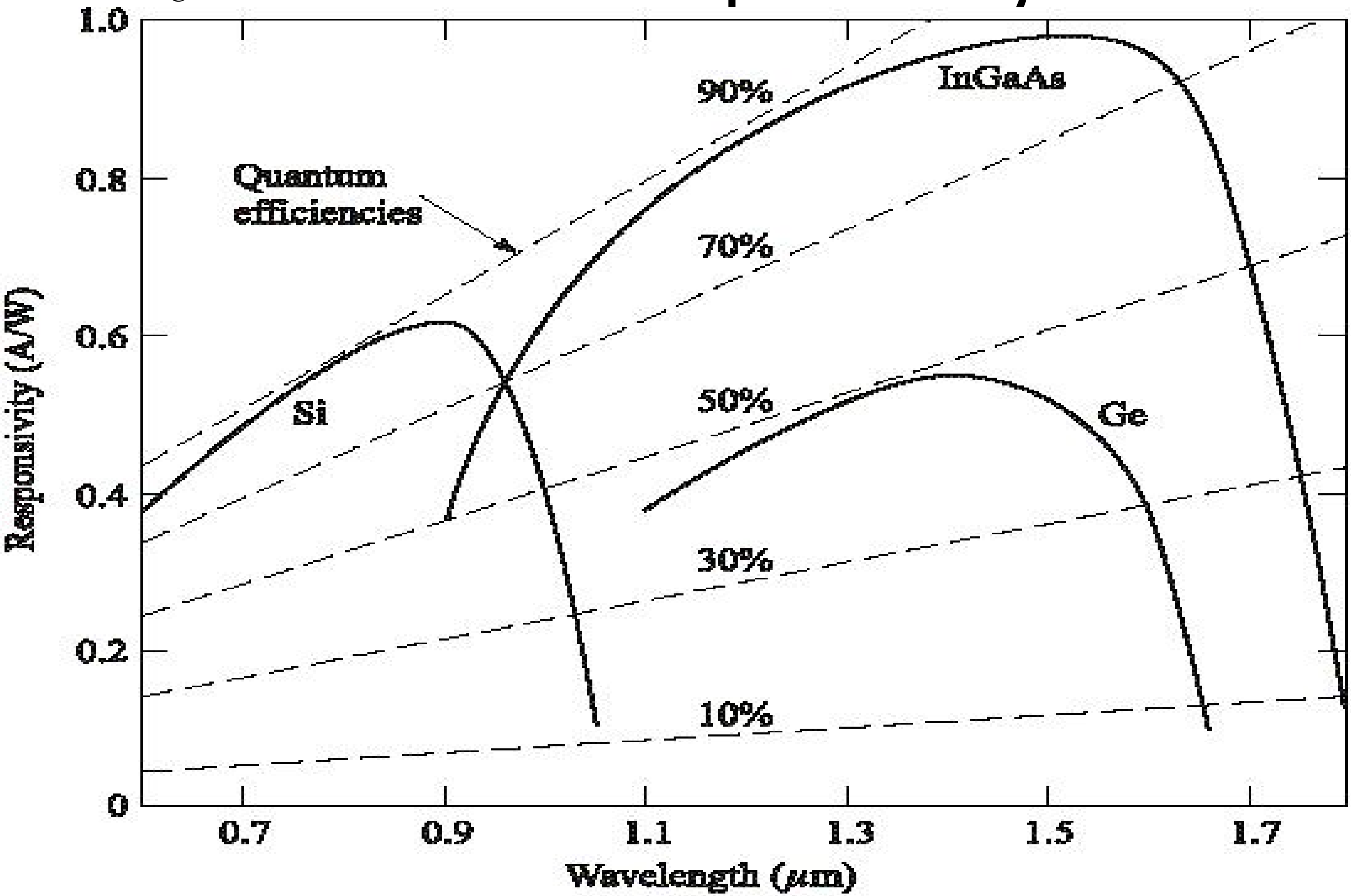
Responsivity ($\Re$)

***Responsivity is the ratio of photocu*rrent to the incident optical power on the photodetector.**

$$\Re = \frac{I_p}{P_0} = \frac{\eta q}{h\nu} \quad \text{mA/mW}$$

$$\lambda_c = \frac{hc}{E_g}$$

Responsivity



- In a 100ns pulse, 6*10^6 photons at a wavelength 1300 nm absorbed by a InGaAs photodetector. On the average 3.9*10^6 electron hole pairs are generated. Calculate the quantum efficiency

- Quantum Efficiency (η) = number of e-h pairs generated / number of incident photons

$$\eta = 0.65 = 65\%$$

Photons of energy 1.53*10^-19 J are incident on a photodiode which has a responsivity of 0.65 A/W. If the optical power level is 10 μW, calculate the generated photocurrent.

$$I_p = RP_0$$

$$= 6.5 \mu A$$

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 diode. Determine the quantum efficiency and responsivity of the photodiode at 0.85 μm.

$$\eta = 0.4 = 40\%$$

$$\Re = \frac{I_p}{P_0} = \frac{\eta q}{h\nu} = \frac{0.4 \times 1.602 \times 10^{-19} \times 0.85 \times 10^{-6}}{6.626 \times 10^{-34} \times 2.998 \times 10^{8}}$$

$$= 0.274 A/W$$

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.

the photon energy $E = hf = hc/\lambda$.

$$\lambda = \frac{hc}{E} = \frac{6.626 \times 10^{-34} \times 2.998 \times 10^{8}}{1.5 \times 10^{-19}} = 1.32\ \mu\text{m}$$

$$\text{Responsivity } R = \frac{\eta e}{hf} = \frac{0.65 \times 1.602 \times 10^{-19}}{1.5 \times 10^{-19}} = 0.694\ \text{A W}^{-1}$$

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

Avalanche Photodiode

Avalanche Photodiode

- More sophisticated structure than the PIN photodiode in order to create an extremely high electric field region($3*10^5$ V/cm).
- Internally multiplies the primary signal photocurrent.

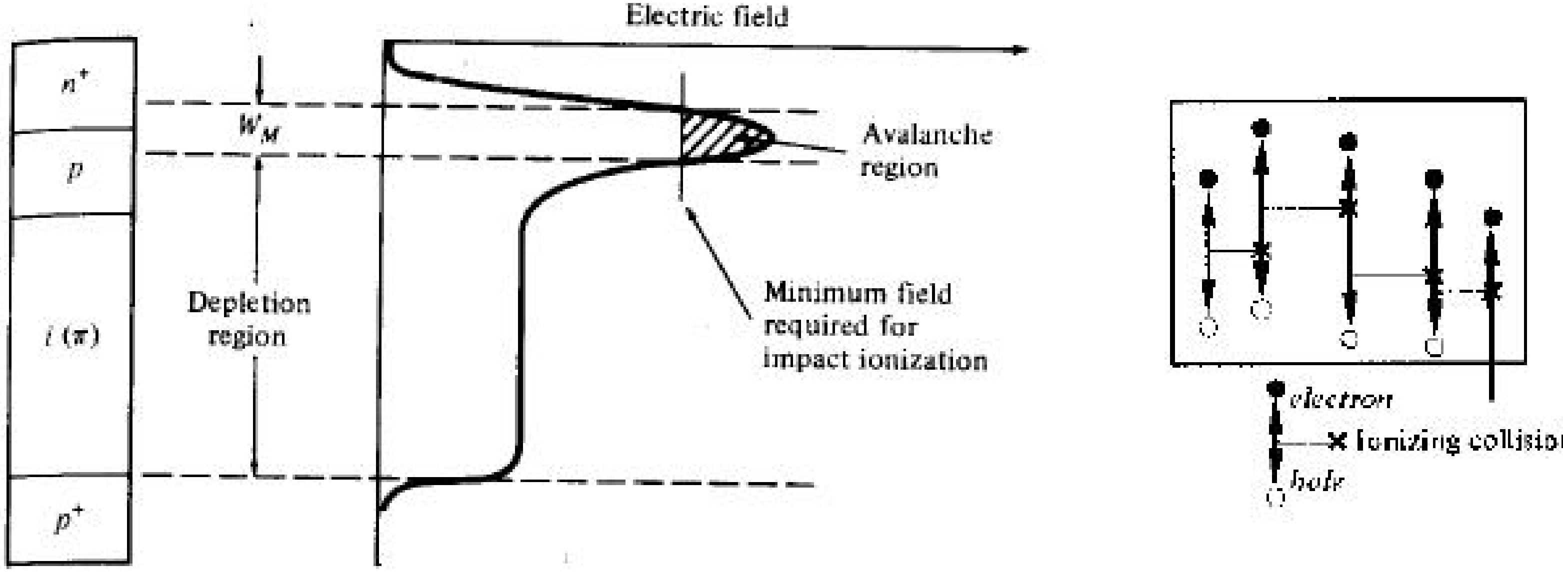
Impact Ionization

- The photo generated carriers must traverse a region where a very high electric field is present.
- In this region, a photogenerated hole or electron can gain enough energy to excite new-electron hole pairs.

Avalanche Effect

- The newly created carriers are also accelerated by the high electric field, thus gaining enough energy to cause further impact ionization.
- This phenomenon is the **avalanche effect**.
- Often requires high reverse bias voltages(50 to 400 V) in order that the new carriers created can themselves produce additional carriers.

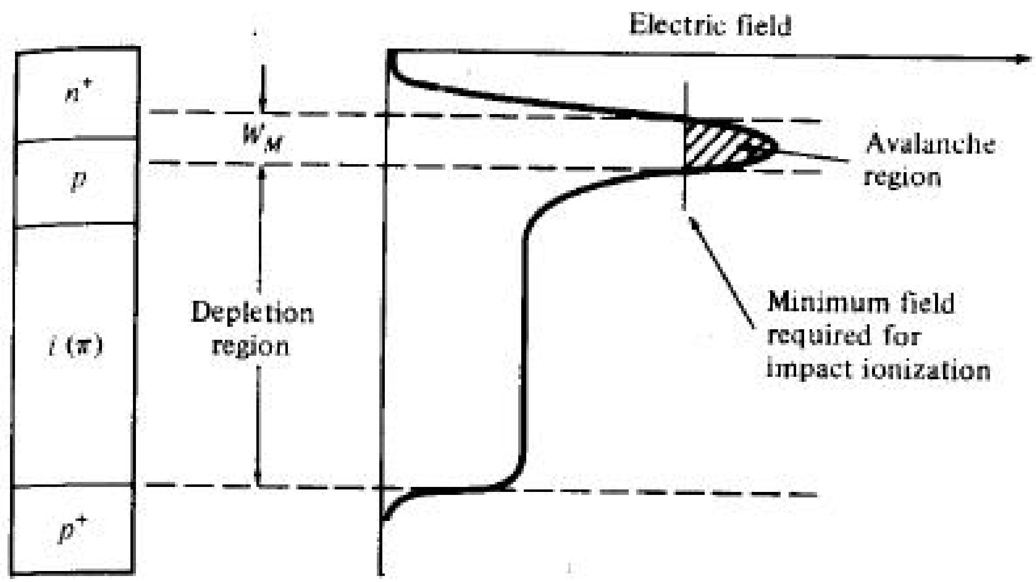
Reach Through Avalanche Photodiode



Reach-through avalanche photodiode structure and the electric fields in the depletion and multiplication regions.

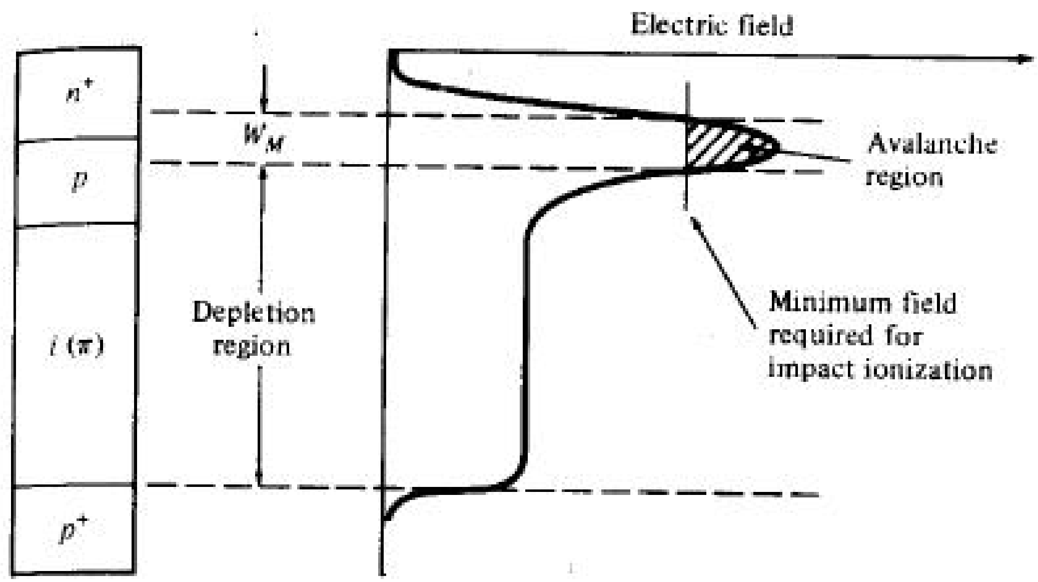
Reach Through Avalanche Photodiode(RAPD)

- Commonly used structure for achieving carrier multiplication with very little excess noise.
- RAPD is composed of a high-resistivity p-type material deposited as an epitaxial layer on a p^+substrate followed by the construction of an n^+ layer.
- The configuration is referred to as **$p^+\pi pn^+$** reach-through structure.
- The π layer is the intrinsic layer with p doping.



Reach Through Avalanche Photodiode(RAPD)

- When a low reverse-bias voltage is applied, most of the potential drop is across the pn+ junction.
- The depletion layer widens with increasing bias until a certain voltage is reached.
- At this voltage the peak electric field at the pn+ junction is about 5-10 percent below that needed to cause avalanche breakdown.
- At this point , the depletion layer just “reaches through” to the nearly intrinsic π region.



Reach Through Avalanche Photodiode(RAPD)

- Light enters the device through the p+ region and is absorbed in the π material.
- After being absorbed, the photon gives up its energy, thereby creating-electron-hole pairs.
- The photogenerated electrons drift through the π region in the pn+ region, where a high electric field exists where carrier multiplication takes place.

Ionization Rate

Average number of electron-hole pairs created by a carrier per unit distance travelled.

Electron ionization rate= α

Hole ionization rate= β

Ratio K= α/β ***is a measure of the photodetector performance.***

Reach Through Avalanche Photodiode(RAPD)

Avalanche PD's have an internal gain *M*

$$\boxed{M = \frac{I_M}{I_p}}$$

I_M: average value of the total multiplied current
I_p: primary unmultiplied photocurrent
M = 1 for *PIN* diodes

The responsivity of the Avalanche PD's is given by

$$\boxed{\Re_{APD} = \Re_{PIN} M}$$

Benefits and Drawbacks of avalanche photodiode's

Benefits

- Detection of very low light levels often encountered in optical fiber communications.
- Provide an increase in sensitivity between 5 and 15 dB over PIN photodiodes.
- Wider dynamic range.

Drawbacks

- Fabrication difficulties due to their more complex structure and hence increased cost.
- Random nature of the gain mechanism which gives an additional noise contribution.
- Often high bias voltages requires which are wavelength dependant.
- Temperature compensation is necessary to stabilize the operation of the device.

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.

$$R = \frac{\eta e \lambda}{hc} \qquad = \frac{0.8 \times 1.602 \times 10^{-19} \times 0.9 \times 10^{-6}}{6.626 \times 10^{-34} \times 2.998 \times 10^{8}} \qquad = 0.581 \text{ A W}^{-1}$$

$$I_p = P_o R \qquad \begin{aligned} &= 0.5 \times 10^{-6} \times 0.581 \\ &= 0.291 \ \mu\text{A} \end{aligned}$$

$$M = \frac{I}{I_p} \qquad \begin{aligned} &= \frac{11 \times 10^{-6}}{0.291 \times 10^{-6}} \\ &= 37.8 \end{aligned}$$

A silicon APD has a quantum efficiency of 65 % at a wavelength of 900 nm. Suppose 0.5 µW of optical power produces a multiplied photocurrent of 10 µA.

Find the multiplication factor M.

$$I_p = RP_0 = \frac{\eta q}{h\nu} P_0 = 0.235 \mu A$$

$$M = \frac{I_M}{I_P} = 43$$

Signal to Noise Ratio

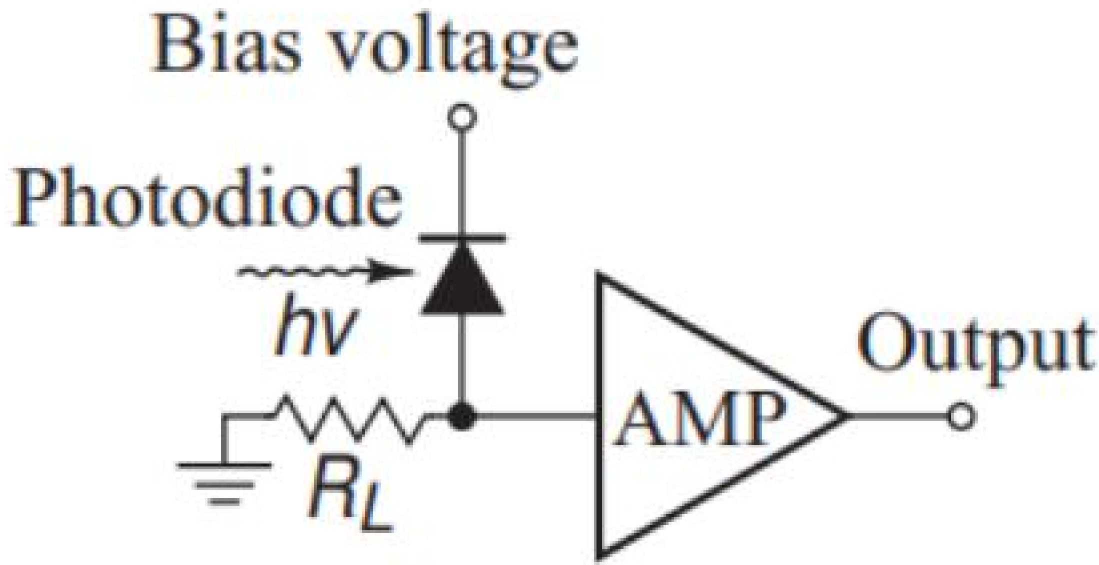
$$SNR = \frac{\text{Signal power from photocurrent}}{\text{Detector Noise + Amplifier Noise}}$$

For high SNR

- The Photodetector must have a large quantum efficiency (large responsivity or gain) to generate large signal power
- Detector and amplifier noise must be low

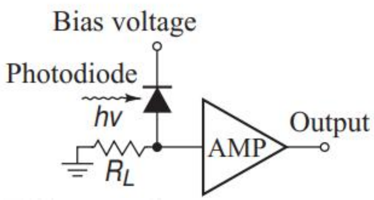
SNR Can NOT be improved by amplification

Simple model of a photodetector receiver



Detector Current

If a modulated signal of optical power $P(t)$ falls on the detector, the primary photocurrent $i_{ph}(t)$ generated is



$$i_{ph}(t) = \frac{\eta q}{h\nu} P(t)$$

The primary current consists of a dc value I_p, which is the average photocurrent due to the signal power, and a signal component $i_p(t)$.

For *pin* photodiodes the mean-square signal current $\left\langle i_s^2 \right\rangle$ is

$$\left\langle i_s^2 \right\rangle = \sigma_{s,\ pin}^2 = \left\langle i_p^2(t) \right\rangle$$

where σ is the variance. For avalanche photodetectors,

$$\left\langle i_s^2 \right\rangle = \sigma_{s,\ \mathrm{APD}}^2 = \left\langle i_p^2(t) \right\rangle M^2$$

where M is the average of the statistically varying avalanche gain

Quantum (Shot Noise)

The quantum or shot noise arises from the statistical nature of the production and collection of photoelectrons when an optical signal is incident on a photodetector

$$\left\langle i_{\text{shot}}^2 \right\rangle = \sigma_{\text{shot}}^2 = 2qI_p B_e M^2 F(M)$$

F(M): **APD Noise Figure**

F(M) ~= M^x ($0 \leq x \leq 1$) **depends on the material**

For PIN diodes *F(M) and M* are unity.

I_p: Mean Detected Current

B_e = Bandwidth

Dark/Leakage Current Noise

There will be some (dark and leakage) current without any incident light. This current generates two types of noise

Bulk Dark Current Noise
(Due to electrons and holes thermally generated)

$$\left\langle i_{DB}^{2} \right\rangle = \sigma_{DB}^{2} = 2qI_{D} M^{2} F(M) B_{e}$$

I_D: Dark Current

Surface Leakage Current Noise
(Due to surface defects , bias voltage , cleanliness and surface area.)

$$\left\langle i_{DS}^{2} \right\rangle = \sigma_{DS}^{2} = 2qI_{L} B_{e}$$

(not multiplied by M)

I_L: Leakage Current

Thermal Noise

The photodetector load resistor R_L contributes a mean-square thermal (Johnson) noise current

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

K_B: Boltzmann's constant = 1.38054 X 10$^{(-23)}$ J/K
T is the absolute Temperature

- **Quantum and Thermal are the important noise mechanisms in all optical receivers**
- **RIN (Relative Intensity Noise) will also appear in analog links**

An InGaAs pin photodiode has the following parameters at a wave length of 1300 nm: I_D = 4 nA, η = 0.90, R_L = 1000 Ω, and the surface leakage current is negligible. The incident optical power is 300 nW (–35 dBm), and the receiver bandwidth is 20 MHz. Find the various noise terms of the receiver.

The primary photocurrent

$$I_p = RP_0 = \frac{\eta q}{h\nu} P_0 = \frac{\eta q \lambda}{hc} P_0$$

$$= \frac{(0.90)(1.6\times10^{-19}\ \mathrm{C})(1.3\times10^{-6}\ \mathrm{m})}{(6.625\times10^{-34}\ \mathrm{J\cdot s})(3\times10^{8}\ \mathrm{m/s})} 3\times10^{-7}\ \mathrm{W}$$

$$= 0.282\ \mu\mathrm{A}$$

An InGaAs pin photodiode has the following parameters at a wave length of 1300 nm: I_D = 4 nA, η = 0.90, R_L = 1000 Ω, and the surface leakage current is negligible. The incident optical power is 300 nW (–35 dBm), and the receiver bandwidth is 20 MHz. Find the various noise terms of the receiver.

The mean-square shot noise current for a pin photodiode is

$$\left\langle i_{\text{shot}}^2 \right\rangle = 2qI_pB_e$$

$$= 2(1.6 \times 10^{-19}\ \text{C})(0.282 \times 10^{-6}\ \text{A})(20 \times 10^{6}\ \text{Hz})$$

$$= 1.80 \times 10^{-18}\ \text{A}^2$$

or $$\left\langle i_{\text{shot}}^2 \right\rangle^{1/2} = 1.34\ \text{nA}$$

An InGaAs pin photodiode has the following parameters at a wave length of 1300 nm: I_D = 4 nA, η = 0.90, R_L = 1000 Ω, and the surface leakage current is negligible. The incident optical power is 300 nW (–35 dBm), and the receiver bandwidth is 20 MHz. Find the various noise terms of the receiver.

The mean-square dark current is

$$\left\langle i_{DB}^2 \right\rangle = 2qI_D B_e$$

$$= 2(1.6 \times 19^{-19}\ \text{C})(4 \times 10^{-9}\ \text{A})(20 \times 10^{6}\ \text{Hz})$$

$$= 2.56 \times 10^{-20}\ \text{A}^2$$

$$\left\langle i_{DB}^2 \right\rangle^{1/2} = 0.16\,\text{nA}$$

An InGaAs pin photodiode has the following parameters at a wave length of 1300 nm: I_D = 4 nA, η = 0.90, R_L = 1000 Ω, and the surface leakage current is negligible. The incident optical power is 300 nW (–35 dBm), and the receiver bandwidth is 20 MHz. Find the various noise terms of the receiver.

The mean-square thermal noise current for the receiver is

$$\left\langle i_T^2 \right\rangle = \frac{4k_B T}{R_L} B_e = \frac{4(1.38 \times 10^{-23}\ \mathrm{J/K})(293\mathrm{K})}{1\ \mathrm{k}\Omega} B_e$$

$$= 323 \times 10^{-18}\ \mathrm{A}^2$$

$$\left\langle i_T^2 \right\rangle^{1/2} = 18\ \mathrm{nA}$$

Thus for this receiver the rms thermal noise current is about 14 times greater than the rms shot noise current and about 100 times greater than the rms dark current.

Signal to Noise Ratio

Detected current = AC component (i_p) + DC component (I_p)

Signal Power = $<i_p{}^2>M^2$

$$\frac{S}{N} = \frac{\left\langle i_p^2 \right\rangle M^2}{2q(I_p + I_D)\, M^2\, F(M) B_e + 2qI_L B_e + 4k_B T B_e / R_L}$$

- Typically not all the noise terms will have equal weight.
- For PIN photodiodes, the dominating noise currents are the Thermal noise currents and the active elements of the amplifier circuitry.
- For avalanche photodiodes, the thermal noise is of lesser importance and the photodetector noises usually dominate.

Signal to Noise Ratio

In general, in the expression for S/N, one can ignore the negligible leakage current. Furthermore, the term involving I_D can be dropped when the average signal current is much larger than the dark current. The signal-to-nose ratio then becomes

$$\frac{S}{N} = \frac{\left\langle i_p^2 \right\rangle M^2}{2qI_p M^2 F(M) B_e + 4k_B T B_e / R_L}$$

Since the noise figure F(M) increases with M, there always exist an optimum value of M that maximizes the SNR. For sinusoidally modulated signal, the optimum value of M is given by

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

Where F(M) is approximated by M^x

Consider a Si APD operating at 300°K and with a load resistor $R_L = 1000\ \Omega$. For this APD assume the responsivity $\mathscr{R} = 0.65$ A/W and let $x = 0.3$. (*a*) If dark current is neglected and 100 nW of optical power falls on the photodetector, what is the optimum avalanche gain? (*b*) What is the SNR if $B_e = 100$ MHz? (*c*) How does the SNR of this APD compare with the corresponding SNR of a Si *pin* photodiode? Assume the leakage current is negligible.

(*a*) Neglecting dark current and with $I_p = \mathscr{R}P$, we have

$$M_{opt} = \left(\frac{4k_BT}{xqR_L\mathscr{R}P} \right)^{1/(x+2)}$$

$$= \left[\frac{4(1.38 \times 10^{-23})(300)}{0.3(1.60 \times 10^{-19})(1000)(0.65)(100 \times 10^{-9})} \right]^{1/2.3}$$

$$= 42$$

Consider a Si APD operating at 300°K and with a load resistor $R_L = 1000\ \Omega$. For this APD assume the responsivity $\mathscr{R} = 0.65$ A/W and let $x = 0.3$. (a) If dark current is neglected and 100 nW of optical power falls on the photodetector, what is the optimum avalanche gain? (b) What is the SNR if $B_e = 100$ MHz? (c) How does the SNR of this APD compare with the corresponding SNR of a Si *pin* photodiode? Assume the leakage current is negligible.

(b) Neglecting dark current and with $F(M) = M^x = (42)^{0.3}$, we have

$$\frac{S}{N} = \frac{\langle i_p^2 \rangle M^2}{2qI_p M^2 F(M) B_e + 4k_B T B_e / R_L}$$

$$\text{SNR} = \frac{(\mathscr{R}\text{PM})^2}{\left[2q\mathscr{R}\text{PM}^{2.3} + \left(\frac{4k_B T}{R_L}\right)\right] B_e}$$

(*b*) Neglecting dark current and with $F(M) = M^x = (42)^{0.3}$, we have

$$\mathrm{SNR} = \frac{(\mathscr{R}\mathrm{PM})^2}{\left[2q\mathscr{R}\mathrm{PM}^{2.3} + \left(\frac{4k_BT}{R_L}\right)\right]B_e}$$

$$= \frac{[(0.65)(100\times10^{-9})(42)]^2}{\left[2(1.6\times10^{-19})(0.65)(100\times10^{-9})42^{2.3} + \left(\frac{4(1.38\times10^{-23})(300)}{(1000)}\right)\right](100\times10^{6})}$$

$$= 659$$

or in decibels, SNR = 10 log 659 = 28.2 dB

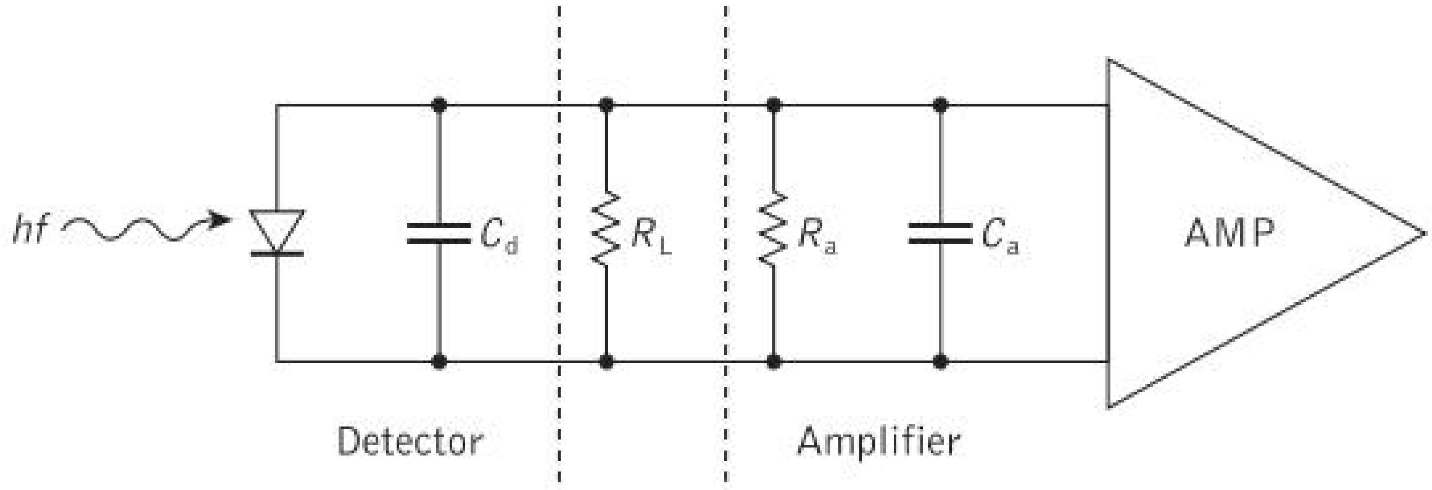
Consider a Si APD operating at 300°K and with a load resistor $R_L = 1000\ \Omega$. For this APD assume the responsivity $\mathscr{R} = 0.65$ A/W and let $x = 0.3$. (*a*) If dark current is neglected and 100 nW of optical power falls on the photodetector, what is the optimum avalanche gain? (*b*) What is the SNR if $B_e = 100$ MHz? (*c*) How does the SNR of this APD compare with the corresponding SNR of a Si *pin* photodiode? Assume the leakage current is negligible.

(*c*) For a *pin* photodiode with $M = 1$, the above equation yields SNR(*pin*)

$$= 2.3 = 3.5 \text{ dB}.$$

Thus, compared to a pin photodiode, the APD improves the SNR by 24.7 dB.

Receiver capacitance and bandwidth

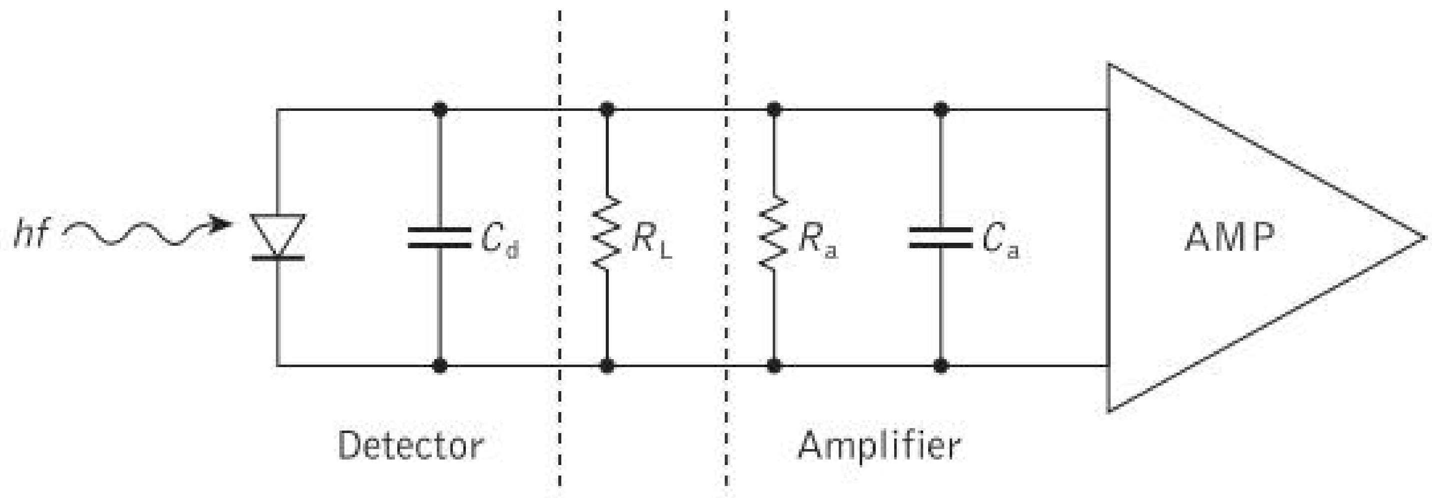


The equivalent circuit for the front end of an optical fiber receiver

The total capacitance for the front end of an optical receiver C_T is given by

$$C_T = C_d + C_a$$

where Cd is the detector capacitance and Ca is the amplifier input capacitance



We assume here that R_L is the total loading on the detector and therefore have neglected the amplifier input resistance R_a.

The reciprocal of the time constant $2\pi R_L C_T$ must be greater than, or equal to, the post detection bandwidth B.

$$\frac{1}{2\pi R_L C_T} \geq B$$

A photodiode has a capacitance of 6 pF. Calculate the maximum load resistance which allows an 8 MHz post-detection bandwidth. Determine the bandwidth penalty with the same load resistance when the following amplifier also has an input capacitance of 6 pF.

The maximum bandwidth is given by

$$B = \frac{1}{2\pi R_L C_d}$$

Therefore the maximum load resistance

$$R_L\,(\text{max}) = \frac{1}{2\pi C_d B} \qquad = \frac{1}{2\pi \times 6 \times 10^{-12} \times 8 \times 10^6}$$

$$= 3.32\ \text{k}\Omega$$

A photodiode has a capacitance of 6 pF. Calculate the maximum load resistance which allows an 8 MHz post-detection bandwidth.Determine the bandwidth penalty with the same load resistance when the following amplifier also has an input capacitance of 6 pF.

Thus for an 8 MHz bandwidth the maximum load resistance is 3.32 kΩ. Also, considering the amplifier capacitance, the maximum bandwidth

$$B = \frac{1}{2\pi R_L(C_d + C_a)} \quad = \frac{1}{2\pi \times 3.32 \times 10^3 \times 12 \times 10^{-12}}$$

$$= 4\ \text{MHz}$$

As would be expected, the maximum post-detection bandwidth is halved

A good silicon APD ($x = 0.3$) has a capacitance of 5 pF, negligible dark current and is operating with a post-detection bandwidth of 50 MHz. When the photocurrent before gain is 10^{-7} A and the temperature is 18 °C, determine the maximum SNR improvement between $M = 1$ and $M = M_{op}$ assuming all operating conditions are maintained.

The maximum value of the load resistor

$$R_L = \frac{1}{2\pi C_d B} \qquad = \frac{1}{2\pi \times 5 \times 10^{-12} \times 50 \times 10^6} \qquad = 635.5\ \Omega$$

When $M = 1$, the SNR is given by

$$\frac{S}{N} = \frac{I_p^2}{2eBI_p + \dfrac{4KTB}{R_L}}$$

where $I_d = 0$ and $F_n = 1$.

A good silicon APD ($x = 0.3$) has a capacitance of 5 pF, negligible dark current and is operating with a post-detection bandwidth of 50 MHz. When the photocurrent before gain is 10^{-7} A and the temperature is 18 °C, determine the maximum SNR improvement between $M = 1$ and $M = M_{op}$ assuming all operating conditions are maintained.

The shot noise is: $$2eBI_p = 2 \times 1.602 \times 10^{-19} \times 50 \times 10^{6} \times 10^{-7}$$

$$= 1.602 \times 10^{-18}\ \text{A}^2$$

and the thermal noise is:

$$\frac{4KTB}{R_L} = \frac{4 \times 1.381 \times 10^{-23} \times 291 \times 50 \times 10^{6}}{636.5} = 1.263 \times 10^{-15}\ \text{A}^2$$

It may be noted that the thermal noise is dominating. Therefore:

$$\frac{S}{N} = \frac{10^{-14}}{1.602 \times 10^{-18} \times 1.263 \times 10^{-15}} = 7.91$$

A good silicon APD ($x = 0.3$) has a capacitance of 5 pF, negligible dark current and is operating with a post-detection bandwidth of 50 MHz. When the photocurrent before gain is 10^{-7} A and the temperature is 18 °C, determine the maximum SNR improvement between $M = 1$ and $M = M_{op}$ assuming all operating conditions are maintained.

and the SNR in dB is:

$$\frac{S}{N} = 10 \log_{10} 7.91$$

$$= 8.98 \text{ dB}$$

Thus the SNR when $M = 1$ is 9.0 dB.

A good silicon APD ($x = 0.3$) has a capacitance of 5 pF, negligible dark current and is operating with a post-detection bandwidth of 50 MHz. When the photocurrent before gain is 10^{-7} A and the temperature is 18 °C, determine the maximum SNR improvement between $M = 1$ and $M = M_{op}$ assuming all operating conditions are maintained.

When $M = M_{op}$ and $x = 0.3$,

$$M_{op}^{2+x} = \frac{4KT}{xeR_L I_p}$$

where $I_d = 0$ and $F_n = 1$. Hence:

$$M_{op}^{2.3} = \frac{4 \times 1.381 \times 10^{-23} \times 291}{0.3 \times 1.602 \times 10^{-19} \times 636.5 \times 10^{-7}}$$

$$\begin{aligned} M_{op} &= (5.255 \times 10^{3})^{0.435} \\ &= 41.54 \end{aligned}$$

A good silicon APD ($x = 0.3$) has a capacitance of 5 pF, negligible dark current and is operating with a post-detection bandwidth of 50 MHz. When the photocurrent before gain is 10^{-7} A and the temperature is 18 °C, determine the maximum SNR improvement between $M = 1$ and $M = M_{op}$ assuming all operating conditions are maintained.

and the SNR in dB is:

$$\frac{S}{N} = 10 \log_{10} 1.78 \times 10^3$$

$$= 32.50 \text{ dB}$$

Therefore the SNR when $M = M_{op}$ is 32.5 dB and the SNR improvement over $M = 1$ is 23.5 dB.

Link Impairment consideration and system design

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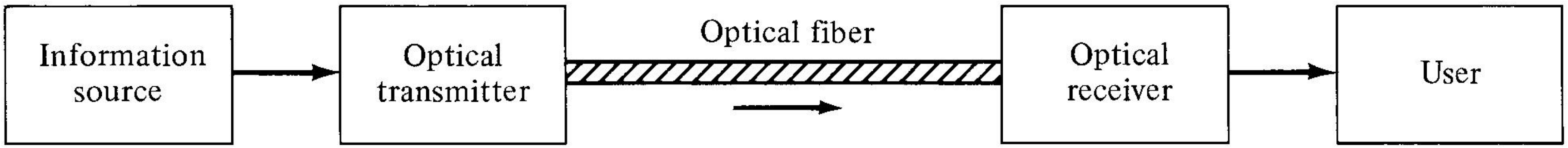
Associate Professor ,
SENSE,VIT.

Overview

- In this section we develop a simple point-to-point digital transmission link design considering
  - Link power budget calculations and
  - Link rise time calculations

A link should satisfy both these budgets

Simple point-to-point link



This p-p link forms the basis for examining more complex systems

System Requirements

1. Transmission Distance
2. Data Rate for a given BER

Selecting the Fiber

Bit rate and distance are the major factors

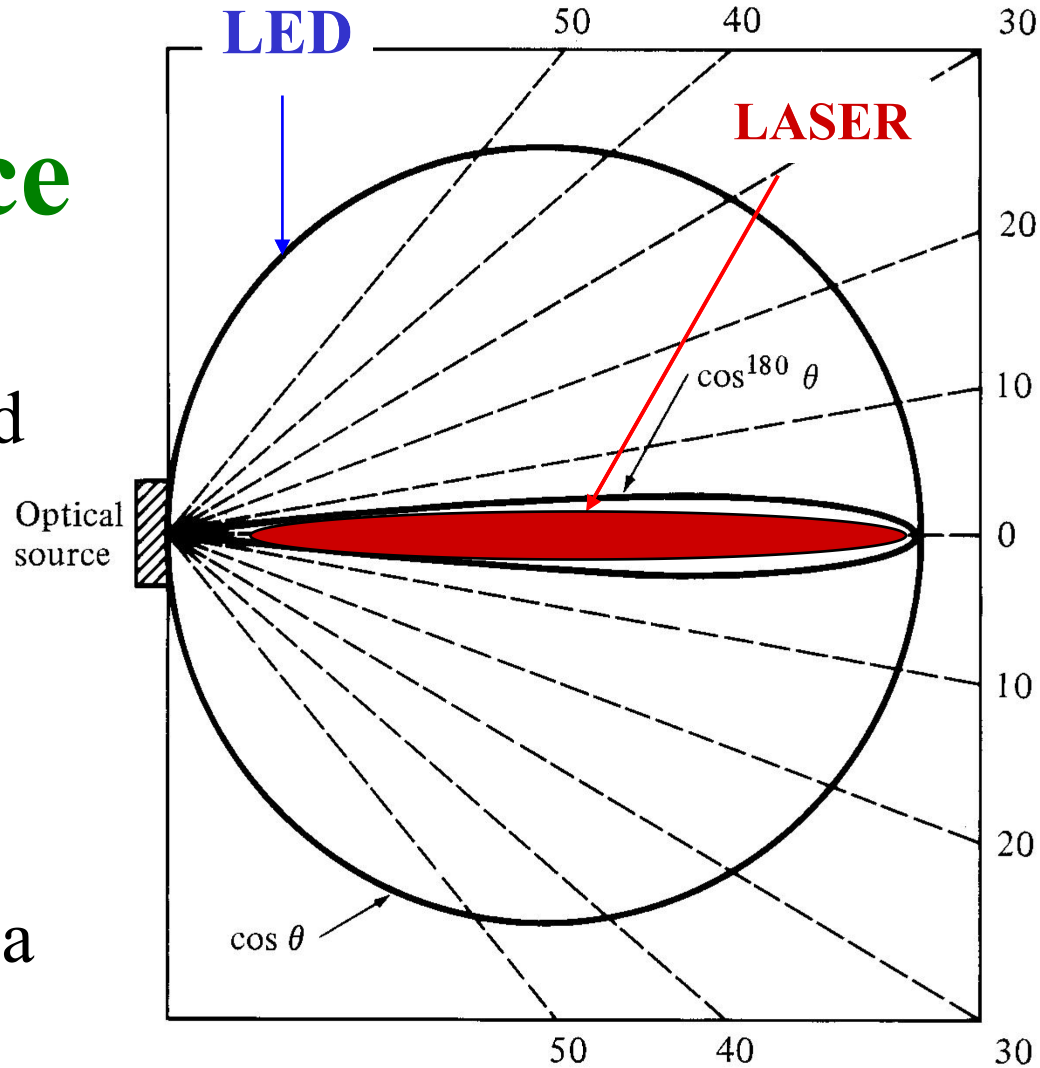
Other factors to consider: attenuation (depends on?) and distance-bandwidth product (depends on?) cost of the connectors, splicing etc.

Then decide

- Multimode or single mode
- Step or graded index fiber

Selecting the Optical Source

- Emission wavelength
- Spectral line width and number of modes
- Output power
- Stability
- Emission pattern
- Effective radiating area



Selecting the detector

- Type of detector
  - **APD**: High sensitivity but complex, high bias voltage (40V or more) and expensive
  - **PIN:** Simpler, thermally stable, low bias voltage (5V or less) and less expensive
- Responsivity (that depends on the avalanche gain & quantum efficiency)
- Operating wavelength and spectral selectivity
- Speed and photosensitive area
- Sensitivity (depends on noise and gain)

Design Considerations

- Link Power Budget
  - There is enough power margin in the system to meet the given BER
- Rise Time Budget
  - Each element of the link is fast enough to meet the given bit rate

These two budgets give necessary conditions for satisfactory operation

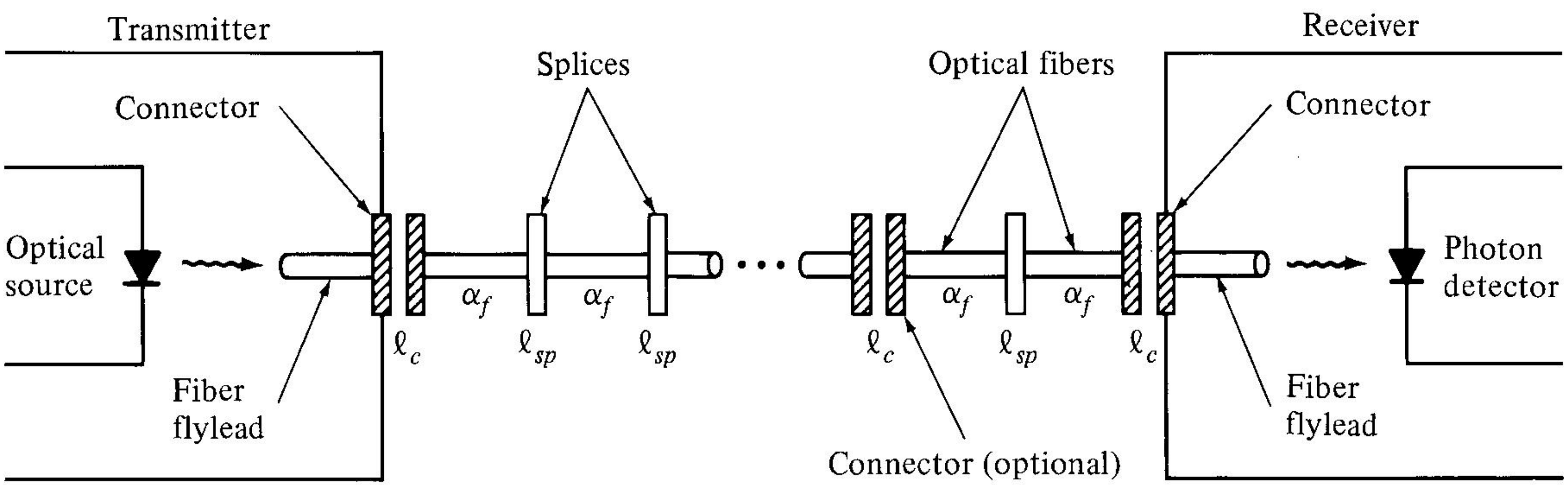
Link Power Budget

The link loss budget is derived from the sequential loss contributions of each element in the link expressed in dB as

$$loss = 10\log\frac{P_{out}}{P_{in}}$$

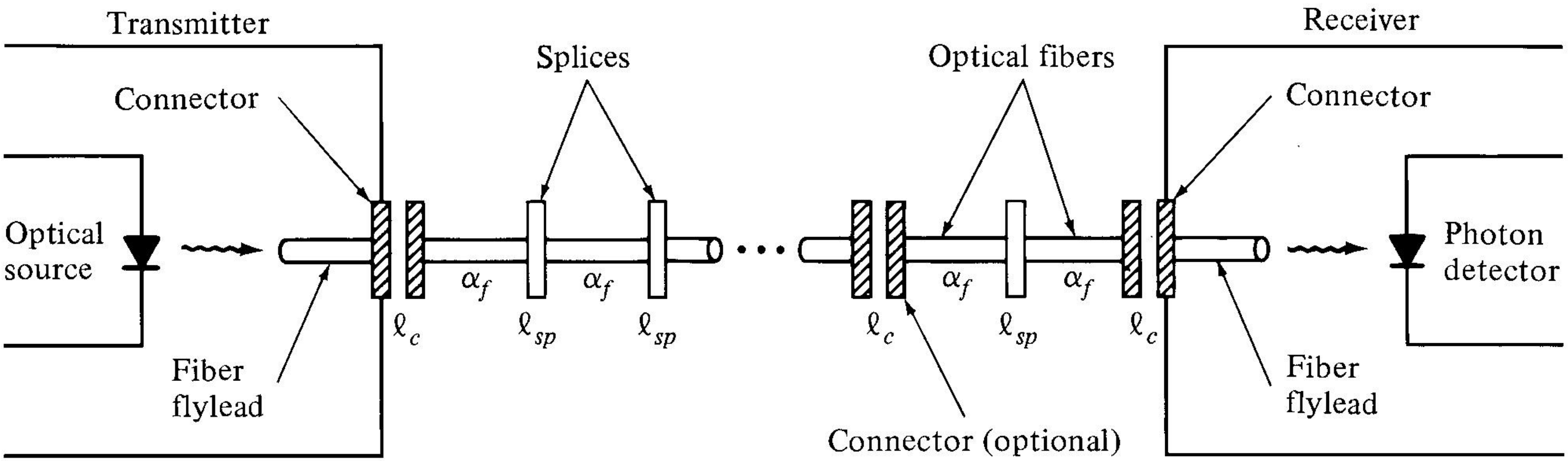
where

- P_{in} is the power emanating into the loss element
- P_{out} is the power emanating out of the loss element



Optical power-loss model

Optical power-loss model

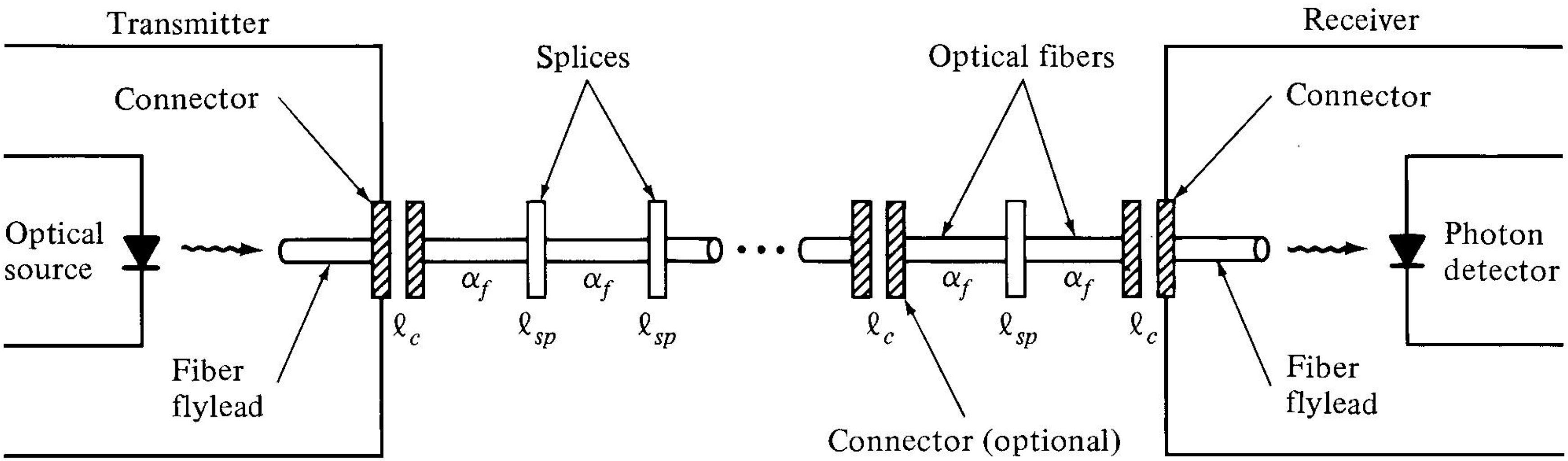


$$P_T = P_s - P_R = ml_c + nl_{sp} + \alpha_f L + \text{System Margin}$$

P_T: Total loss; P_s : Source power; P_R: Rx sensitivity

m connectors; n splices

Optical power-loss model



$$P_T = P_s - P_R = ml_c + nl_{sp} + \alpha_f L + \text{System Margin}$$

where

- l_c is the connector loss
- α_f is the fibre attenuation (dB/Km)
- L is the transmission distance
- system margin is nominally taken as 6 dB

Consider a 1550 nm laser diode that launched a +3 dBm optical power level into a fibre flylead, an InGaAs APD with -32 dBm sensitivity at 2.5 Gb/s, and a 60 Km long optical cable with a 0.3 dB/Km attenuation. Assume that here a short optical jumper cable is needed at each end between the end of the transmission cable and the SONET equipment rack. Assume that each jumper cable introduces a loss of 3 dB. In addition, assume a 1 dB connector loss occurs at each fibre joint.

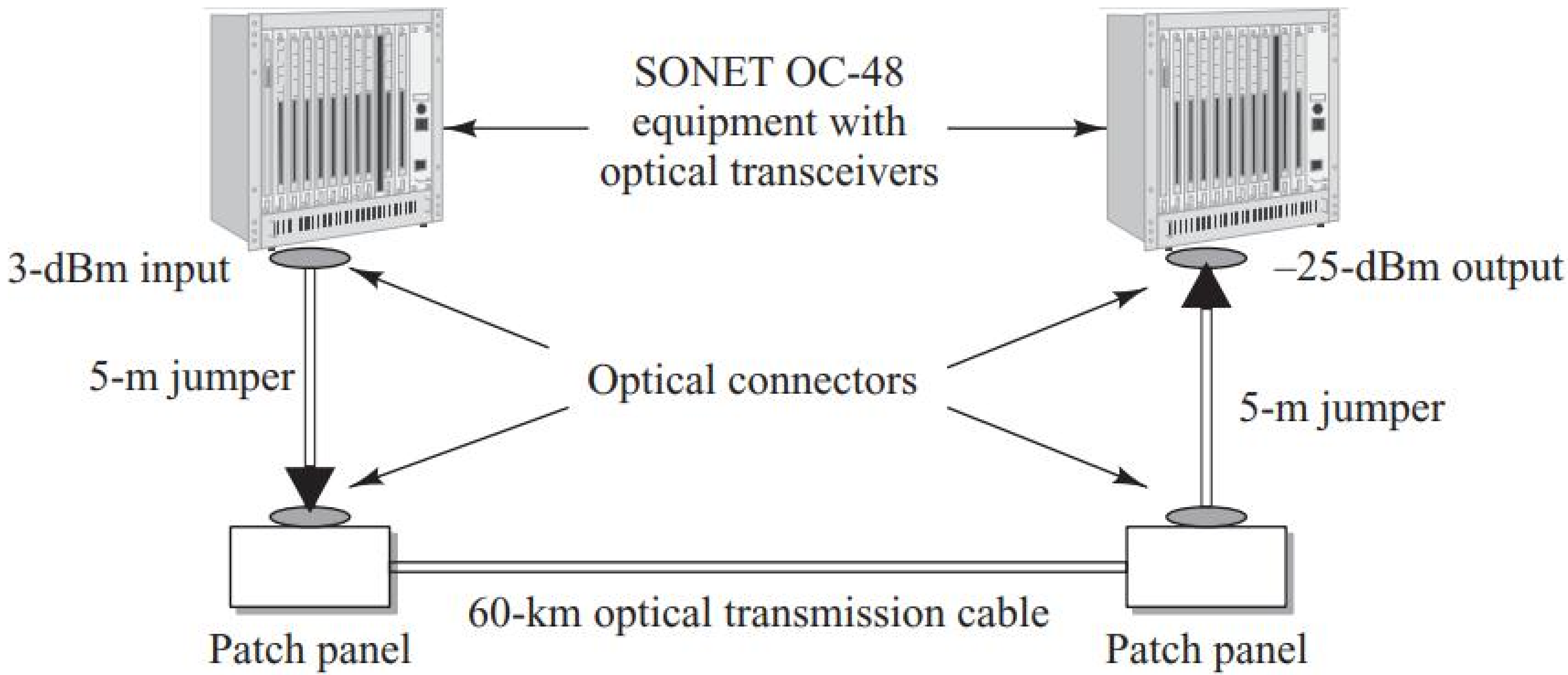


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Table below lists the components in column 1 and the associated optical output, sensitivity, or loss in column 2. Column 3 gives the power margin available after subtracting the component loss from the total optical power loss that is allowed between the light source and the photodetector, which, in this case, is 35 dB. Adding all the losses results in a final power margin of 7 dB.

Example of a spreadsheet for calculating an optical-link power budget

Component/loss parameter	Output/sensitivity/loss	Power margin (dB)
Laser output	3 dBm	
APD sensitivity at 2.5 Gb/s	−32 dBm	
Allowed loss [3 − (−32)]		35
Source connector loss	1 dB	34
Jumper + connector loss	3 + 1 dB	30
Cable attenuation (60 km)	18 dB	12
Jumper + connector loss	3 + 1 dB	8
Receiver connector loss	1 dB	7 (final margin)

An optical system has the following characteristics:

LED power (*Ps*) = 2 mW (3 dBm)

LED to fiber loss (*L*sf) = 3 dB

Fiber loss per km (*F*L) = 0.5 dB/km

Fiber length (*L*) = 40 km

Connector loss (*L*conn) = 1 dB (one connector between two 20-km fiber lengths)

Fiber to detector loss (*L*fd) = 3 dB

Receiver sensitivity (Pr) = –36 dBm

Find the loss margin.

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

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

*L*m = 3 dBm – 3 dB – (40 km × 0.5 dB/km) – 1 dB – 3 dB – (–36 dBm) = 12 dB

The optical power budget for a system is given by the following expression:

$$P_i = P_o + C_L + M_a \text{ dB}$$

where Pi is the mean input optional power launched into the fiber, Po is the mean incident optical power required at the receiver and C_L (or C_{LD} when there is a dispersion–equalization penalty) is the total channel loss

When total channel loss is substituted,

$$P_i = P_o + (\alpha_{fc} + \alpha_j)L + \alpha_{cr} + M_a \text{ dB}$$

α_{fc} is the fiber cable loss in dB/km, α_j is the loss due to joints (generally splices) in dB/km , α_{cr} is the connector loss in dB, M_a is the safety margin.

When Dispersion equalization penalty is included,

$$P_i = P_o + (\alpha_{fc} + \alpha_j)L + \alpha_{cr} + D_L + M_a \text{ dB}$$

This allows the maximum link length without repeaters to be determined.

The following parameters are established for a long-haul single-mode optical fiber system operating at a wavelength of 1.3 μm:

Mean power launched from the laser transmitter	–3 dBm
Cabled fiber loss	0.4 dB km^{-1}
Splice loss	0.1 dB km^{-1}
Connector losses at the transmitter and receiver	1 dB each
Mean power required at the APD receiver:	
when operating at 35 Mbit s^{-1} (BER 10^{-9})	–55 dBm
when operating at 400 Mbit s^{-1} (BER 10^{-9})	–44 dBm
Required safety margin	7 dB

Estimate:

(a) The maximum possible link length without repeaters when operating at 35 Mbit s^{-1} (BER 10^{-9}). It may be assumed that there is no dispersion–equalization penalty at this bit rate.

(b) The maximum possible link length without repeaters when operating at 400 Mbit s^{-9} (BER 10^{-9}) and assuming no dispersion–equalization penalty.

(c) The reduction in the maximum possible link length without repeaters of (b) when there is a dispersion–equalization penalty of 1.5 dB. It may be assumed for the purposes of this estimate that the reduced link length has the 1.5 dB penalty.

The following parameters are established for a long-haul single-mode optical fiber system operating at a wavelength of 1.3 μm:

Mean power launched from the laser transmitter	−3 dBm
Cabled fiber loss	0.4 dB km^{-1}
Splice loss	0.1 dB km^{-1}
Connector losses at the transmitter and receiver	1 dB each
Mean power required at the APD receiver:	
when operating at 35 Mbit s^{-1} (BER 10^{-9})	−55 dBm
when operating at 400 Mbit s^{-1} (BER 10^{-9})	−44 dBm
Required safety margin	7 dB

Estimate:

(a) The maximum possible link length without repeaters when operating at 35 Mbit s^{-1} (BER 10^{-9}). It may be assumed that there is no dispersion–equalization penalty at this bit rate.

(a) When the system is operating at 35 Mbit s^{-1} an optical power budget may be performed using

$$P_i - P_o = (\alpha_{fc} + \alpha_j)L + \alpha_{cr} + M_a \text{ dB}$$

$$-3 \text{ dBm} - (-55 \text{ dBm}) = (\alpha_{fc} + \alpha_j)L + \alpha_{cr} + M_a$$

$$(\alpha_{fc} + \alpha_j)L = 52 - \alpha_{cr} - M_a$$

$$0.5L = 52 - 2 - 7$$

$$L = \frac{43}{0.5} = 86 \text{ km}$$

The following parameters are established for a long-haul single-mode optical fiber system operating at a wavelength of 1.3 μm:

Mean power launched from the laser transmitter	−3 dBm
Cabled fiber loss	0.4 dB km^{-1}
Splice loss	0.1 dB km^{-1}
Connector losses at the transmitter and receiver	1 dB each
Mean power required at the APD receiver:	
when operating at 35 Mbit s^{-1} (BER 10^{-9})	−55 dBm
when operating at 400 Mbit s^{-1} (BER 10^{-9})	−44 dBm
Required safety margin	7 dB

(b) The maximum possible link length without repeaters when operating at 400 Mbit s^{-9} (BER 10^{-9}) and assuming no dispersion–equalization penalty.

(b) When the system is operating at 400 Mbit s^{-1} an optical power budget may be performed using

$$P_i - P_o = (\alpha_{fc} + \alpha_j)L + \alpha_{cr} + M_a \text{ dB}$$

$$-3 \text{ dBm} - (-44 \text{ dBm}) = (\alpha_{fc} + \alpha_j)L + \alpha_{cr} + M_a$$

$$(\alpha_{fc} + \alpha_j)L = 41 - 2 - 7$$

$$L = \frac{32}{0.5} = 64 \text{ km}$$

The following parameters are established for a long-haul single-mode optical fiber system operating at a wavelength of 1.3 μm:

Mean power launched from the laser transmitter	−3 dBm
Cabled fiber loss	0.4 dB km^{-1}
Splice loss	0.1 dB km^{-1}
Connector losses at the transmitter and receiver	1 dB each
Mean power required at the APD receiver:	
when operating at 35 Mbit s^{-1} (BER 10^{-9})	−55 dBm
when operating at 400 Mbit s^{-1} (BER 10^{-9})	−44 dBm
Required safety margin	7 dB

(c) The reduction in the maximum possible link length without repeaters of (b) when there is a dispersion–equalization penalty of 1.5 dB. It may be assumed for the purposes of this estimate that the reduced link length has the 1.5 dB penalty.

(c) Performing the optical power budget including dispersion-equalization penalty gives:

$$P_i - P_o = (\alpha_{fc} + \alpha_j)L + \alpha_{cr} + D_L + M_a$$

$$0.5L = 41 - 2 - 1.5 - 7$$

$$L = \frac{30.5}{0.5} = 61 \text{ km}$$

Thus there is a reduction of 3 km in the maximum possible link length without repeaters

Rise Time Budget

- Convenient method for determining the dispersion limitation of an optical fiber link-Each element of the link is fast enough to meet the given bit rate.
- Total rise time depends on:
  - Transmitter rise time (t_{tx})
  - Group Velocity Dispersion (t_{GVD})
  - Modal dispersion rise time (t_{mod})
  - Receiver rise time (t_{rx})

$$t_{sys} = \left[\sum_{i=1}^{n} t_i^2 \right]^{1/2}$$

Total rise time of a digital link should not exceed 70% for a NRZ bit period, and 35% of a RZ bit period

Rise Time

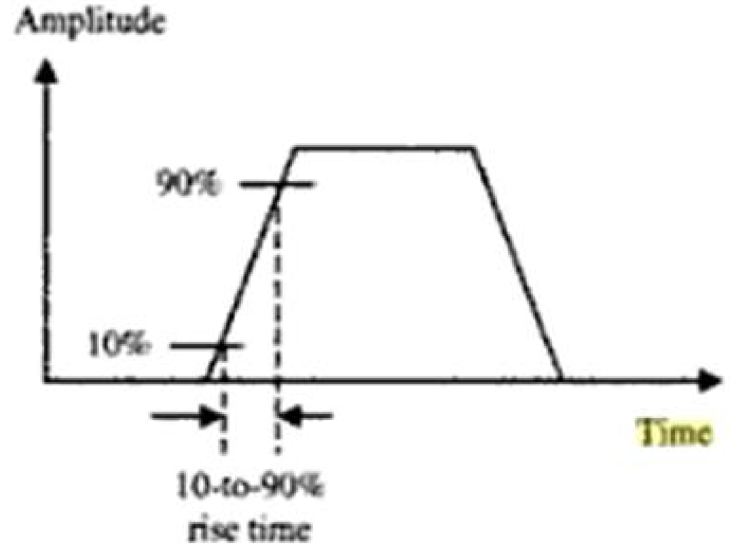

Figure 16.6. Illustration of the 10 to 90 percent rise time of a pulse.

Rise Time…

$$t_{rx} = 350/B_{rx} \text{ ns; where}$$

B_{rx} is receiver bandwidth in MHz

Similarly

$$t_{tx} = 350\,/\,B_{tx} \quad \text{ns}$$

Assuming both transmitter and receiver as first order low pass filters

Modal Dispersion Rise Time

Bandwidth $B_M(L)$ due to modal dispersion of a link length L is empirically given by,

$$B_M(L) = B_o / L^q$$

B_0 is the BW of a 1 km length of cable(MHz-km product) and q ~0.5-1 is the modal equilibrium factor

$$t_{\text{mod}}(\text{ns}) = 440 / B_M = 440 L^q / B_0$$

Where B_0 is in MHzKm, B_M is in MHz

Group Velocity Dispersion

$$t_{GVD} = |D| L \sigma_\lambda$$

Where,

D is the dispersion parameter (ps/km.nm)

σ_λ is the half power spectral width of the source (nm)

L is the distance in km

$$t_{sys} = \left[t_{tx}^2 + t_{rx}^2 + D^2 \sigma_\lambda^2 L^2 + \frac{440^2 L^{q2}}{B_0^2} \right]^{1/2}$$

For an RZ pulse format, $B_T(\max) = \frac{0.35}{T_{syst}}$

Alternatively, for an NRZ pulse format $B_T(\max) = \frac{0.7}{T_{syst}}$

The bit rate

$B_T = 1/\tau$ where τ is the pulse duration

Thus the upper limit on T_{syst} should be less than 35% of the bit interval for an RZ pulse format and less than 70% of the bit interval for an NRZ pulse format.

Problem 1

An LED together with its drive circuit has a rise time of 15ns.Taking a typical LED spectral width of 40nm, the material dispersion rise time degradation is 21ns over the 6-km link. Assuming the receiver has a 25-MHZ bandwidth,

1.Find the rise time degradation from the receiver.

2. If the fiber we select has a 400-MHz.km bandwidth-distance product and with q=0.7, find the modal dispersion-induced fiber rise time.

3.Calculate the total rise time of the link

$$t_{rx} = 350/B_{rx} = 14 \text{ ns}$$

$$t_{\text{mod}}(\text{ns}) = 440 / B_M = 440 L^q / B_0 = 3.9 \text{ ns}$$

$$t_{\text{sys}} = \left(t_{tx}^2 + t_{\text{mat}}^2 + t_{\text{mod}}^2 + t_{rx}^2\right)^{1/2}$$

$$= \left[(15 \text{ ns})^2 + (21 \text{ ns})^2 + (3.9 \text{ ns})^2 + (14 \text{ ns})^2\right]^{1/2}$$

$$= 30 \text{ ns}$$

Problem 2

An optical fiber system is to be designed to operate over an 8 km length without repeaters. The rise times of the chosen components are:

Source (LED) 8 ns

Fiber: intermodal 5 ns km^{-1}

(pulse broadening) intramodal 1 ns km^{-1}

Detector (p–i–n photodiode) 6 ns

From system rise time considerations, estimate the maximum bit rate that may be achieved on the link when using an NRZ format.

$$t_{sys} = \left(t_{tx}^2 + t_{mat}^2 + t_{mod}^2 + t_{rx}^2\right)^{1/2}$$

$$t_{sys} = 42\, ns$$

$$B_{T(max)} = \frac{0.7}{t_{sys}}$$

$$B_{T(max)} = 16.66\, M\, bit/s$$

Problem 3

An LED together with its drive circuit has a rise time of 0.025ns. Taking a typical LED spectral width of 40nm, the material dispersion rise time degradation is 21ns over the 6-km link. Assuming the receiver has a 25-MHZ bandwidth,

1. Find the rise time degradation from the receiver.
2. If the fiber we select has a 400-MHz.km bandwidth-distance product and with q=0.6, find the modal dispersion-induced fiber rise time.
3. Calculate the total rise time of the link .

From system rise time considerations, estimate the maximum bit rate that may be achieved on the link when using an RZ format.

$$t_{sys} = \left(t_{tx}^2 + t_{mat}^2 + t_{mod}^2 + t_{rx}^2\right)^{1/2}$$

$$t_{sys} = 25\ ns$$

$$B_{T(max)} = \frac{0.35}{t_{sys}}$$

$$B_{T(max)} = 14\ Mbits/s$$

Power conversion

$$P_{[dBm]} = 10\log\left(\frac{P_{[mW]}}{1_{[mW]}}\right)$$

Components are chosen for a digital optical fiber link of overall length 7 km and operating at 20 Mbit s^{-1} using an RZ code. It is decided that an LED emitting at 0.85 μm with graded index fiber to a *p–i–n* photodiode is a suitable choice for the system components, giving no dispersion–equalization penalty. An LED which is capable of launching an average of 100 μW of optical power (including the connector loss) into a graded index fiber of 50 μm core diameter is chosen. The proposed fiber cable has an attenuation of 2.6 dB km^{-1} and requires splicing every kilometer with a loss of 0.5 dB per splice. There is also a connector loss at the receiver of 1.5 dB. The receiver requires mean incident optical power of −41 dBm in order to give the necessary BER of 10^{-10}, and it is predicted that a safety margin of 6 dB will be required.

Write down the optical power budget for the system and hence determine its viability.

Solution:

Mean optical power launched into the fiber from the transmitter (100 μm)	–10 dBm
Receiver sensitivity at 20 Mbit s^{-1} (BER 10^{-10})	–41 dBm
Total system margin	31 dB
Cabled fiber loss (7×2.6 dB km^{-1})	18.2 dB
Splice losses (6×0.5 dB)	3.0 dB
Connector loss (1×1.5 dB)	1.5 dB
Safety margin	6.0 dB
Total system loss	28.7 dB
Excess power margin	2.3 dB

Based on the figures given, the system is viable and provides a 2.3 dB excess power margin. This could give an extra safety margin to allow for possible future splices if these were not taken into account within the original safety margin.

A D–IM analog optical fiber link of length 2 km employs an LED which launches mean optical power of −10 dBm into a multimode optical fiber. The fiber cable exhibits a loss of 3.5 dB km^{-1} with splice losses calculated at 0.7 dB km^{-1}. In addition there is a connector loss at the receiver of 1.6 dB. The *p–i–n* photodiode receiver has a sensitivity of −25 dBm for an SNR ($\overline{i_{sig}^2}/\overline{i_N^2}$) of 50 dB and with a modulation index of 0.5. It is estimated that a safety margin of 4 dB is required. Assuming there is no dispersion–equalization penalty:

(a) Perform an optical power budget for the system operating under the above conditions and ascertain its viability.

(b) Estimate any possible increase in link length which may be achieved using an injection laser source which launches mean optical power of 0 dBm into the fiber cable. In this case the safety margin must be increased to 7 dB.

A D–IM analog optical fiber link of length 2 km employs an LED which launches mean optical power of –10 dBm into a multimode optical fiber. The fiber cable exhibits a loss of 3.5 dB km^{-1} with splice losses calculated at 0.7 dB km^{-1}. In addition there is a connector loss at the receiver of 1.6 dB. The *p–i–n* photodiode receiver has a sensitivity of –25 dBm for an SNR ($\overline{i_{sig}^2}/\overline{i_N^2}$) of 50 dB and with a modulation index of 0.5. It is estimated that a safety margin of 4 dB is required. Assuming there is no dispersion–equalization penalty:

Mean power launched into the fiber cable from the LED transmitter	–10 dBm
Mean optical power required at the *p–i–n* photodiode receiver for SNR of 50 dB and a modulation index of 0.5	–25 dBm
Total system margin	15 dB
Fiber cable loss (2 × 3.5)	7.0 dB
Splice losses (2 × 0.7)	1.4 dB
Connector loss at the receiver	1.6 dB
Safety margin	4.0 dB
Total system loss	14.0 dB
Excess power margin	1.0 dB

Hence the system is viable, providing a small excess power margin.

(b) Estimate any possible increase in link length which may be achieved using an injection laser source which launches mean optical power of 0 dBm into the fiber cable. In this case the safety margin must be increased to 7 dB.

(b) In order to calculate any possible increase in link length

$$P_i - P_o = (\alpha_{fc} + \alpha_j)L + \alpha_{cr} + M_a \text{ dB}$$

Therefore:

$$0 \text{ dBm} - (-25 \text{ dBm}) = (3.5 + 0.7)L + 1.6 + 7.0$$

and:

$$4.2L = 25 - 8.6 = 16.4 \text{ dB}$$

giving:

$$L = \frac{16.4}{4.2} = 3.9 \text{ km}$$

Hence the use of the injection laser gives a possible increase in the link length of 1.9 km or almost a factor of 2. It must be noted that in this case the excess power margin has been reduced to zero.

WDM Concepts and Components

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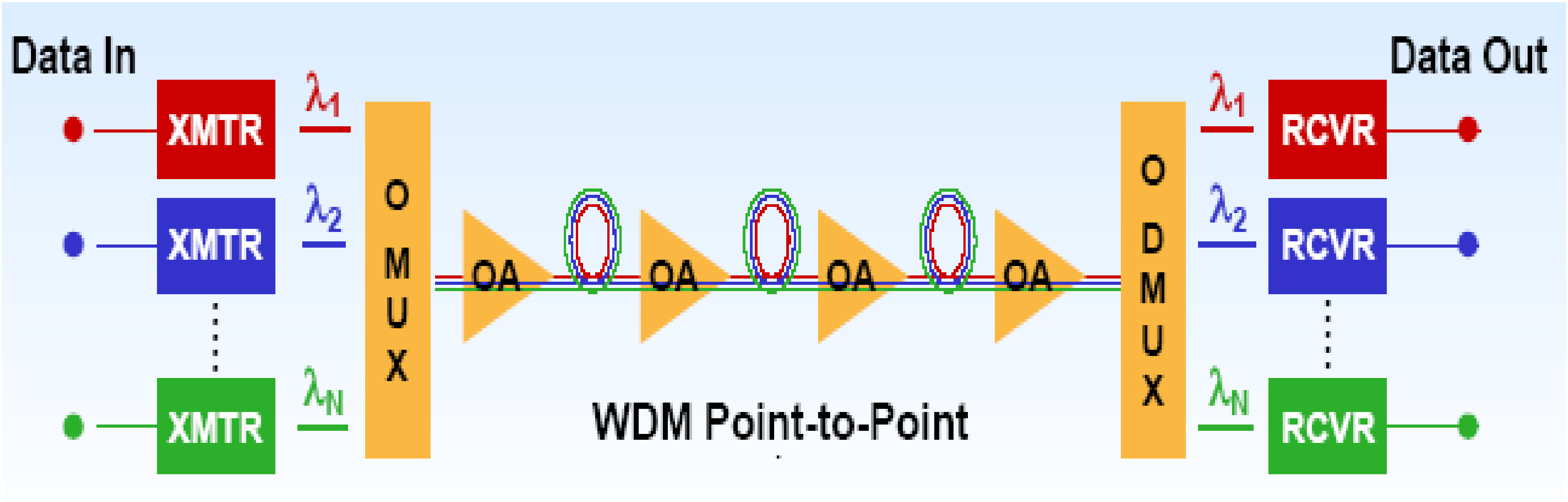
Part 1: WDM Concept

Why WDM?

- 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

Wavelength Division Multiplexing



- Passive/active devices are needed to combine, distribute, isolate and amplify optical power at different wavelengths

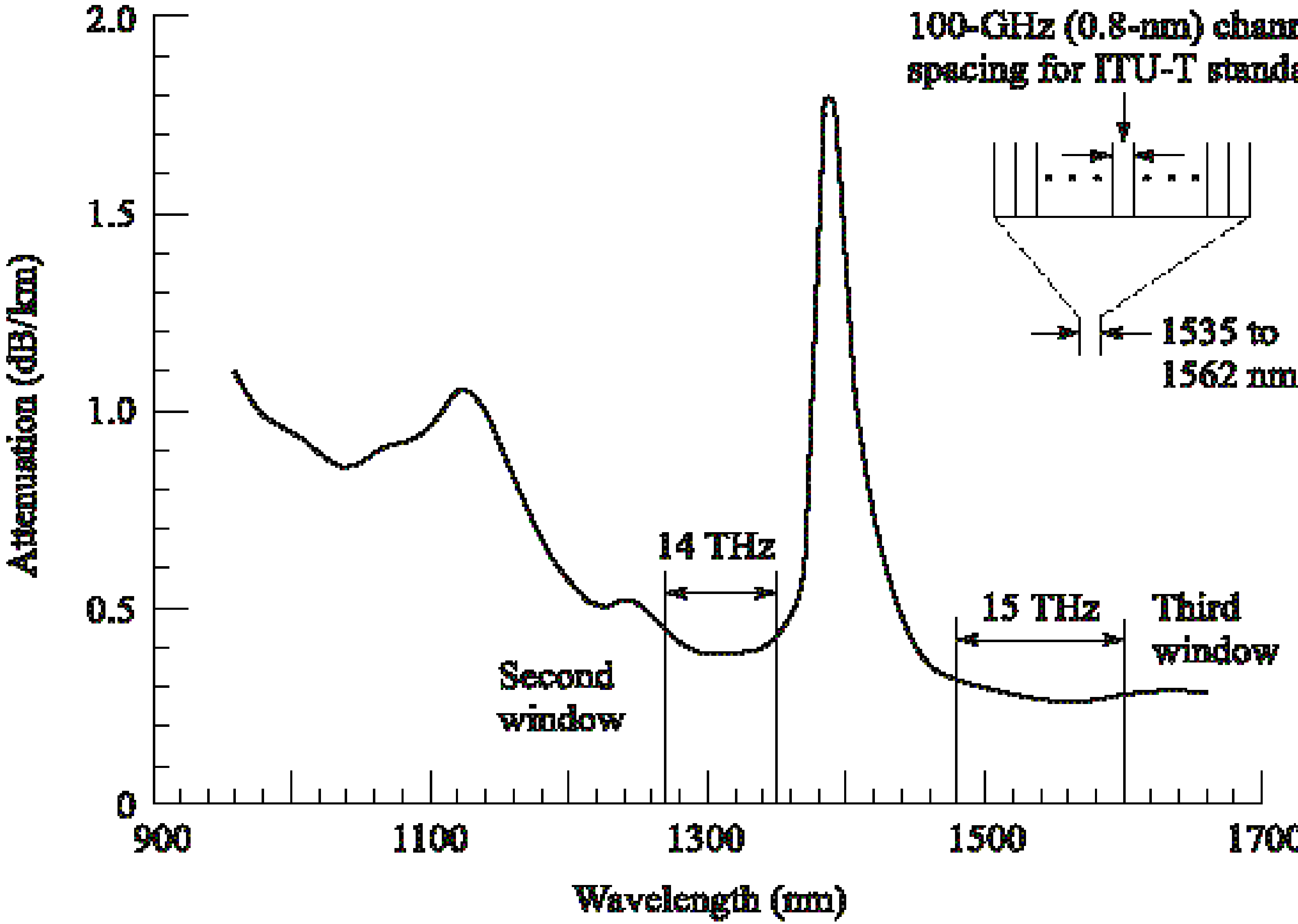
WDM, CWDM and DWDM

- 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
- The range of standardized channel grids includes 50, 100, 200 and 1000 GHz spacing
- Wavelength spacing practically depends on:
  - laser linewidth
  - optical filter bandwidth

ITU-T Standard Transmission DWDM windows



Part II: WDM Devices

Key Components for WDM

Passive Optical Components(requires no external control)

- Wavelength Selective Splitters
- Wavelength Selective Couplers

Active Optical Components(can be controlled electronically)

- Tunable Optical Filter
- Tunable Source
- Optical amplifier
- Add-drop Multiplexer and De-multiplexer

Passive Devices

- These operate completely in the optical domain (no O/E conversion) and does not need electrical power
- Split/combine light stream Ex: *N X N* couplers, power splitters, power taps and star couplers
- Technologies: - Fiber based or
  - Optical waveguides based
  - Micro (Nano) optics based
- Fabricated using optical fiber or waveguide (with special material like InP, $LiNbO_3$)

Optical Couplers

- A fiber optic coupler is a device that can distribute the optical signal (power) from one fiber among two or more fibers.

- A fiber optic coupler can also combine the optical signal from two or more fibers into a single fiber.

- Fiber optic couplers attenuate the signal much more than a connector or splice because the input signal is divided among the output ports.

- A basic fiber optic coupler has N input ports and M output ports.

- N and M typically range from 1 to 64.

- The number of input ports and output ports vary depending on the intended application for the coupler.

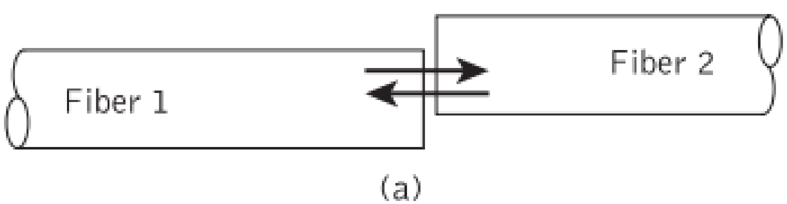
- Types of fiber optic couplers include optical splitters, optical combiners, X couplers, star couplers, and tree couplers.

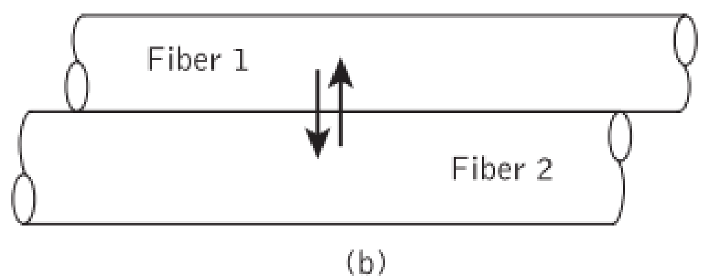
Classification of Optical couplers:

- Optical fiber couplers are often passive devices in which the power transfer takes place either:

(a) through the fiber core cross-section by butt jointing the fibers or by using some form of imaging optics between the fibers (core interaction type); or

(b) through the fiber surface and normal to its axis by converting the guided core modes to both cladding and refracted modes which then enable the power-sharing mechanism (surface interaction type).





(a) core interaction type;

(b) surface interaction type

Multiport optical fiber couplers

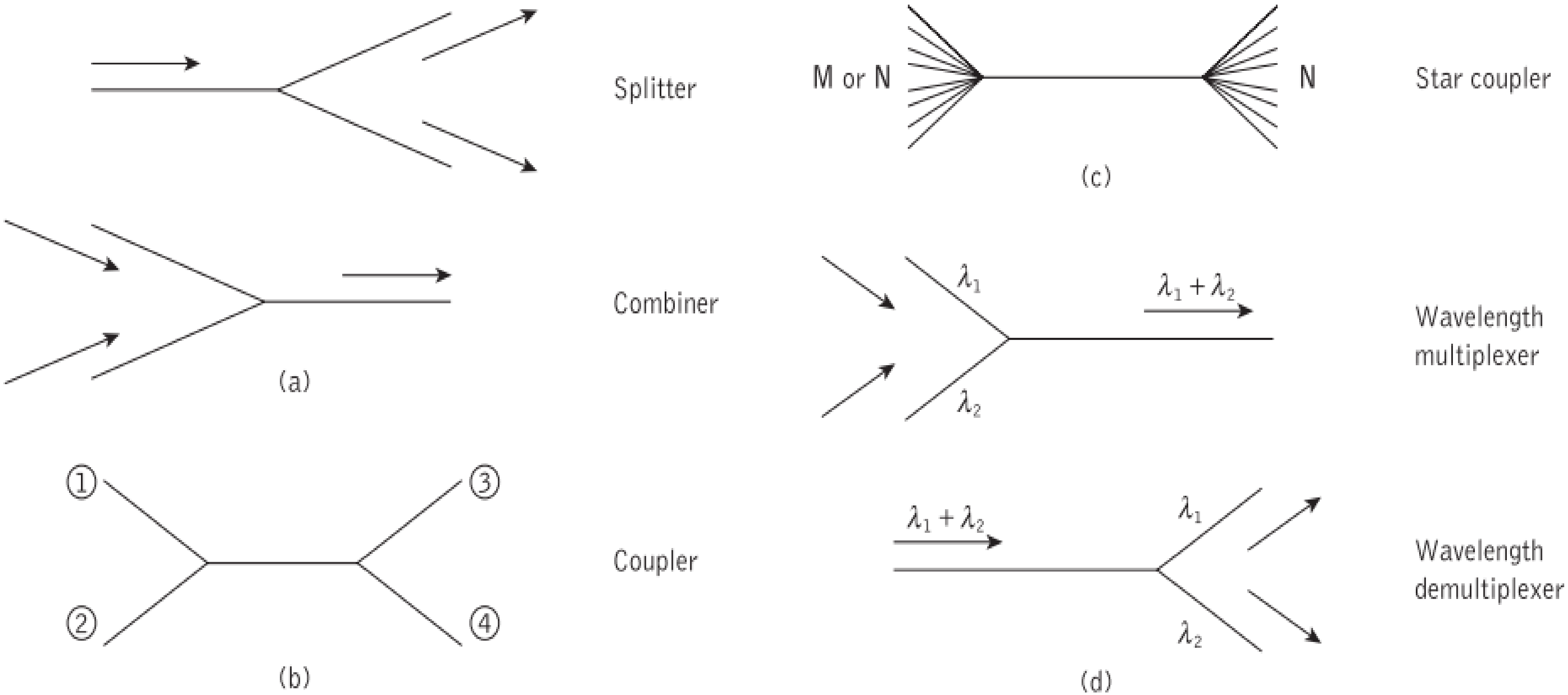
Multiport optical fiber couplers can also be subdivided into the following three main groups.

1. Three- and four-port* couplers, which are used for signal splitting, distribution and combining.

2. Star couplers, which are generally used for distributing a single input signal to multiple outputs.

3. Wavelength division multiplexing (WDM) devices, which are a specialized form of coupler designed to permit a number of different peak wavelength optical signals to be transmitted in parallel on a single fiber.

   - WDM couplers either combine the different wavelength optical signal onto the fiber (i.e. multiplex) or separate the different wavelength optical signals output from the fiber (i.e. demultiplex).



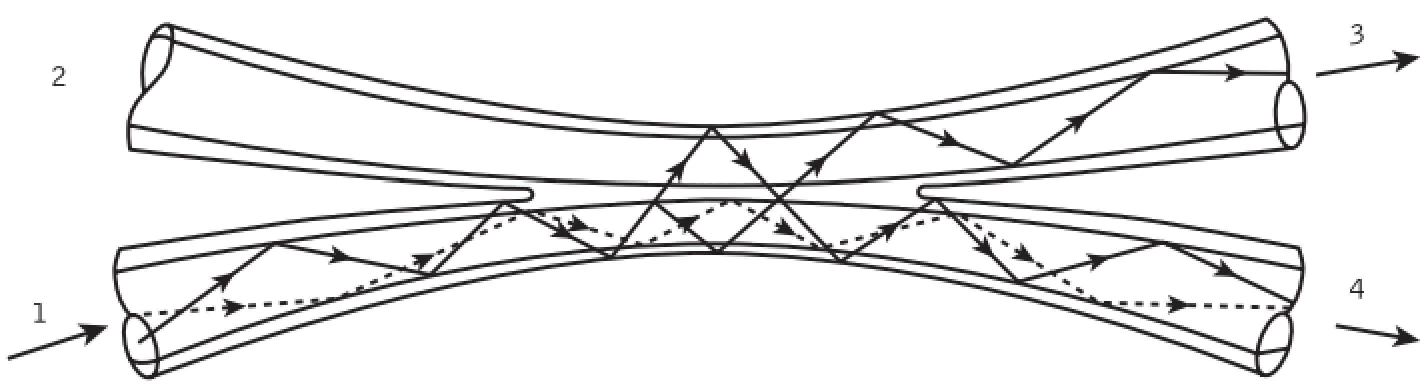
Optical fiber coupler types and functions: (a) three-port couplers; (b) four-port coupler; (c) star coupler; (d) wavelength division multiplexing and demultiplexing couplers

Three- and four-port couplers

- The most common method for manufacturing couplers is the fused biconical taper (FBT) technique.

- The fibers are generally twisted together and then spot fused under tension such that the fused section is elongated to form a biconical taper structure.

- A three-port coupler is formed by removing one of the input fibers. Optical power launched into the input fiber propagates in the form of guided core modes.



Structure and principle of operation for the fiber fused biconical taper coupler

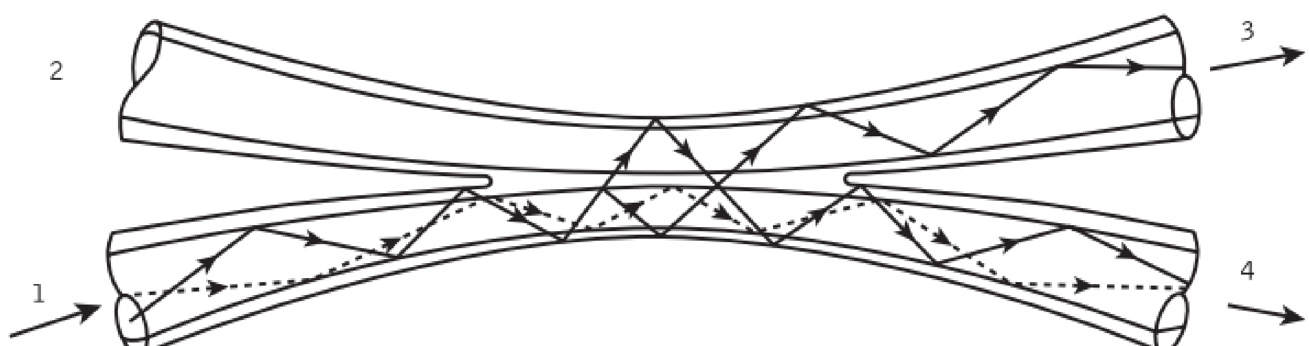
Loss Parameters

- The excess loss which is defined as the ratio of power input to power output is given by:

$$\text{Excess loss (four-port coupler)} = 10 \log_{10} \frac{P_1}{(P_3 + P_4)} \text{ (dB)}$$

- The insertion loss, however, is generally defined as the loss obtained for a particular port to-port optical path

$$\text{Insertion loss (ports 1 to 4)} = 10 \log_{10} \frac{P_1}{P_4} \text{ (dB)}$$



Loss Parameters

- The crosstalk which provides a measure of the directional isolation achieved by the device is the ratio of the backscattered power received at the second input port to the input power which may be written as:

$$\text{Crosstalk (four-port coupler)} = 10 \log_{10} \frac{P_2}{P_1} \text{ (dB)}$$

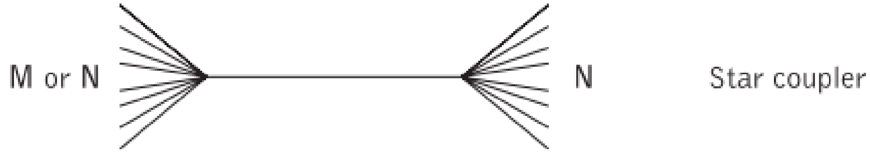
- The splitting or coupling ratio indicates the percentage division of optical power between the output ports.

$$\text{Split ratio} = \left[\frac{P_3}{(P_3 + P_4)}\right] \times 100\%$$

$$= \left[1 - \frac{P_4}{(P_3 + P_4)}\right] \times 100\%$$

Star couplers

- Star couplers distribute an optical signal from a single-input fiber to multiple-output fibers.



(c)

- In an ideal star coupler the optical power from any input fiber is evenly distributed among the output fibers.

- The total loss associated with the star coupler comprises its theoretical splitting loss together with the excess loss.

- The splitting loss is related to the number of output ports N following:

$$\text{Splitting loss (star coupler)} = 10 \log_{10} N \text{ (dB)}$$

- For a reflective star coupler N is equal to the total number of ports (both input and output combined).

Star couplers

- For a single input port and multiple output ports where j = 1, N, then the excess loss is given by:

$$\text{Excess loss (star coupler)} = 10 \log_{10}\left(P_i \Big/ \sum_{1}^{N} P_j\right) \text{(dB)}$$

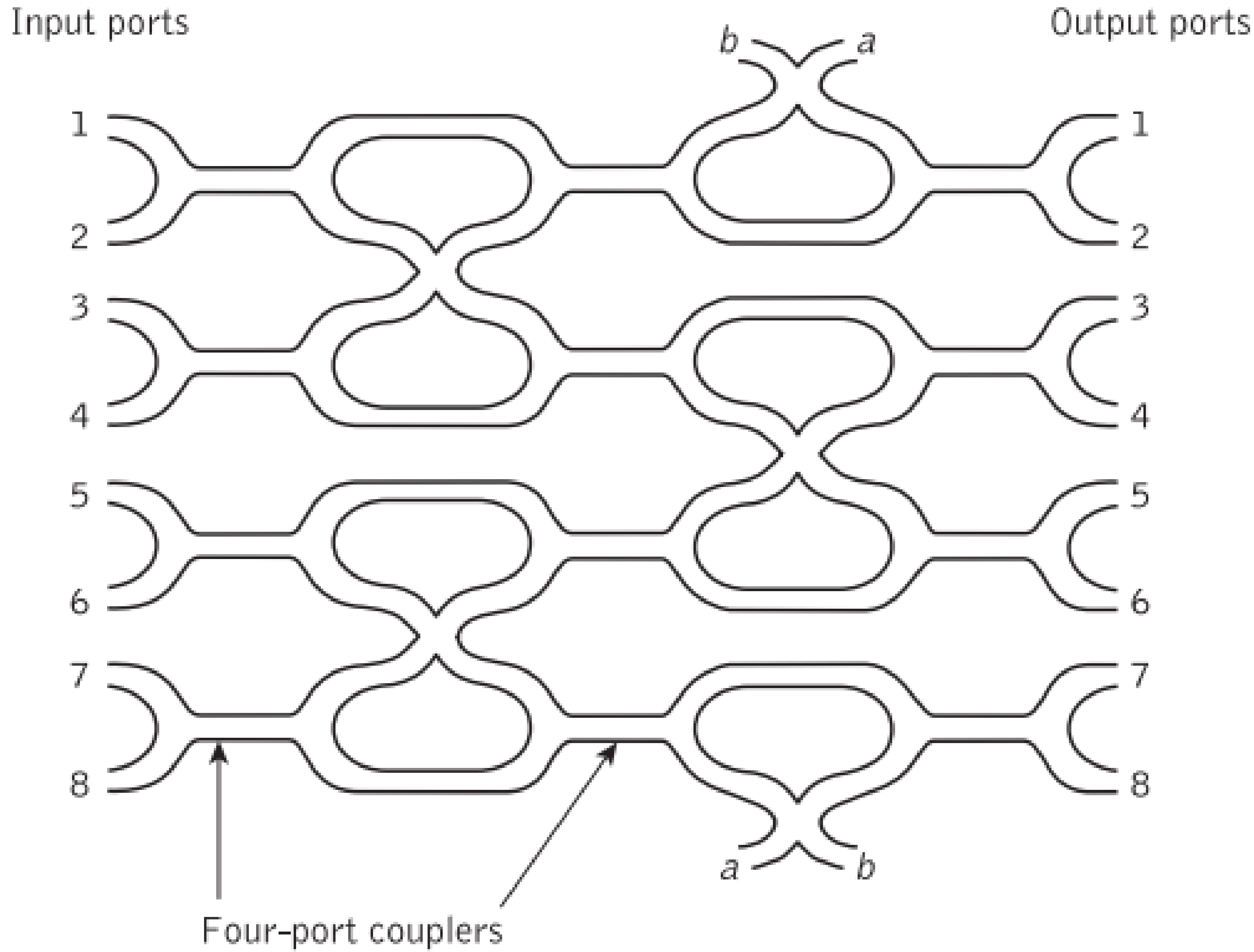
- The insertion loss between any two ports on the star coupler may be obtained in a similar manner to the four-port coupler

$$\text{Insertion loss (ports 1 to 4)} = 10 \log_{10} \frac{P_1}{P_4} \text{(dB)}$$

- The crosstalk between any two input ports is given by

$$\text{Crosstalk (four-port coupler)} = 10 \log_{10} \frac{P_2}{P_1} \text{(dB)}$$

Star couplers-Ladder Type



The 8 × 8 star coupler formed by cascading 12 four-port couplers (ladder coupler). This strategy is often used to produce low-loss single-mode fiber star or tree couplers

Star couplers-Ladder Type

- An alternative strategy for the realization of a star coupler is to construct a ladder coupler.

- The ladder coupler generally comprises a number of cascaded stages, each incorporating three- or four-port FBT couplers in order to obtain a multiport output.

- The ladder coupler consists of three stages, which gives eight output ports.

- It must be noted, however, that when three-port couplers are used such devices do not form symmetrical star couplers* in that they provide a 1 × N rather than N × N configuration.

Star couplers-Ladder Type

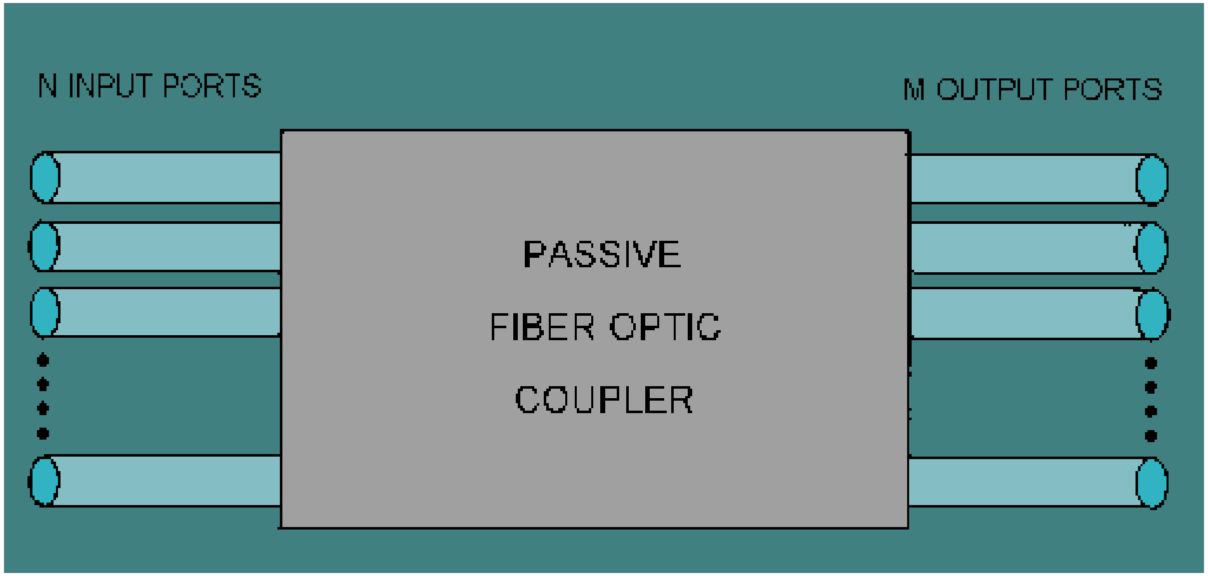
- Nevertheless, the ladder coupler presents a useful device to achieve a multiport output with relatively low insertion loss.

- Furthermore, when four-port couplers are employed, then a true N × N star coupler may be obtained.

- It may be deduced that the number of output ports N obtained with an M-stage ladder coupler is 2^M.

- These devices have found relatively widespread application for the production of single-mode fiber star couplers.

Basic Fiber Optic Couplers



N and M typically range from 1 to 64.

Optical Splitter

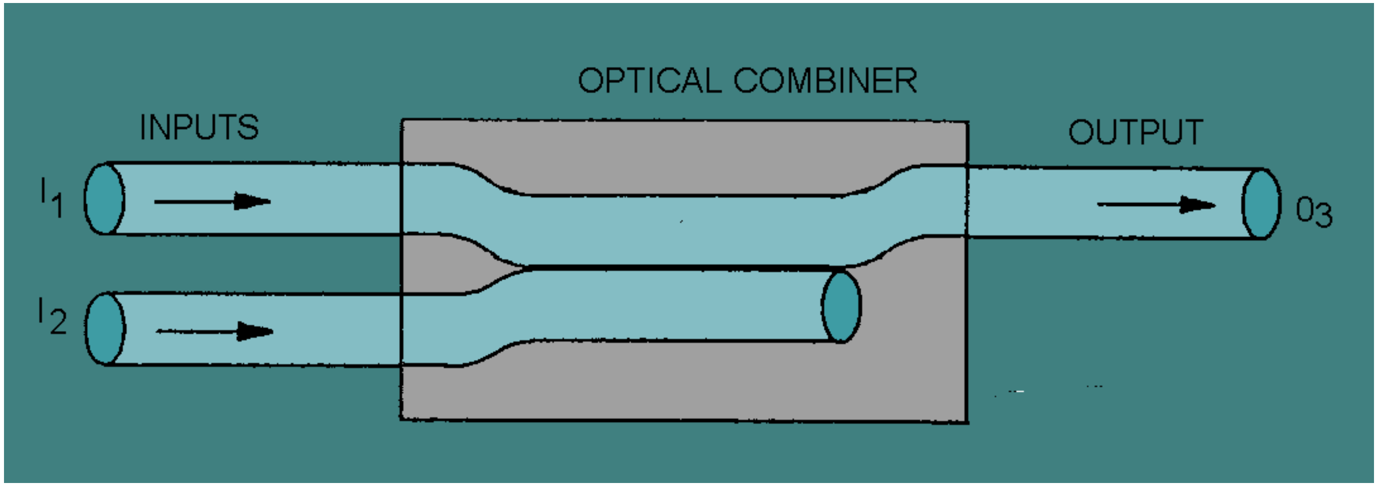
- An **optical splitter** is a passive device that splits the optical power carried by a single input fiber into two output fibers.
- The input optical power is normally split evenly between the two output fibers. This type of optical splitter is known as a **Y-coupler**.
- However, an optical splitter may distribute the optical power carried by input power in an uneven manner.
- An optical splitter may split most of the power from the input fiber to one of the output fibers.
- Only a small amount of the power is coupled into the secondary output fiber.
- This type of optical splitter is known as a **T-coupler, or an optical tap.**

Optical Combiner

- An **optical combiner** is a passive device that combines the optical power carried by two input fibers into a single output fiber.

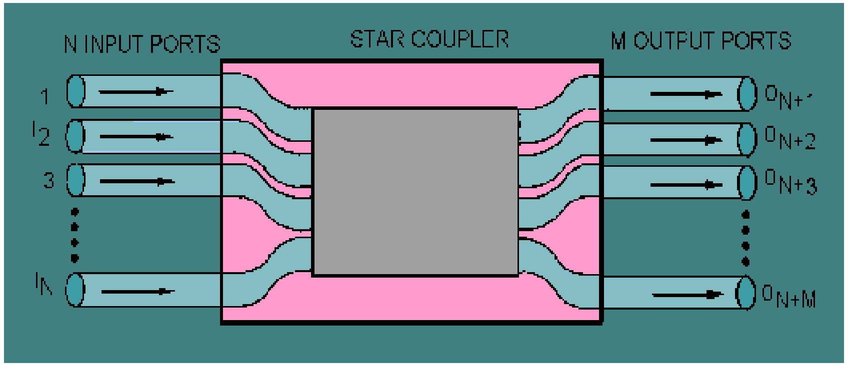
- An **X coupler** combines the functions of the optical splitter and combiner.

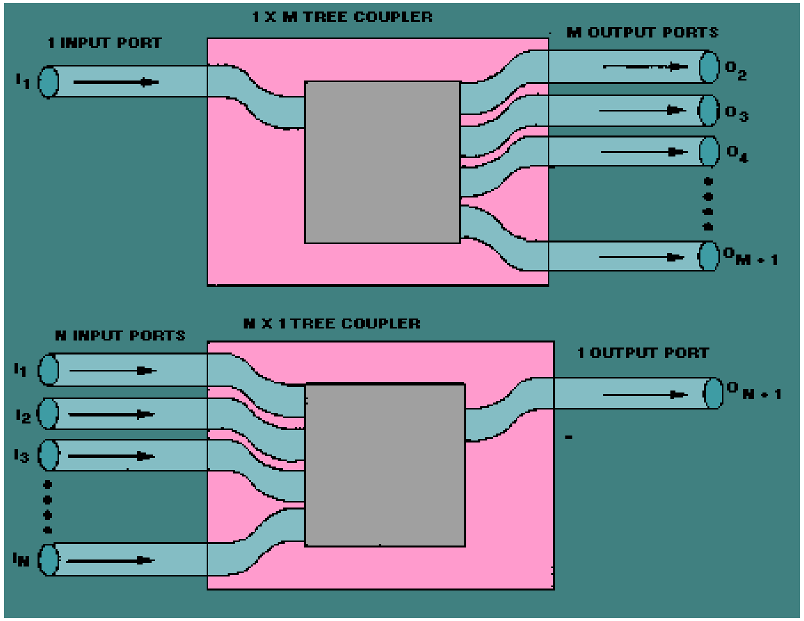
- The X coupler combines and divides the optical power from the two input fibers between the two output fibers. Another name for the X coupler is the 2 X 2 coupler.



Star and Tree Coupler

- Star and tree couplers are multiport couplers that have more than two input or two output ports.
- A star coupler is a passive device that distributes optical power from more than two input ports among several output ports.
- A tree coupler is a passive device that splits the optical power from one input fiber to more than two output fibers.





A four-port multimode fiber FBT coupler has 60 μW optical power launched into port 1. The measured output powers at ports 2, 3 and 4 are 0.004, 26.0 and 27.5 μW respectively. Determine the excess loss, the insertion losses between the input and output ports, the crosstalk and the split ratio for the device.

The excess loss for the coupler may be obtained from

$$\text{Excess loss} = 10 \log_{10} \frac{P_1}{(P_3 + P_4)} = 10 \log_{10} \frac{60}{53.5} = 0.5 \text{ dB}$$

The insertion loss is provided by

$$\text{Insertion loss (ports 1 to 3)} = 10 \log_{10} \frac{P_1}{P_3} = 10 \log_{10} \frac{60}{26} = 3.63 \text{ dB}$$

$$\text{Insertion loss (ports 1 to 4)} = 10 \log_{10} \frac{60}{27.5} = 3.39 \text{ dB}$$

$$\text{Crosstalk} = 10 \log_{10} \frac{P_2}{P_1} = 10 \log_{10} \frac{0.004}{60} = -41.8 \text{ dB}$$

$$\text{Split ratio} = \left[\frac{P_3}{(P_3 + P_4)} \times 100\right] = \frac{26}{53.5} \times 100 = 48.6\%$$

A 32×32 port multimode fiber transmissive star coupler has 1 mW of optical power launched into a single input port. The average measured optical power at each output port is 14 μW. Calculate the total loss incurred by the star coupler and the average insertion loss through the device.

The total loss incurred by the star coupler comprises the splitting loss and the excess loss through the device.

$$\text{Splitting loss} = 10 \log_{10} N = 10 \log_{10} 32 \quad = 15.05 \text{ dB}$$

$$\text{Excess loss} = 10 \log_{10}\left(P_i \Big/ \sum_{1}^{N} P_j\right) = 10 \log_{10}(10^3/32 \times 14) \quad = 3.49 \text{ dB}$$

Hence the total loss for the star coupler:

$$\text{Total loss} = \text{splitting loss} + \text{excess loss} \quad = 15.05 + 3.49 = 18.54 \text{ dB}$$

A 32 × 32 port multimode fiber transmissive star coupler has 1 mW of optical power launched into a single input port. The average measured optical power at each output port is 14 μW. Calculate the total loss incurred by the star coupler and the average insertion loss through the device.

The average insertion loss from the input port to an output port is provided by

$$\text{Insertion loss} = 10 \log_{10} \frac{10^3}{14} = 18.54 \text{ dB}$$

Therefore, as may have been anticipated, the total loss incurred by the star coupler is equivalent to the average insertion loss through the device. This result occurs because the total loss is the loss incurred on a single (average) optical path through the coupler which effectively defines the average insertion loss for the device.

A number of three-port single-mode fiber couplers are utilized in the fabrication of a tree (ladder) coupler with 16 output ports. The three-port couplers each have an excess loss of 0.2 dB with a split ratio of 50%. In addition, there is a splice loss of 0.1 dB at the interconnection of each stage. Determine the insertion loss associated with one optical path through the device.

Solution: The number of stages M within the ladder design is given by $2^M = 16$. Hence $M = 4$. Thus the excess loss through four stages of the coupler with three splices is:

$$\text{Excess loss} = (4 \times 0.2) + (3 \times 0.1) \quad = 1.1 \text{ dB}$$

Assuming a 50% split ratio at each stage, the splitting loss for the coupler may be

$$\text{Splitting loss} = 10 \log_{10} 16 \quad = 12.04 \text{ dB}$$

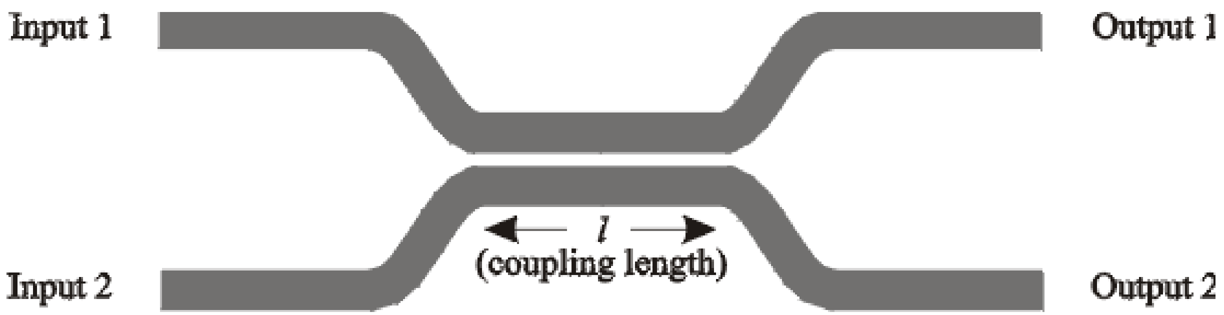
Hence the insertion loss for the coupler which is equivalent to the total loss for one optical path though the device is:

$$\text{Insertion loss} = \text{splitting loss} + \text{excess loss (four stages)}$$

$$= 12.04 + 1.1 = 13.14 \text{ dB}$$

Directional Coupler

Fiber optic couplers should prevent the transfer of optical power from one input fiber to another input fiber.
Directional couplers are fiber optic couplers that prevent this transfer of power between input fibers.
A **symmetrical coupler** transmits the same amount of power through the coupler when the input and output fibers are reversed.



- Power(Output1) = α Power(Input1)
- Power(Output2) = (1- α) Power(Input1)
- α = *coupling ratio= P2/(P1+P2)*
  - Power splitter if α=1/2: 3-dB coupler
  - Tap if α close to 1

Coupler Applications

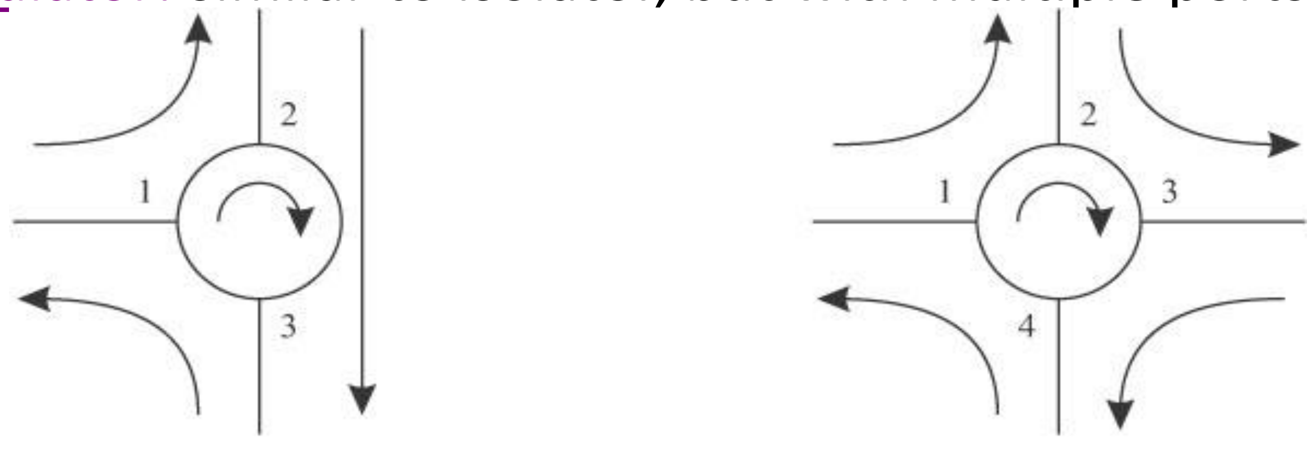
- Applied in system architectures that use more complex link designs that requires multi-port or other types of connections.

- In many cases these types of systems require fiber optic components that can redistribute (combine or split) optical signals throughout the system.

- Couplers are used for monitoring WDM ports and for passively adding channels into a fiber

Isolators and Circulators

- *Extension of coupler concept*
- *Non-reciprocal* => will not work same way if inputs and outputs reversed
- Isolator: allow transmission in one direction, but block all transmission (eg: reflection) in the other
- Circulator: similar to isolator, but with multiple ports.



(a) (b)

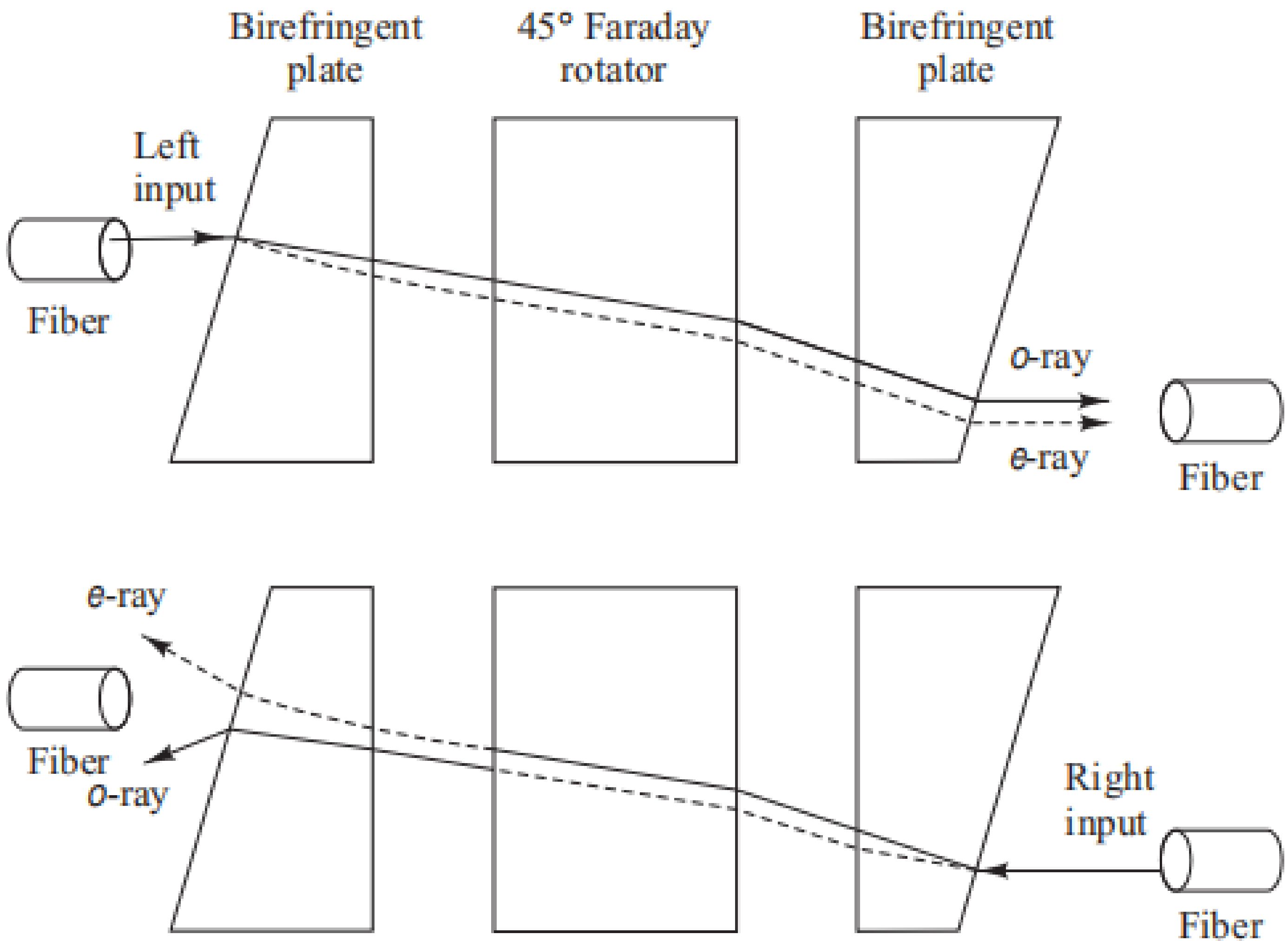
Facts about polarization and polarization-sensitive components

- Light can be represented as a combination of a parallel vibration and a perpendicular vibration, which are called the two orthogonal plane polarization states of a light wave.
- A polarizer is a material or device that transmits only one polarization component and blocks the other.
- A Faraday rotator is a device that rotates the state of polarization (SOP) of light passing through it by a specific angular amount.
- A device made from birefringent materials (called a walk-off polarizer) splits the light signal entering it into two orthogonally (perpendicularly) polarized beams.
- A half-wave plate rotates the SOP of a lightwave by 90°; for example, it converts right circularly polarized light to left circularly polarized light.

Optical Isolators

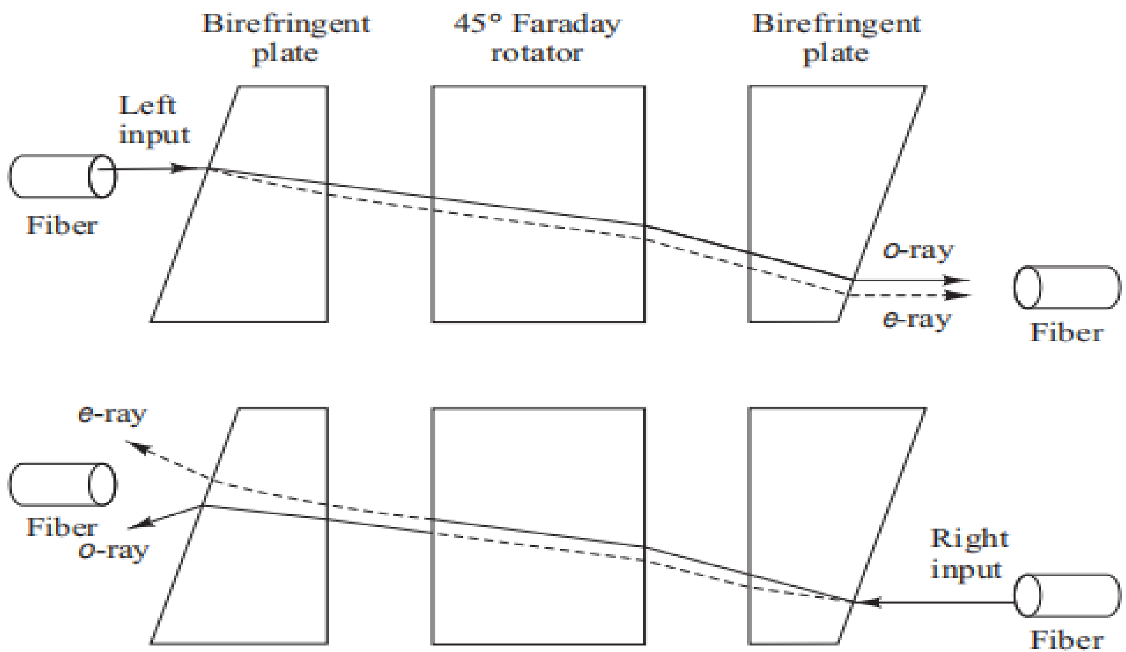
- Optical isolators are devices that allow light to pass through them in only one direction.
- This is important in a number of instances to prevent scattered or reflected light from traveling in the reverse direction.
- One common application of an optical isolator is to keep such backward-traveling light from entering a laser diode and possibly causing instabilities in the optical output.

Polarization-independent isolator



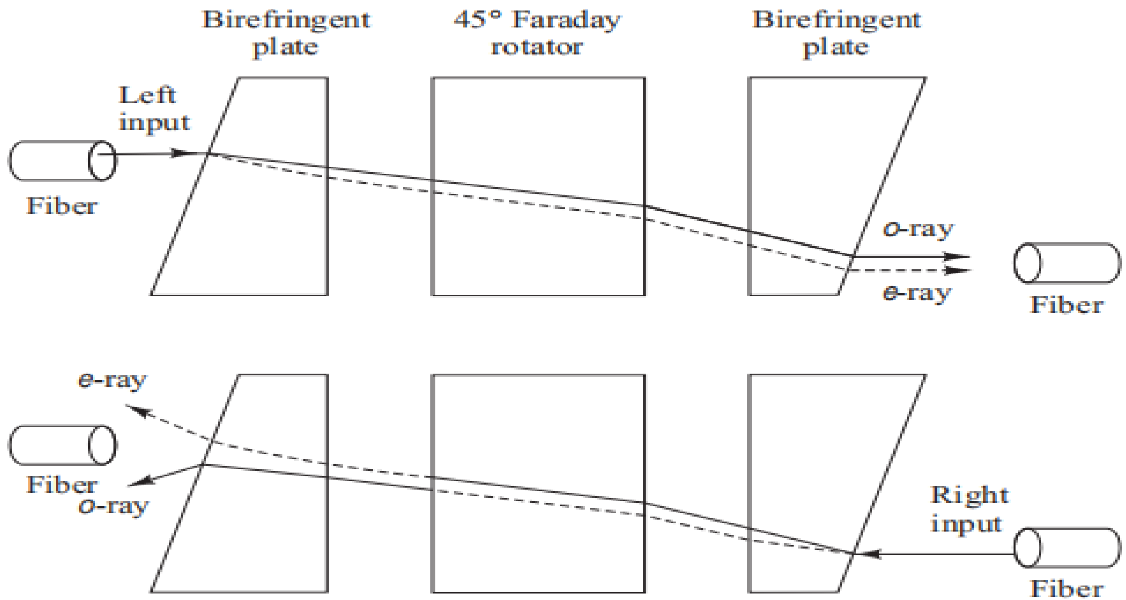
Design and operation of a polarization-independent isolator made of three miniature optical components

Polarization-independent isolator



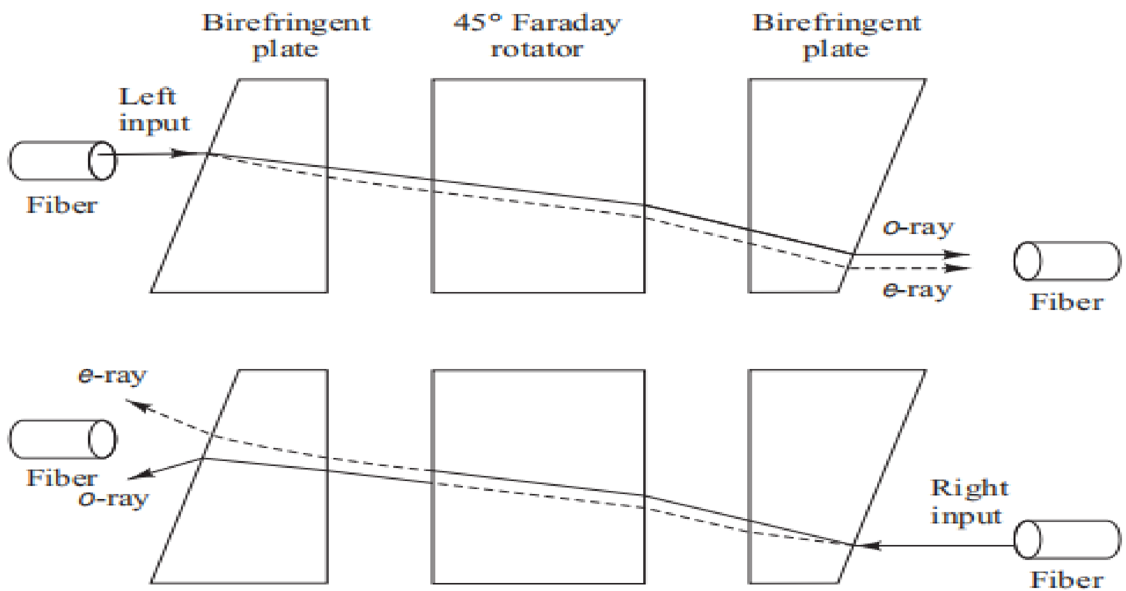
- The core of the device consists of a 45° Faraday rotator that is placed between two wedge-shaped birefringent plates or walk-off polarizers.
- These plates consist of a material such as YVO4 or TiO2.

Polarization-independent isolator



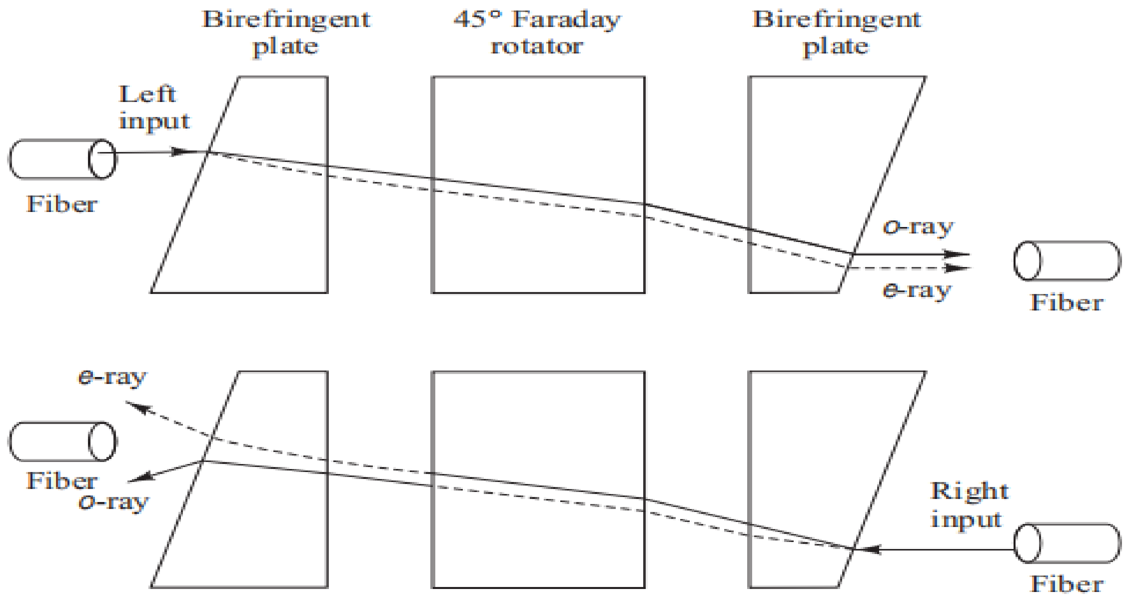
- Light traveling in the forward direction (left to right) is separated into ordinary and extraordinary rays by the first birefringent plate.
- The Faraday rotator then rotates the polarization plane of each ray by 45°.

Polarization-independent isolator



- After exiting the Faraday rotator, the two rays pass through the second birefringent plate.
- The axis of this polarizer plate is oriented in such a way that the relationship between the two types of rays is maintained.
- Thus, when they exit the polarizer, they both are refracted in an identical parallel direction.

Polarization-independent isolator



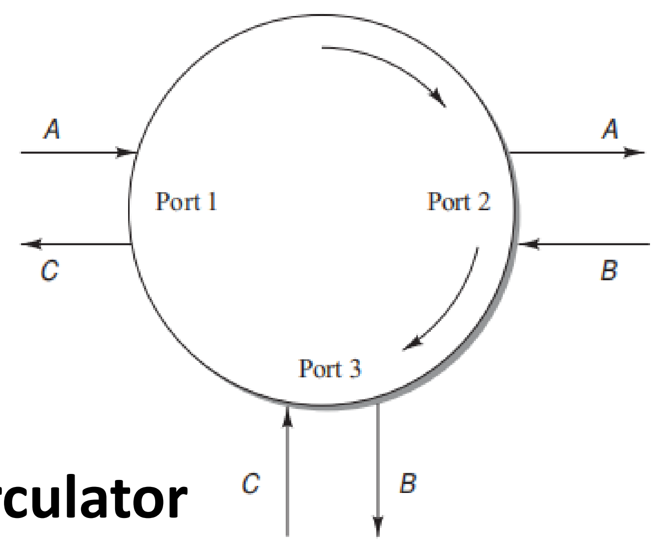
- Going in the reverse direction (right to left), the relationship of the ordinary and extraordinary rays is reversed when exiting the Faraday rotator due to the nonreciprocity of the Faraday rotation.
- Consequently, the rays diverge when they exit the left-hand birefringent plate and are not coupled to the fiber anymore..

Optical Circulators

▪Optical circulator is a non-reciprocal multi-port passive device that directs light sequentially from port to port in only one direction.

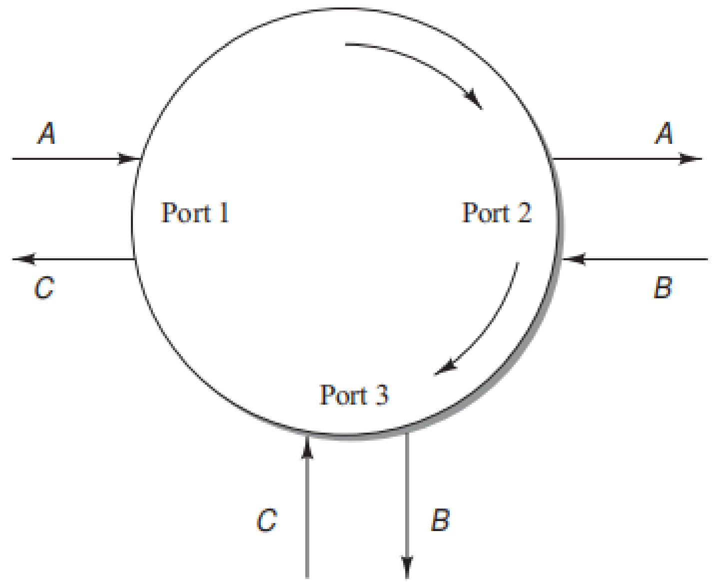
▪The device is used in **optical amplifiers, add/drop multiplexers and dispersion compensation modules.**

▪The operation is similar to an isolator except that its construction is more complex.



Three port circulator

Three Port Circulators



- Typically it consists of a number of walk-off polarizers, half-wave plates, and Faraday rotators and has three or four ports.

- Here an input on port 1 is sent out on port 2, an input on port 2 is sent out on port 3, and an input on port 3 is sent out on port 1.

Four Port Circulators

- Similarly, in a four-port device ideally one could have four inputs and four outputs if the circulator is perfectly symmetrical.

- However, in actual applications it usually is not necessary to have four inputs and four outputs.

- Furthermore, such a perfectly symmetrical circulator is rather tedious to fabricate.

- Therefore in a four-port circulator it is common to have three input ports and three output ports, making port 1 be an input-only port, 2 and 3 being input and output ports, and port 4 be an output only port.

Wavelength Selective Devices

These perform their operation on the incoming optical signal as a function of the wavelength

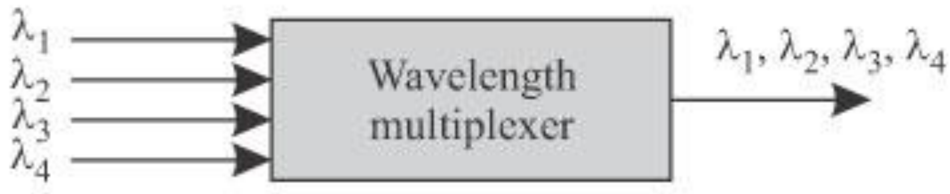
Examples:

- Wavelength add/drop multiplexers
- Wavelength selective optical combiners/splitters
- Wavelength selective switches and routers

Multiplexers, Filters, Gratings

- Wavelength selection technologies…

(a)



(b)

Fiber Bragg Grating

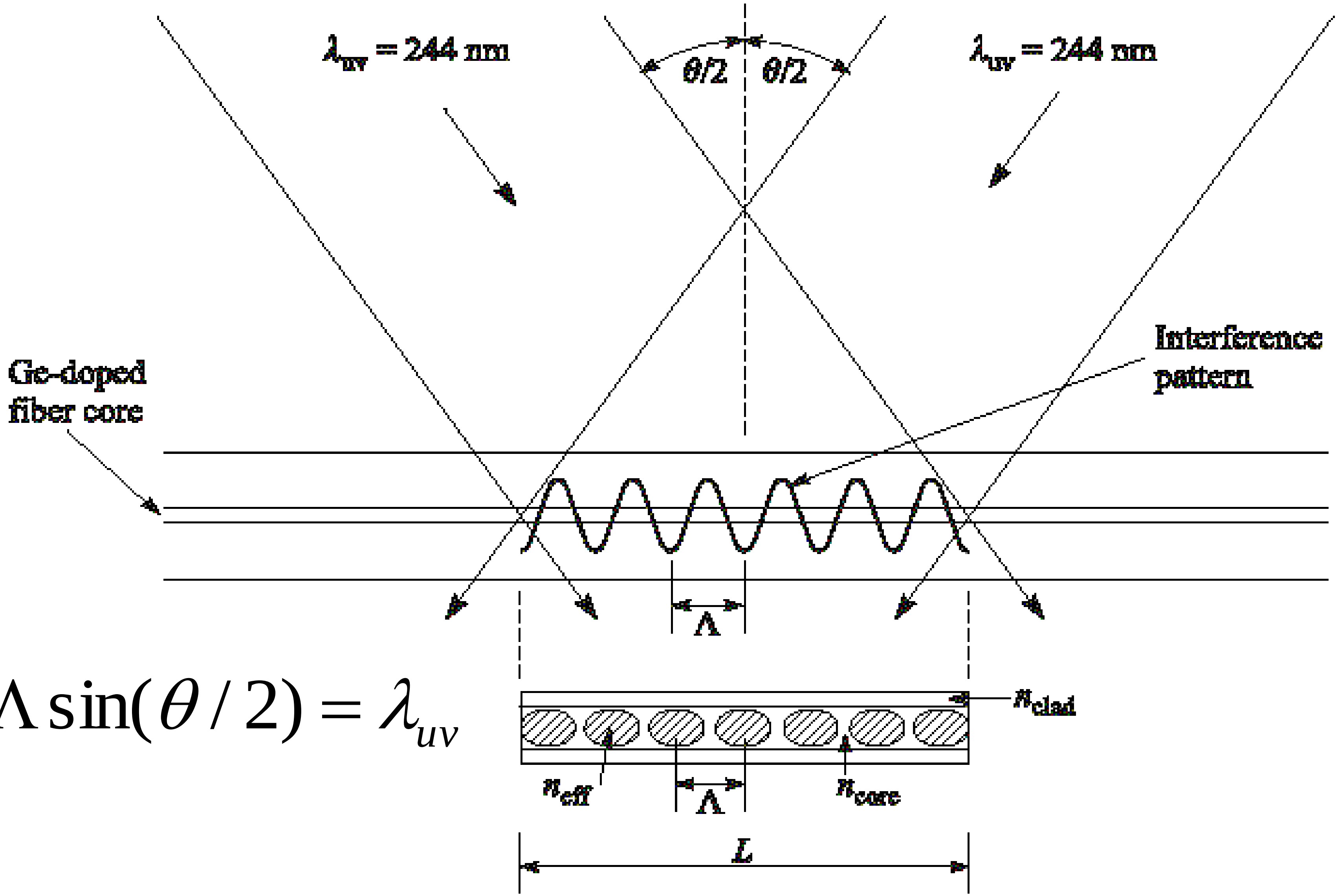
Fiber Bragg Grating

- This is invented at Communication Research Center, Ottawa, Canada
- The FBG has changed the way optical filtering is done
- The FBG changes a single mode fiber (all pass filter) into a wavelength selective filter
- Important element in WDM system for combining and separating individual wavelengths.
- A grating is a periodic structure or perturbation in a material.

Fiber Brag Grating (FBG)

- FBG is a narrow band reflection filter that is fabricated through a photo imprinting process.
- One can induce a change in the refractive index of the core by exposing it to ultraviolet radiation such as 244nm.
- Grating play an important role in:
  - Wavelength filtering
  - Dispersion compensation
  - Optical sensing
  - EDFA Gain flattening
  - Single mode lasers and many more areas

Bragg Grating formation



$$2\Lambda \sin(\theta / 2) = \lambda_{uv}$$

Fiber Brag Grating (FBG)

- It is a reflective device composed of an optical fiber that contains a modulation of its core refractive index over a certain length.
- Fiber grating is made by periodically changing the refraction index in the glass core of the fiber.
- The grating reflects light propagation through fiber, when its wavelength corresponds to modulation periodicity.
- The reflected wavelength is called Bragg wavelength (λ_B)

$$\lambda_B = 2n_{eff}\Lambda$$

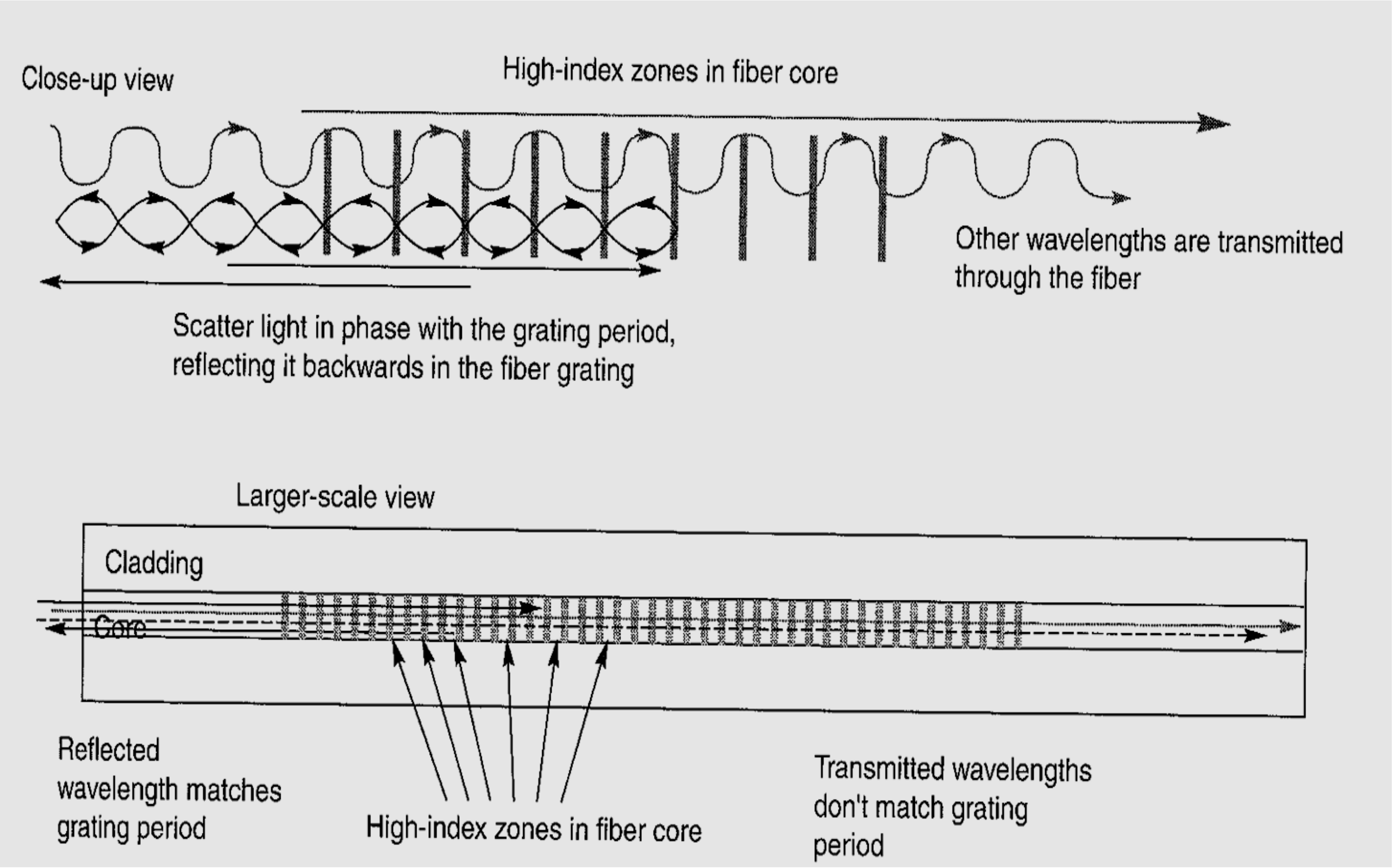
FBG Theory

Exposure to the high intensity UV radiation changes the fiber core *n(z)* permanently as a periodic function of *z*

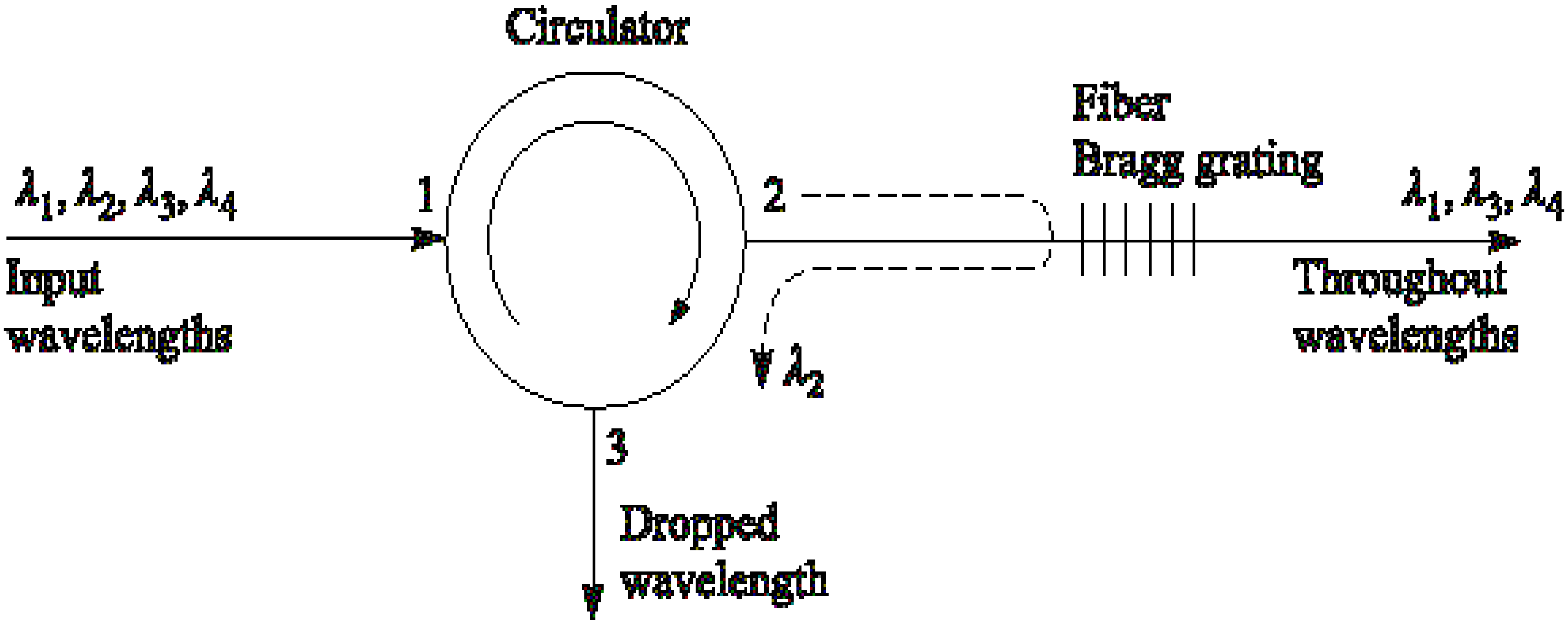
$$n(z) = n_{core} + \delta n[1 + \cos(2\pi z / \Lambda)]$$

z:	Distance measured along fiber core axis
Λ:	Pitch of the grating
n_{core}:	unexposed core refractive index
δn:	photo induced change in the index

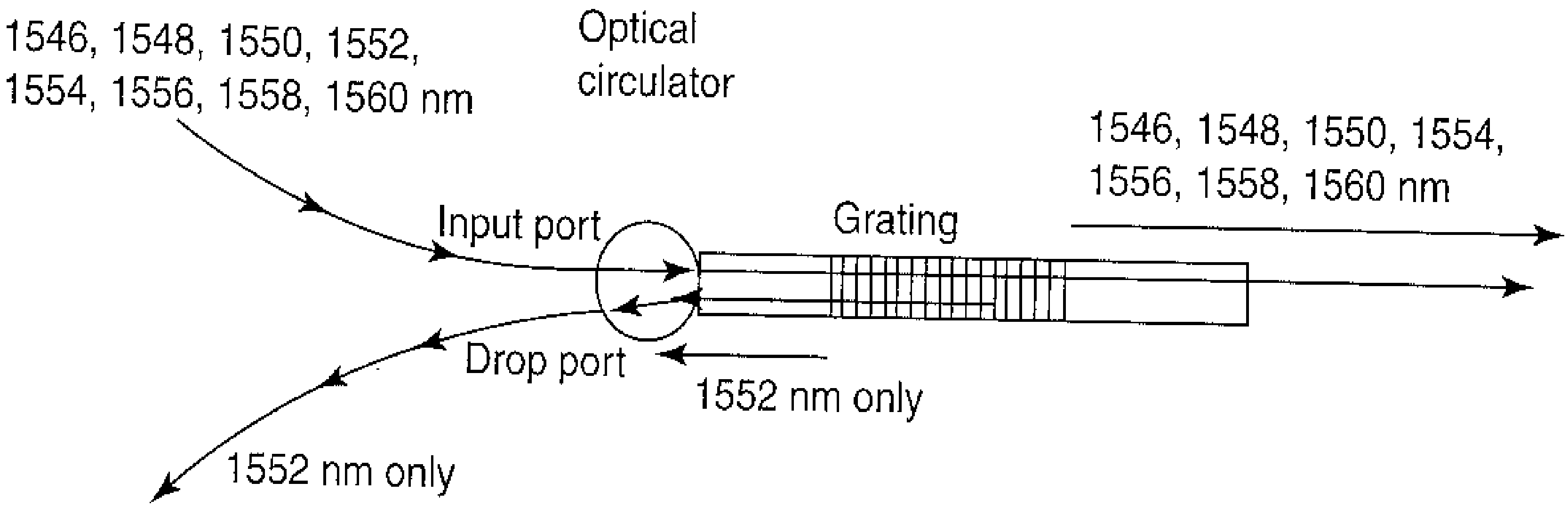
Reflection at FBG



Simple De-multiplexing Function



Wavelength Selective DEMUX



FBG Properties

Advantages

- Easy to manufacture, low cost, ease of coupling
- Low losses – approx. 0.3 db or less
- Polarization insensitive, simple packaging.
- Passive devices

Disadvantages

- Sensitive to temperature and strain.
- Any change in temperature or strain in a FBG causes the grating period and/or the effective refractive index to change, which causes the Bragg wavelength to change.

Interferometers

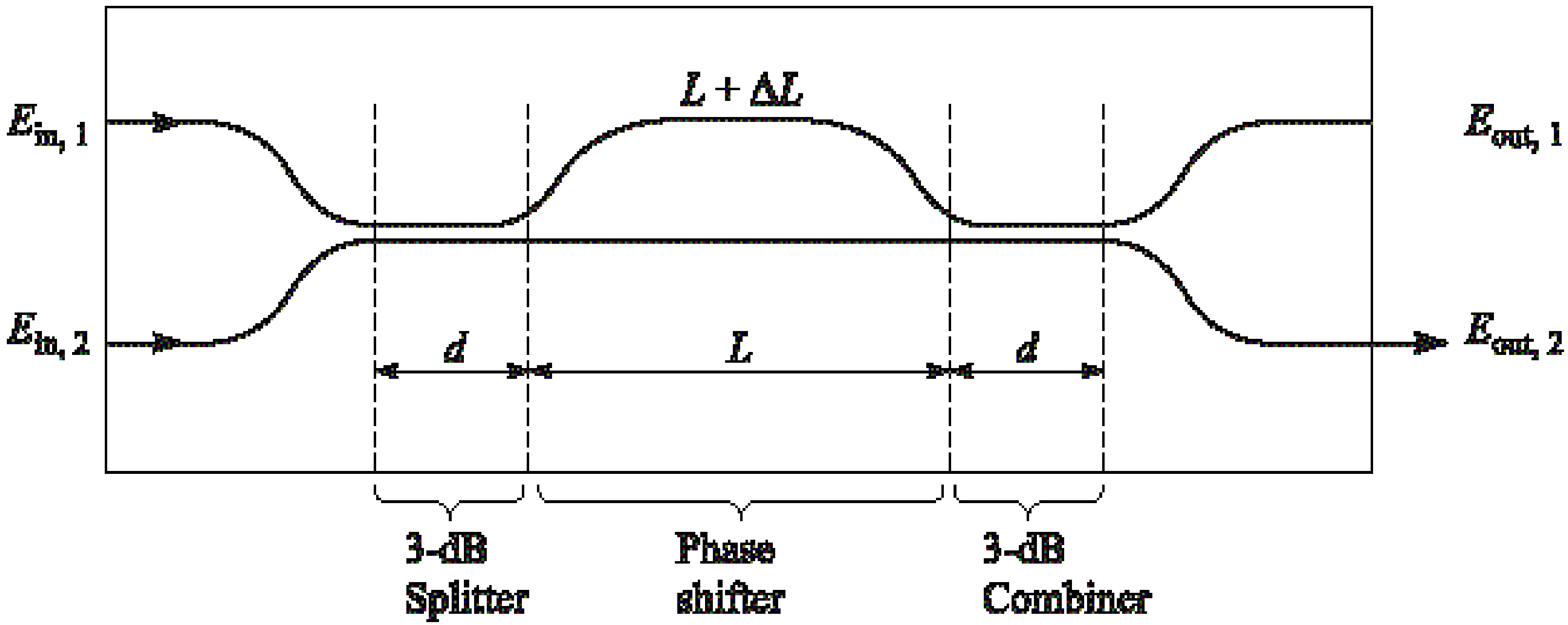
Mach-Zender Interferometer Multiplexers

- An interferometric device uses 2 interfering paths of different lengths to resolve wavelengths
- Wavelength dependant multiplexers can also be made using Mach-Zender interferometry techniques.

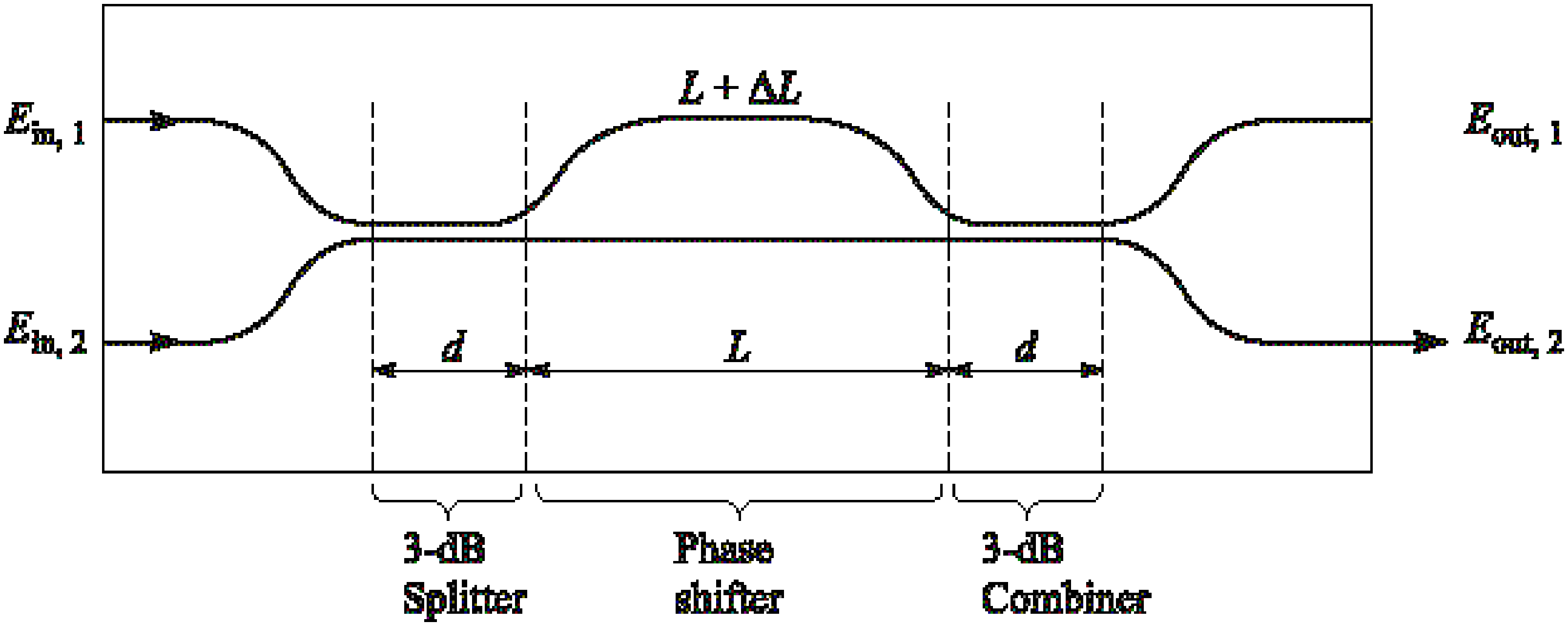
- Typical configuration:
  - Initial 3-dB directional couplers which splits the input signal
  - A central section where one of the waveguides is longer by ΔL to give a wavelength-dependant phase shift between the two arms.
  - Another 3-dB coupler which recombines the signals at the output.

Mach-Zender Interferometer Multiplexers

- ✓ By splitting the input beam and introducing a phase shift in one of the paths, the recombined signals will interfere constructively at one output and destructively at the other.
- ✓ The signals then finally emerge from only one output port.

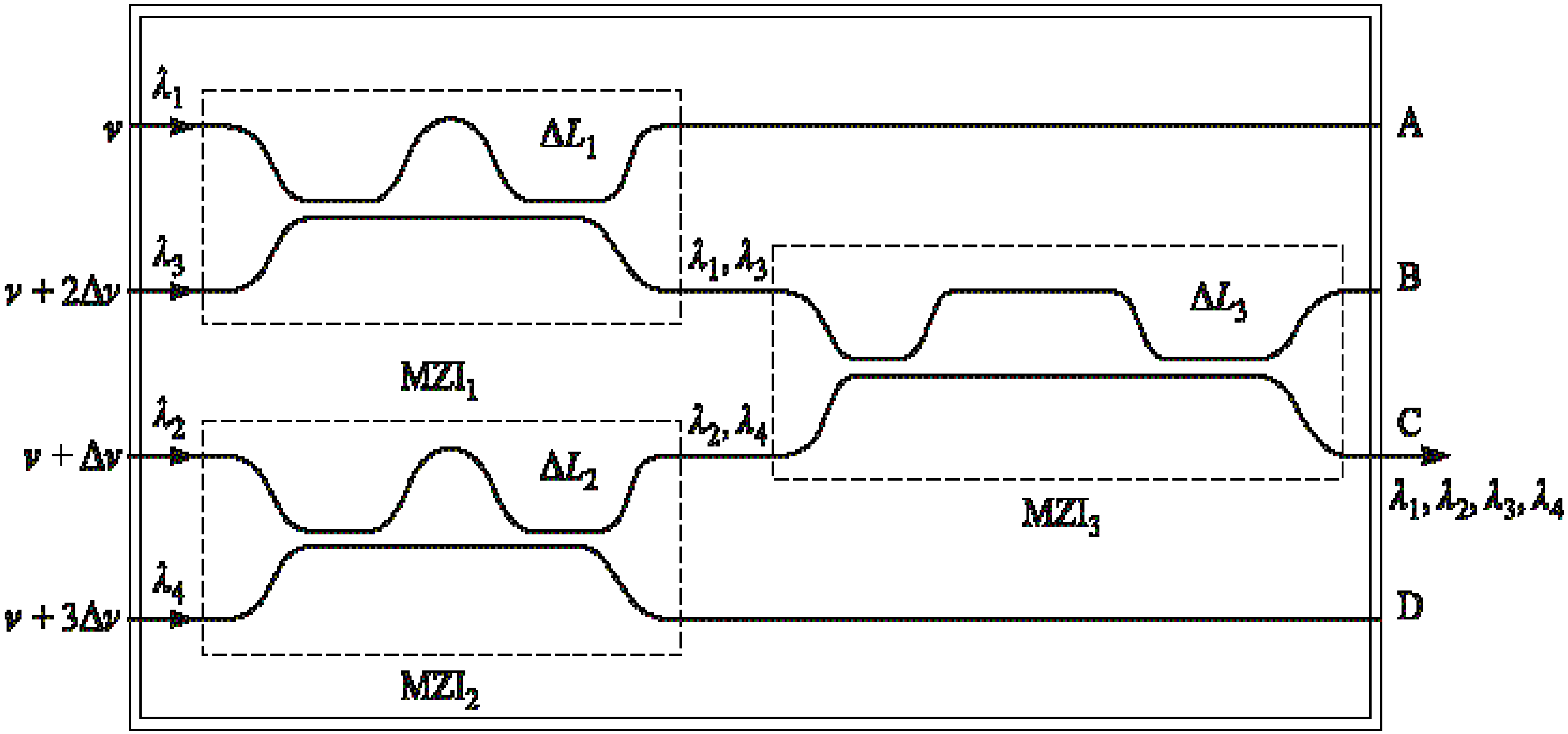


Basic Mach-Zehnder Interferometer



Phase shift of the propagating wave increases with ΔL,
Constructive or destructive interference depending on ΔL

Four-Channel Wavelength Multiplexer



- By appropriately selecting *ΔL,* wavelength multiplexing/de-multiplexing can be achieved

WDM System Performance Issues

- The channel spacing in **WDM** systems must be large enough to prevent interference between adjacent channels. Most WDM systems use 50-GHz channel spacing, such as ITU-G. 692 that accommodates 80 channels over 4 THz.

- **Wavelength Division Multiplexing (WDM)** has one of the major problems related to WDM optical communication systems is FWM (Four wave mixing). Other nonlinear effects are cross talk (linear cross talk and Raman cross talk), SBS, SRS and XPM.

- **Unlike the linear effects which can be compensated**, the nonlinear effects accumulate and degrade the system-performance.

DISPERSION COMPENSATION TECHNIQUES

- Dispersion compensation techniques are used to correct dispersion-induced distortion in optical fiber communication. The most commonly employed techniques for dispersion compensation are as follows:
- **Dispersion compensating fibers (DCFs)**
- DCFs have a negative dispersion that compensates for the positive dispersion of the transmission fiber. DCFs can be placed before, after, or mixed throughout the standard fiber (SMF).
- This is known as pre, post, or symmetrical compensation. DCFs are stable and have low insertion loss.

DISPERSION COMPENSATION TECHNIQUES

- **Fiber Bragg gratings (FBGs)**

FBGs are periodic structures in the fiber that delay the arrival time of specific wavelengths of light.

- **Electronic dispersion compensation (EDC)**

EDC uses digital signal processing techniques to correct dispersion-induced distortion. This method is effective but adds complexity and cost to the communication system.

- **Optical phase conjugation technique (OPCT)**

Optical phase conjugation (OPC) is a nonlinear optical technique that reverses the phase or wavefront variations of an optical beam.

This technique can be used to compensate for distortions ocuuring through dispersion.

Optical Amplifiers

Prof. Dr.G. Aarthi
Associate Professor
SENSE,VIT,Vellore

Optical Amplifiers

- Why is there a requirement for optical amplifiers?

  => Light signal over long distances become attenuated.

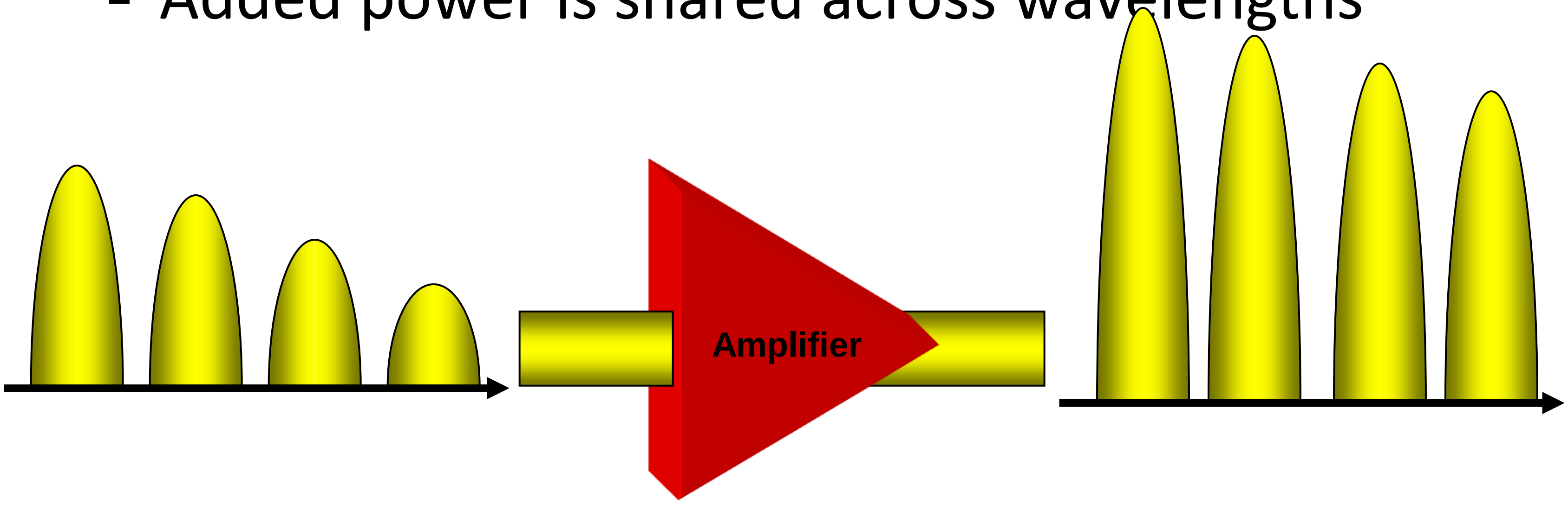
  => Regeneration of the light signal is necessary especially over distances of perhaps several thousand kilometers.

  => The overhead of photo detection to electrical conversions and back to light via a laser diode contributes to high cost .

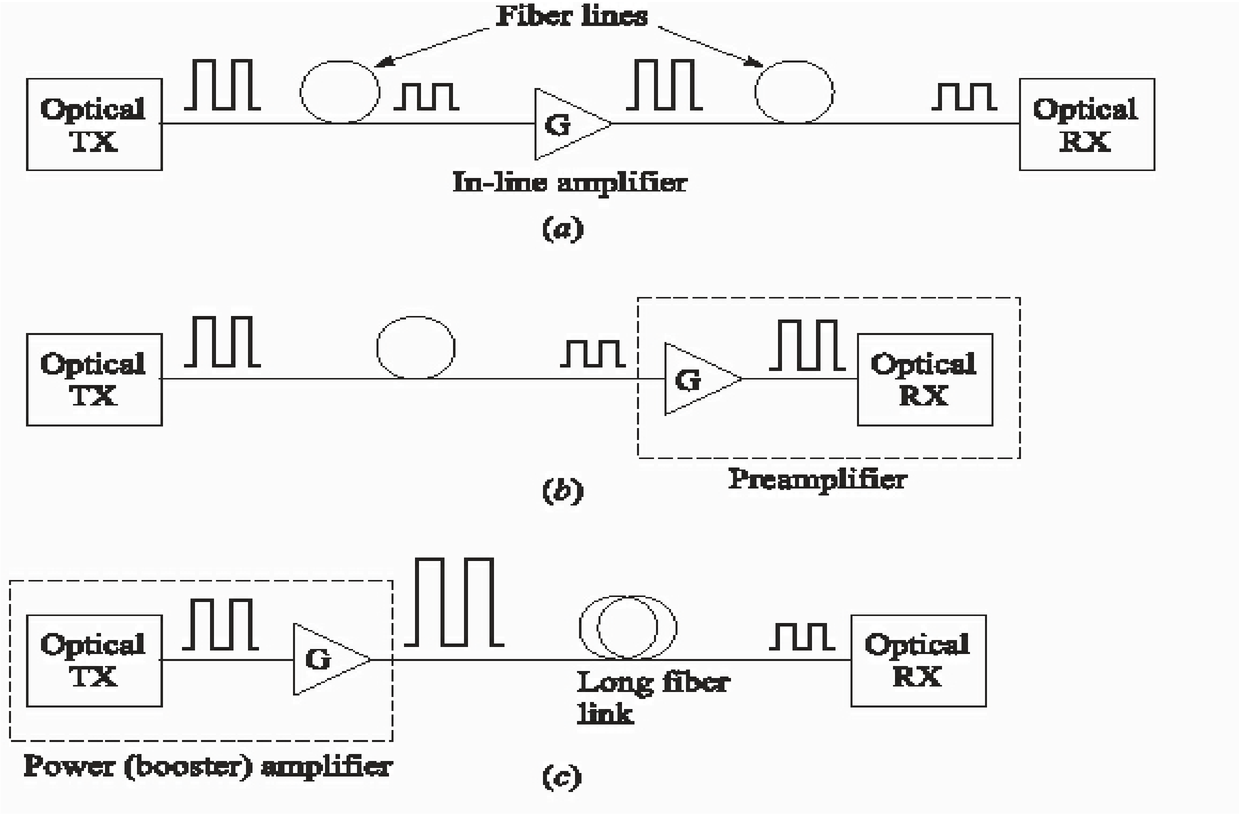
  Optical Amplifiers: EDFA, Raman, SOA.

What is an Optical Amplifier?

- Main function is to amplify received light pulses
  - Amplifies without converting pulses to electrical form
  - Amplifies many wavelengths simultaneously
  - Added power is shared across wavelengths



Applications of optical amplifiers



Applications of optical amplifiers

- In Line Optical Amplifiers

✓ A single mode link does not require a complete regeneration of the signal, simple amplification of the optical signal is sufficient.

✓ In-Line optical amplifiers can be used to compensate for transmission loss and increase the distance between regenerative repeaters.

- Pre Amplifiers

✓ Weak Optical signal is amplified before photo detection so that the SNR degradation caused by thermal noise in the receiver is suppressed.

✓ Preamplifier provides a larger gain factor and a broader bandwidth.

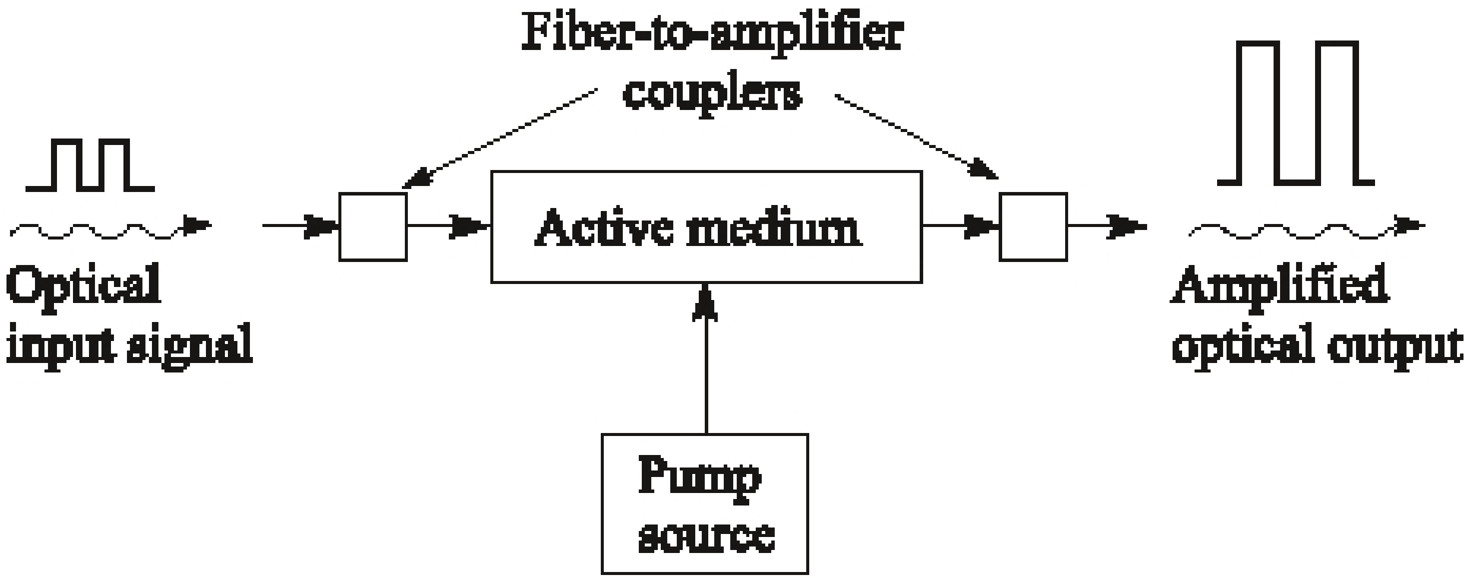
Applications of optical amplifiers

- Power Amplifiers

✓ Power or booster amplifier applications include placing the device immediately after an optical transmitter to boost the transmitted power.

✓ Eg, Using this boosting technique together with an optical preamplifier at the receiving end can enable repeater less undersea transmission distances of 200-250 km.

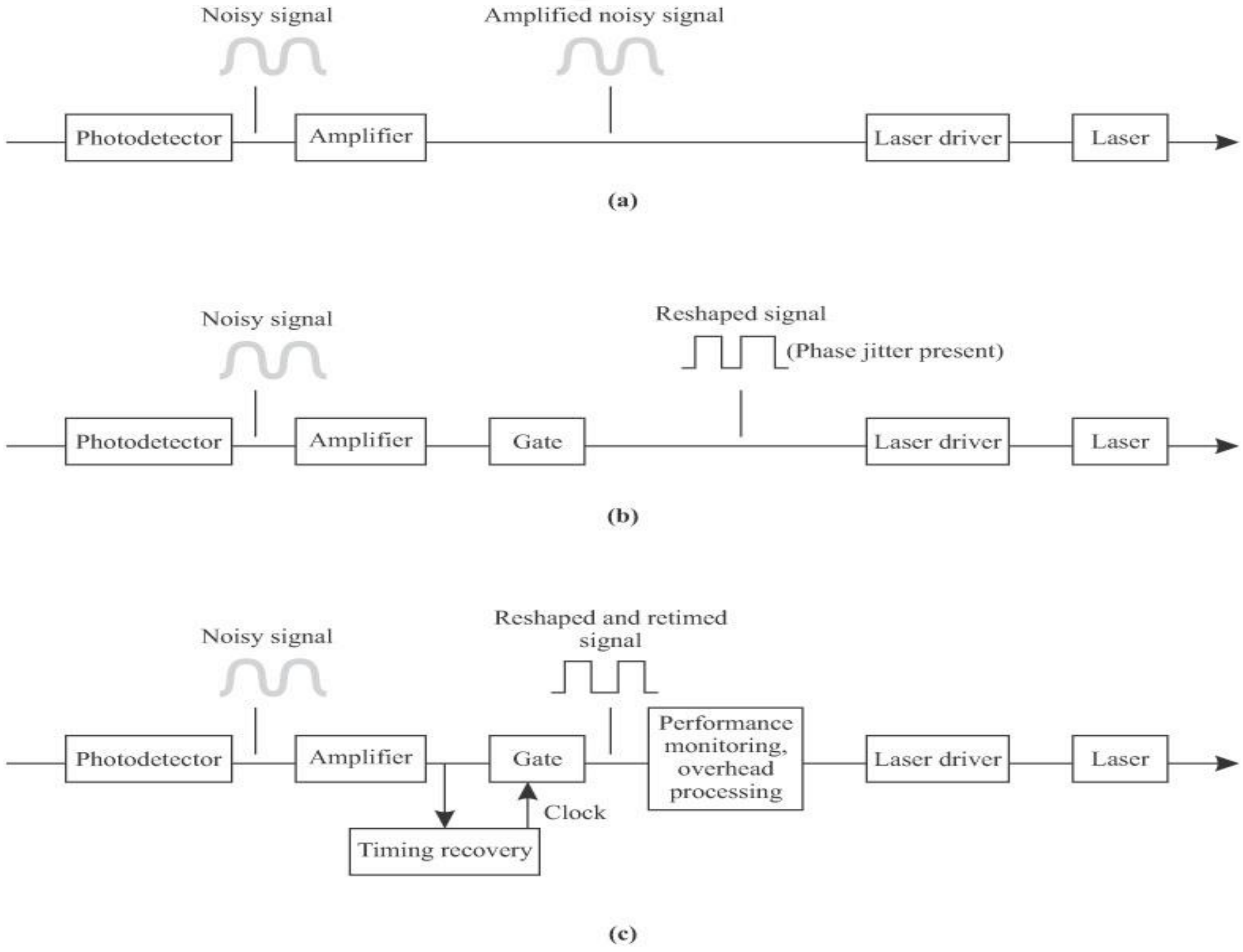
Generic optical amplifier



Regenerators

- 1R— Re-amplify
- 2R— Re-amplify and reshape
- 3R— Re-amplify, reshape, and retime (Note that a multiwavelength 3R repeater is not practical in a high-capacity DWDM network due to the higher number of wavelengths to regenerate and/or the size, power, and cost associated with each wavelength regenerated)

1R, 2R and 3R Regeneration



OEO Regenerator

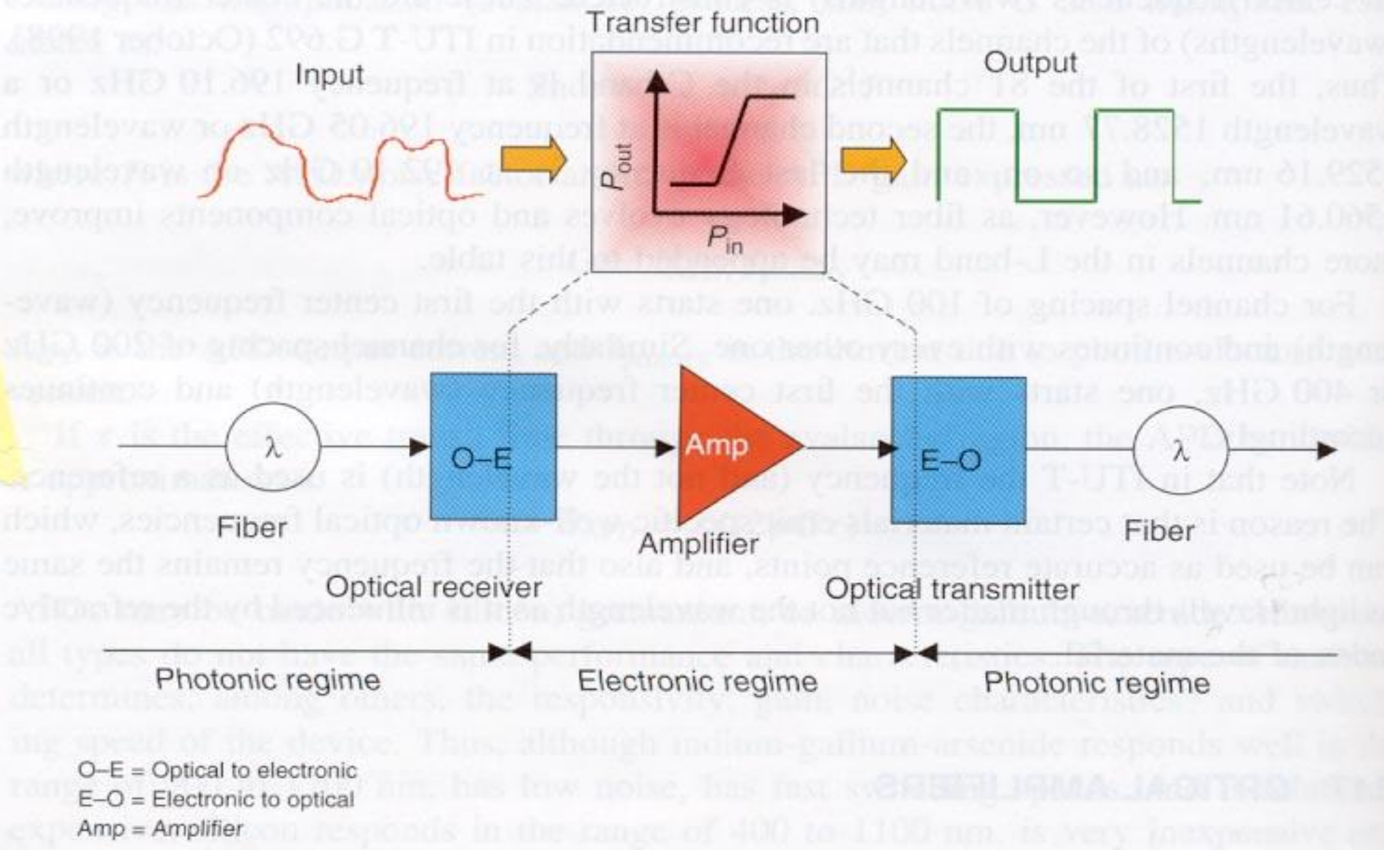


Figure 2.65 The model of a regenerator and the three major functions, optical receiver, electronic amplifier, and optical transmitter.

Regenerators vs O-Amplifiers

- Regenerators specific to bit rate and modulation format used; O-Amps are insensitive (I.e. *transparent*)
- A system with optical amplifiers can be more *easily upgraded* to higher bit rate w/o replacing the amplifiers
- Optical amplifiers have *large gain bandwidths* => key enabler of DWDM

- Issues:
  - Amplifiers introduce additional noise that accumulates
  - Spectral shape of gain (flatness), output power, transient behavior need to be carefully designed

Optical amplifiers

- PDFA— Praseodymium-doped fiber amplifier (1310–1380 nm)
- EDFA— Erbium-doped fiber amplifier (1530–1565 nm)
- GS-EDFA— Gain-shifted EDFA (1565–1625 nm)
- EDTFA— Tellurium-based gain-shifted TDFA (1530–1610 nm)
- GS-TDFA— Gain-shifted thulium-doped fiber amplifier (1490–1530 nm)
- TDFA— Thulium-doped fluoride-based fiber amplifier (1450–1490 nm)
- RFA— Raman fiber amplifier (1420–1650 nm or more)

Optical Amplifier Varieties

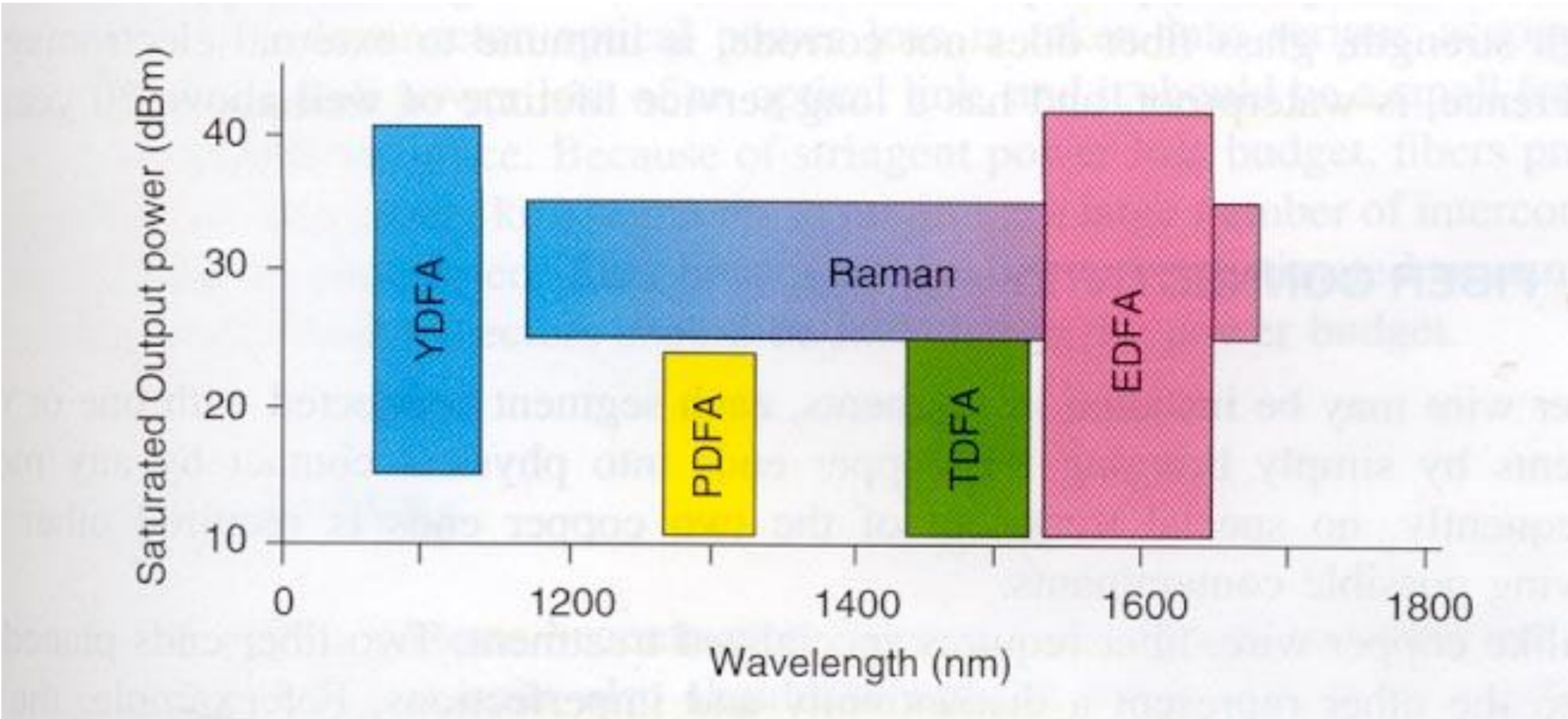
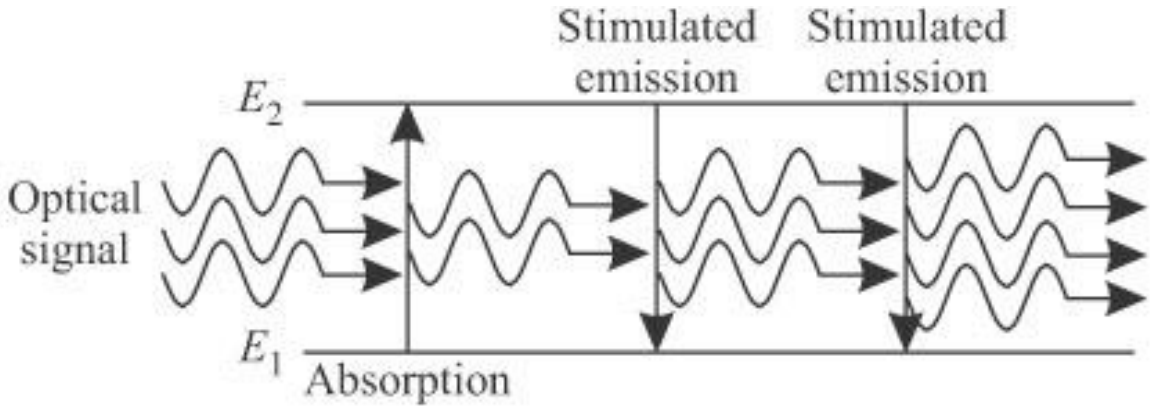


Figure 1.66 Optical amplifiers are many, each suitable for a different spectral range.

Principles: Stimulated Emission

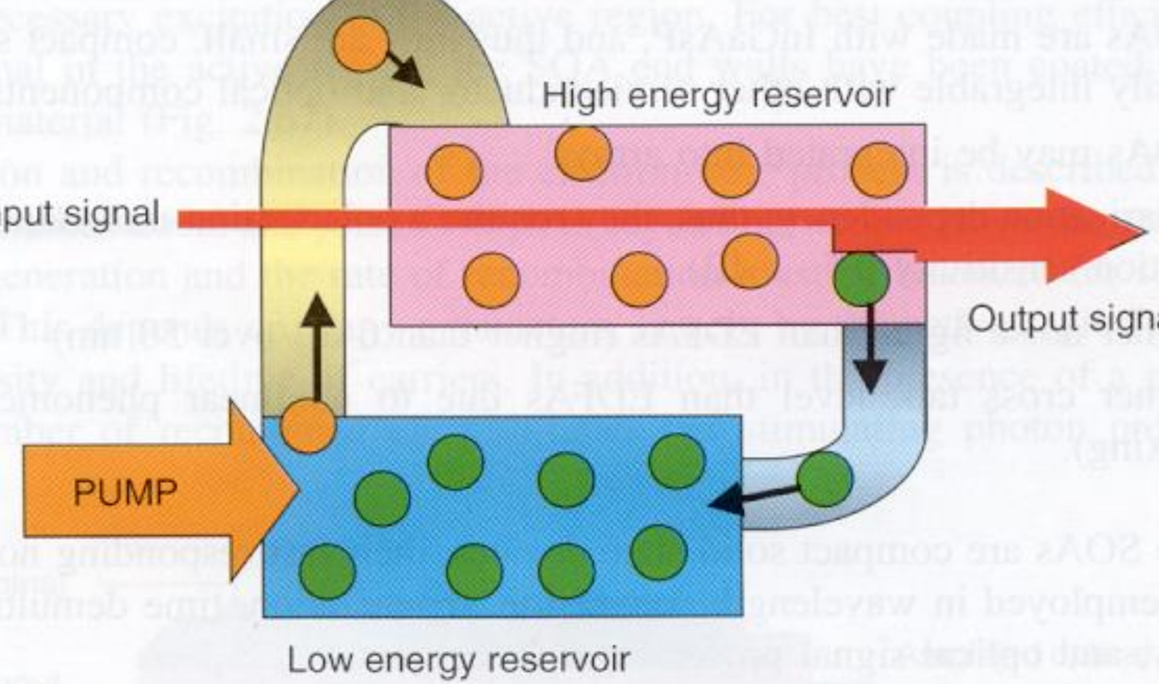
- Transitions between discrete energy levels of atoms accompanied by *absorption* or *emission* of photons
- $E_2 \rightarrow E_1$ can be stimulated by an optical signal
- Resulting photon has *same energy, direction of propagation, phase, and polarization (* coherent*!)*
- If stimulated emission dominates absorption, then we have amplification of signal
- Need to create a "*population inversion*" ($N_2 > N_1$) through a *pumping* process



Spontaneous Emission

- $E_2 \rightarrow E_1$ transitions can be spontaneous (I.e. *independent* of external radiation)
  - The photons are emitted in random directions, polarizations and phase (I.e. incoherent)!
- *Spontaneous emission rate* is a characteristic of the system
  - Amplification of such incoherent radiation happens along with that of incident radiation
  - The amplified spontaneous emission (ASE): appears as noise
  - ASE could saturate the amplifier in certain cases!

Optical Amplification: mechanics



Ions absorb pump energy and are excited to a higher energy reservoir, N_e.

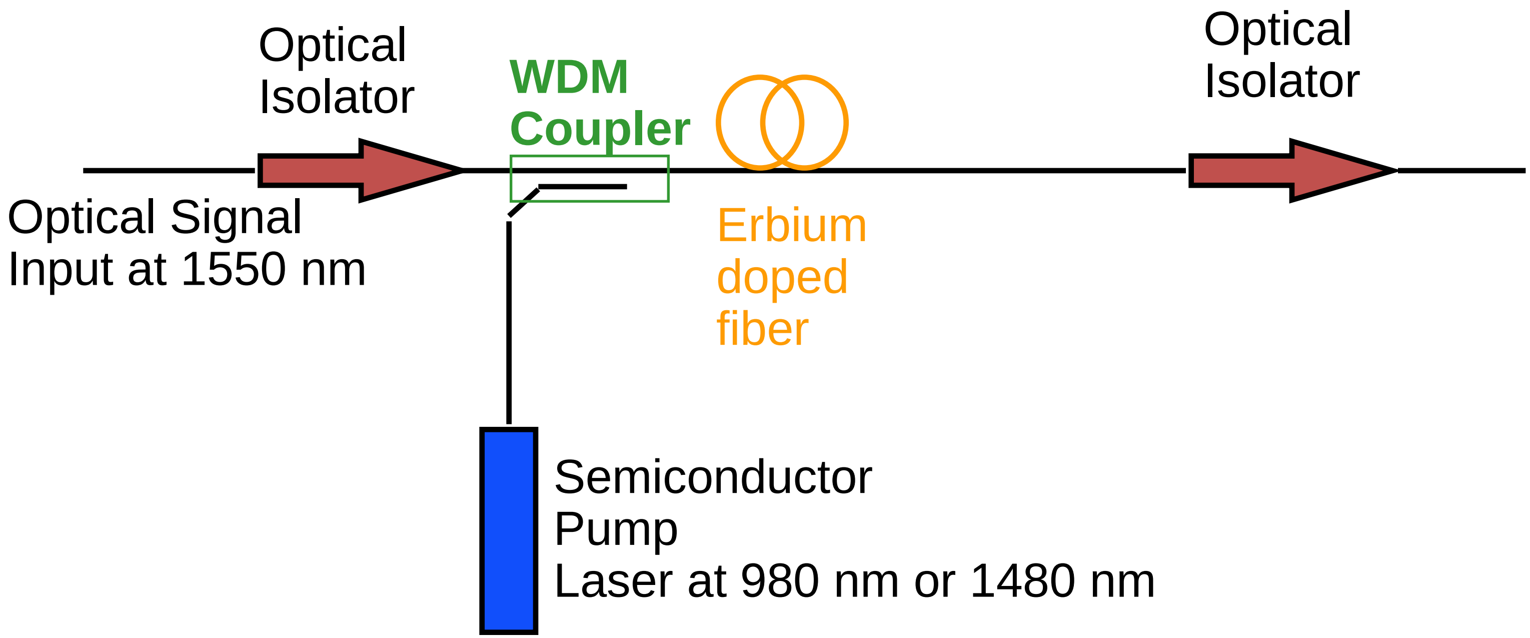
Ions returning to lower energy either by stimulation, N_{st}, or spontaneously, N_{sp}.

Figure 2.68 For sustained amplification, the rate of excitation should be less or equal to the rate of stimulation + the rate of spontaneous emission.

Doped fiber amplifiers

- **Doped fiber amplifiers** (DFAs) are optical amplifiers that use a doped optical fiber as a gain medium to amplify an optical signal.
- The signal to be amplified and a pump laser are multiplexed into the doped fiber, and the signal is amplified through interaction with the doping ions.
- The most common example is the Erbium Doped Fiber Amplifier (EDFA), where the core of a silica fiber is doped with trivalent Erbium ions and can be efficiently pumped with a laser at a wavelength of 980 nm or 1,480 nm, and exhibits gain in the 1,550 nm region.

Basic Construction of EDFA Optical Amplifier

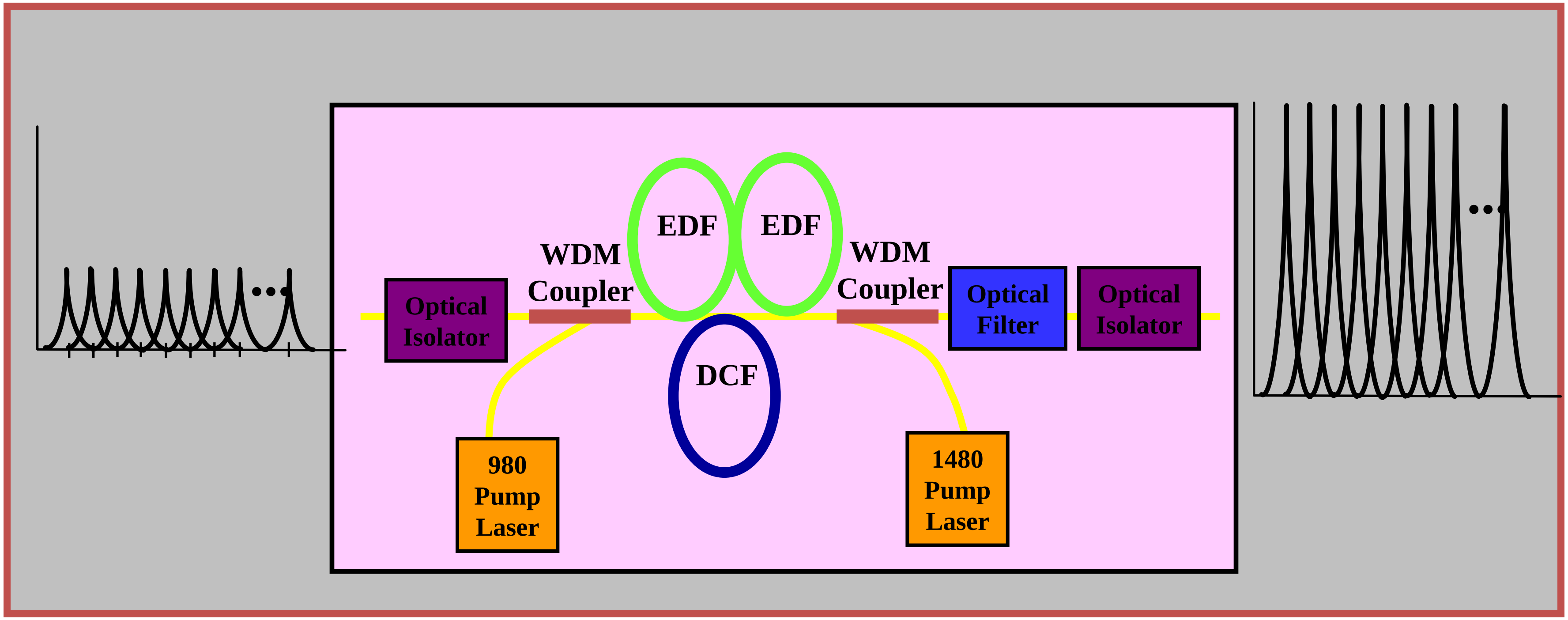


- **Length of fiber:core doped with(rare earth) erbium ions Er^{3+}**
- **Optical Isolators allow light to travel in one direction only**
- **Couplers combines signal & light into erbium Doped Fiber**
- **Pump laser operates at 980nm or 1480nm**
- **Light from pump laser transfers to signal light → Erbium doped fiber**

Why an Erbium Doped Fiber Amplifier ?

- EDFAs provide most gain in the 15XX nm wavelength region
  - Same region where fiber attenuation is at its lowest → bonus!
- Require pump light at shorter wavelengths
  - Either 980nm or 1480nm → understood & cost-effective technology
- Enables optical links over thousands of kilometers
- EDFA doping is optimised for 15xx nm band, do not provide gain in1310nm band

EDFA Enables DWDM!



- **EDFAs** <u>**amplify all λs**</u> **in 1550 window simultaneously**

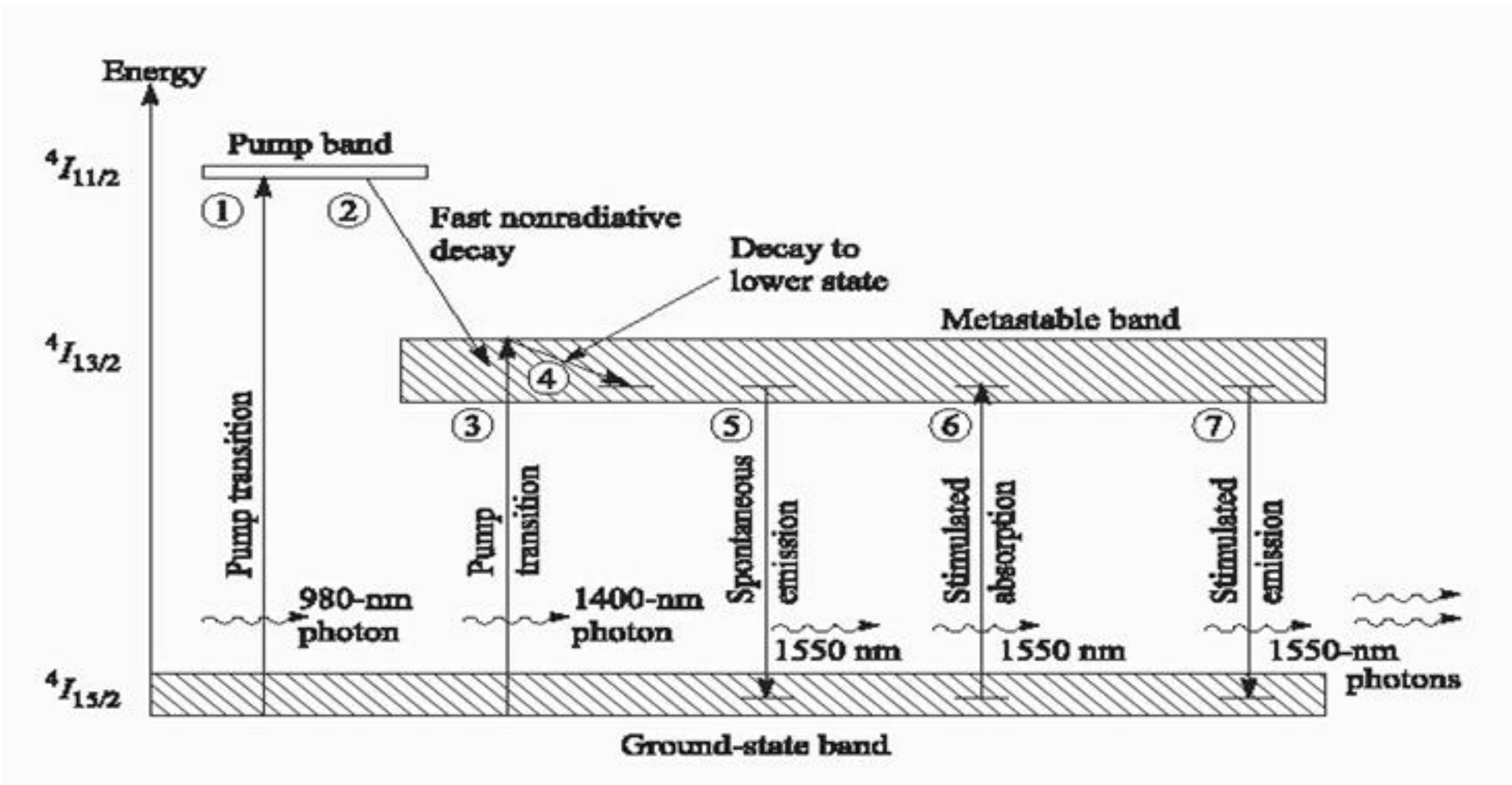
EDFA: Operation

- When **Er^{3+}** ions introduced in silica, electrons disperse into an *energy band* around the lines E_1, E_2, E_3 (Stark splitting)

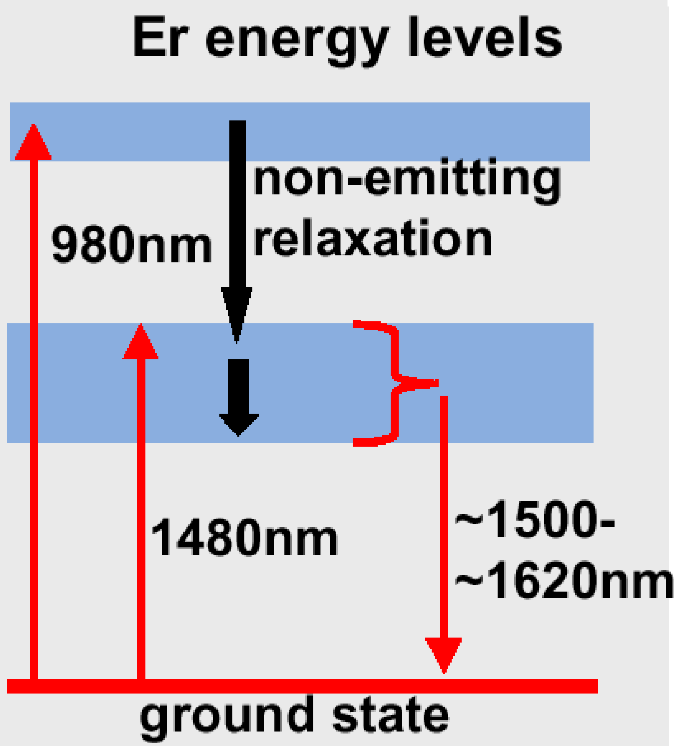
- Within each band, the ion distribution is non-uniform.

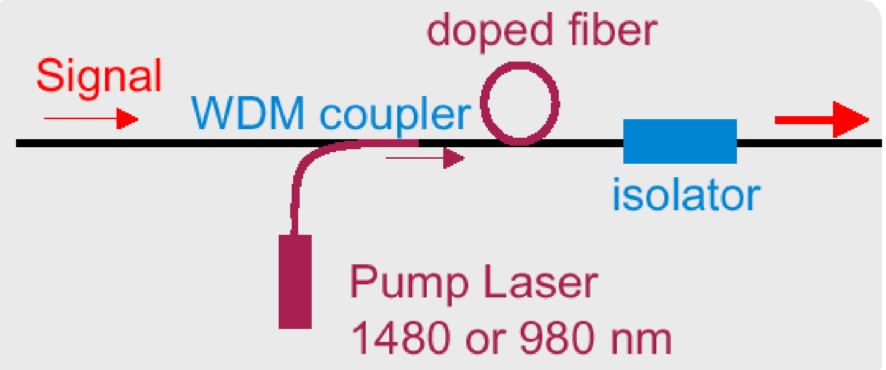
- Due to these effects, a large λ range (50 nm) can be simultaneously amplified & luckily it is in the 1530nm range

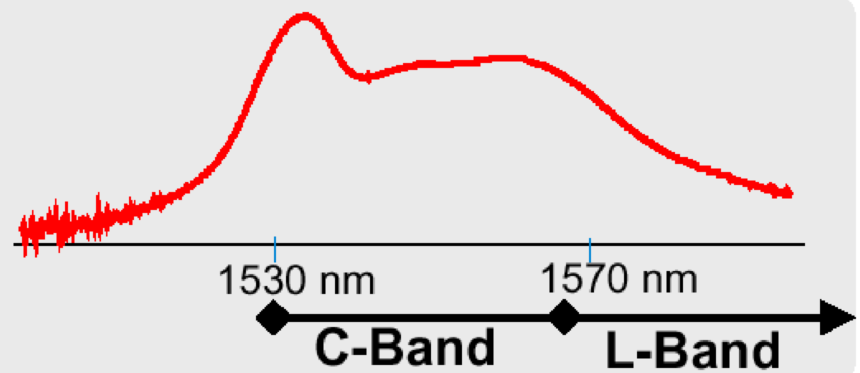
EDFA: Operation



EDFA Pumping



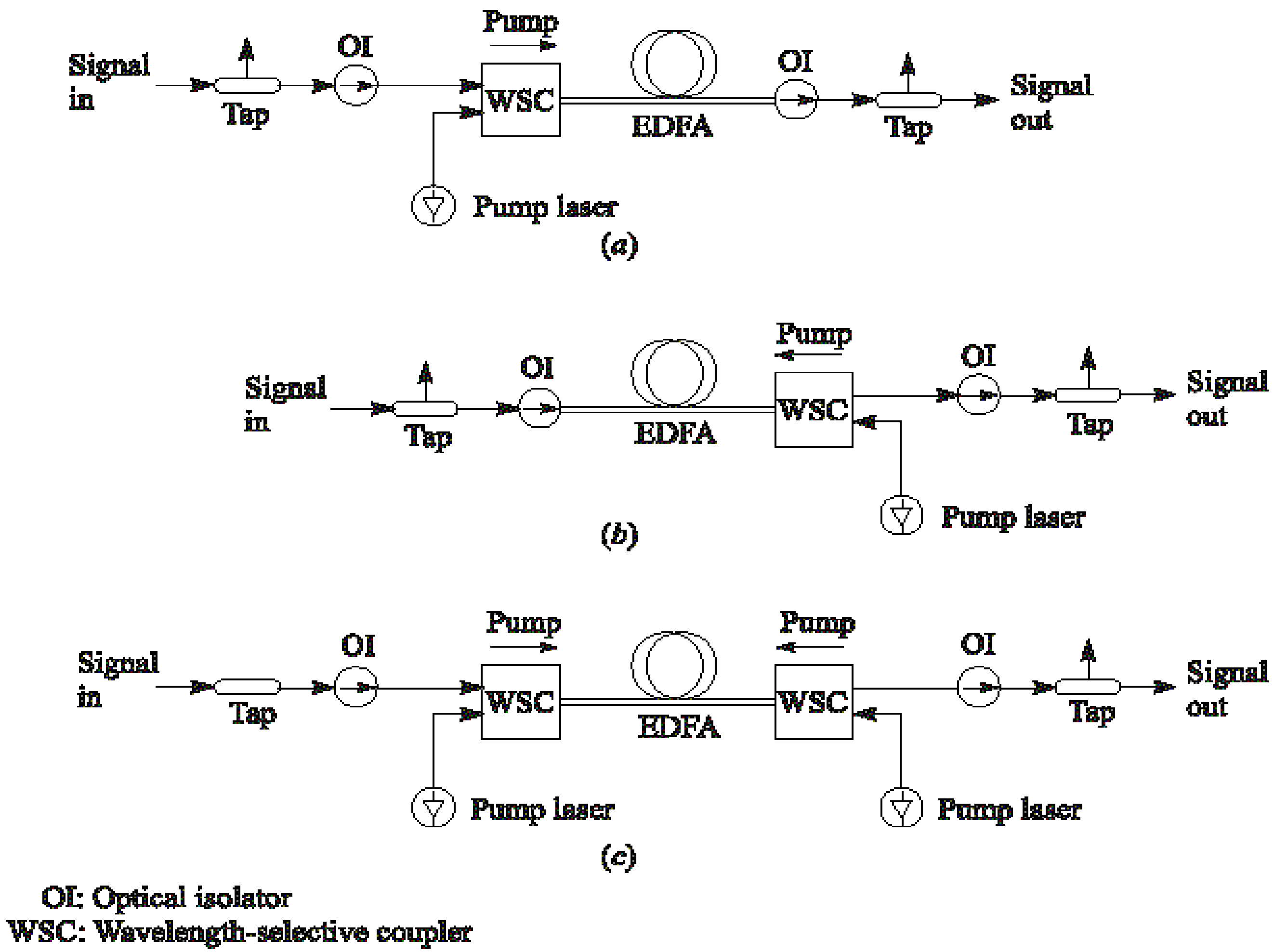




980 nm: high inversion = low noise

1480 nm: good pump energy conversion efficiency (PCE)

EDFA configurations



(a) Co-directional pumping-Pump light injected in same direction as signal flow
(b) Counter-directional pumping-inject pump power in opposite direction of signal
(c) Dual pumping-both directions

EDFA success factors

- Availability of compact and reliable high-power semiconductor pump lasers
- EDFA is an all-fiber device => polarization-independent & easy to couple light in/out
- Wide bandwidth, 20~70 nm
- High gain, 20~40 dB
- High output power, >200mW
- Bit rate, modulation format, power and wavelength insensitive
- Simplicity of device
- No crosstalk introduced while amplifying!

Semiconductor Optical/Laser Amplifiers (SOAs/SLAs)

- Semiconductor optical amplifiers (SOAs) are based on the same technology as laser diodes.

- The attractiveness of this is that SOAs can operate in every fiber wavelength band extending from 1280 nm in the O-band to 1650nm in the U-band.

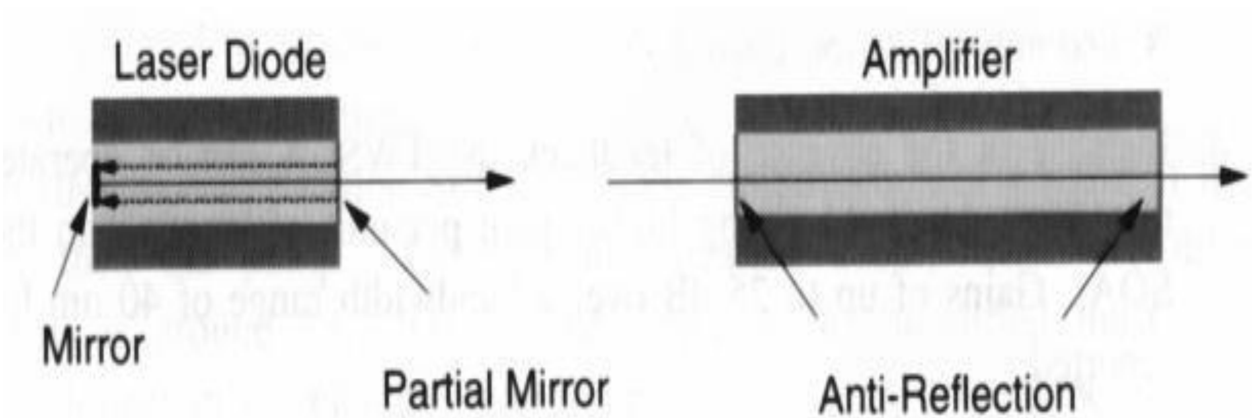
- Furthermore, since they are based on standard semiconductor technology, they can be integrated easily on the same substrate as other optical devices and circuits

- The major types SOAs are
  - Resonant Fabry Perot Amplifier (FPA)
  - Non resonant Travelling Wave Amplifier (TWA)

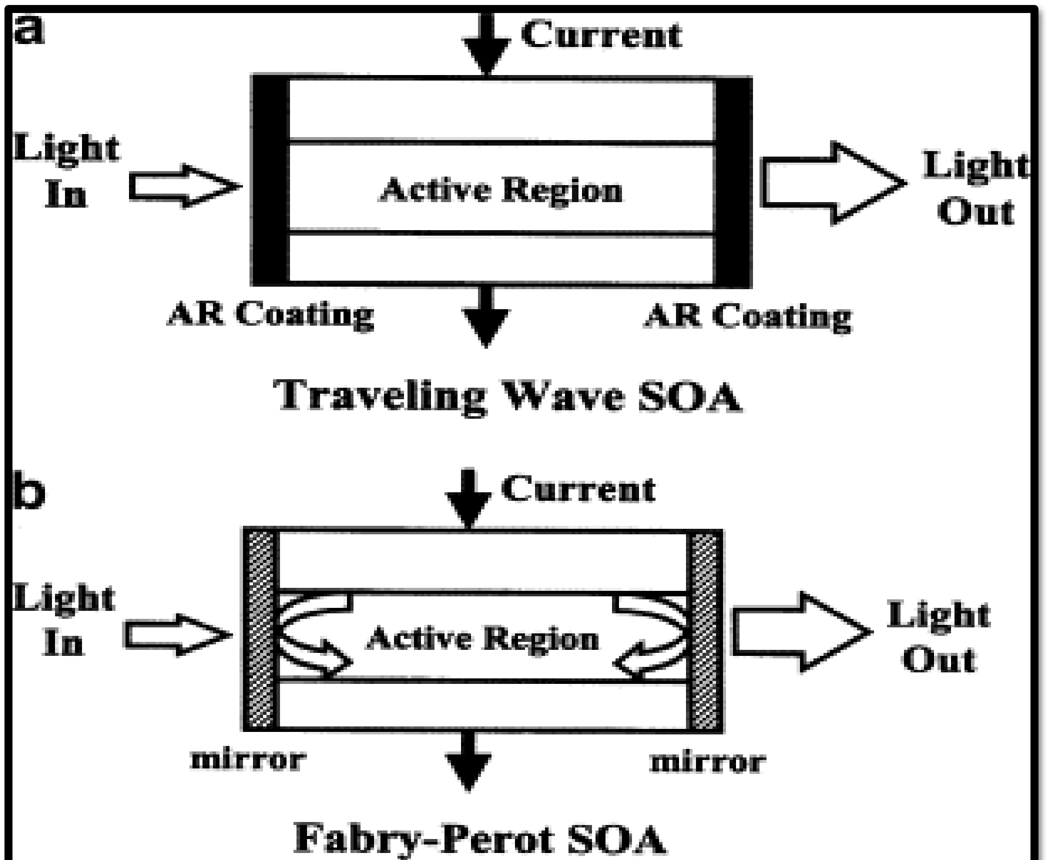
LASER vs SOA

- LASER & SOA - Stimulated emission process - but difference is that;
- LASER diode => amplifier gain medium + facet mirrors
- SOA – gain medium & facets (anti-reflection coating coupled to both fibre ends

=> so light amplified travelling just one time(single pass) in gain medium



FPA & TWA


a
Current
Light In
Active Region
Light Out
AR Coating
AR Coating
Traveling Wave SOA
b
Current
Light In
Active Region
Light Out
mirror
mirror
Fabry-Perot SOA

FPA & TWA

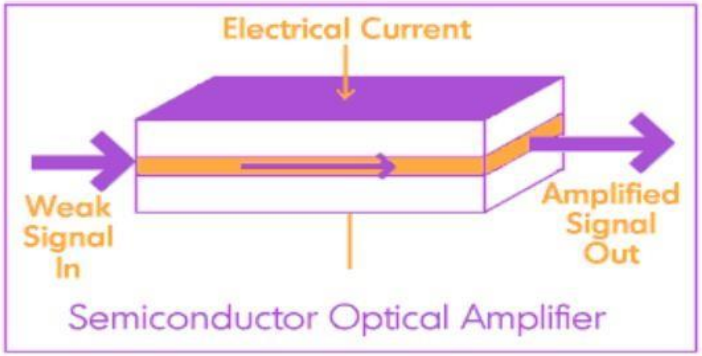
Fabry-Perot amplifiers (FPA)

- When the light enters, it gets amplified as it reflects back and forth between the mirrors until emitted at a higher intensity.
- It is sensitive to temperature and input optical frequency.

Traveling-wave amplifiers (TWA)

- It is the same as FPA except that the end facets are either antireflection coated or cleaved at an angle so that internal reflection does not take place and the input signal gets amplified only once during a single pass through the device.
- They widely used because they have a large optical bandwidth low polarization sensitivity.

Construction and working



- Stimulated emission to amplify an optical signal.
- Active region of the semiconductor.
- Injection current to pump electrons at the conduction band.
- The input signal stimulates the transition of electrons down to the valence band to acquire an amplification.
- Similar to laser diodes, external current injection is the pumping method used to create the population inversion needed for the operation of the gain mechanism in semiconductor optical amplifiers.

Advantages/Applications

- The semiconductor optical amplifier is of small size and electrically pumped.
- It can be potentially less expensive than the EDFA and can be integrated with semiconductor lasers, modulators, etc.
- All four types of nonlinear operations (cross gain modulation, cross phase modulation, wavelength conversion and four wave mixing) can be conducted.
- SOA can be run with a low power laser.

Limitations

- Insufficient power (only a few mW). This is usually sufficient for single channel operation but in a WDM system you usually want up to a few mW per channel.

- Coupling the input fibre into the chip tends to be very lossy. The amplifier must have additional gain to overcome the loss on the input facet.

- SOAs tend to be noisy.

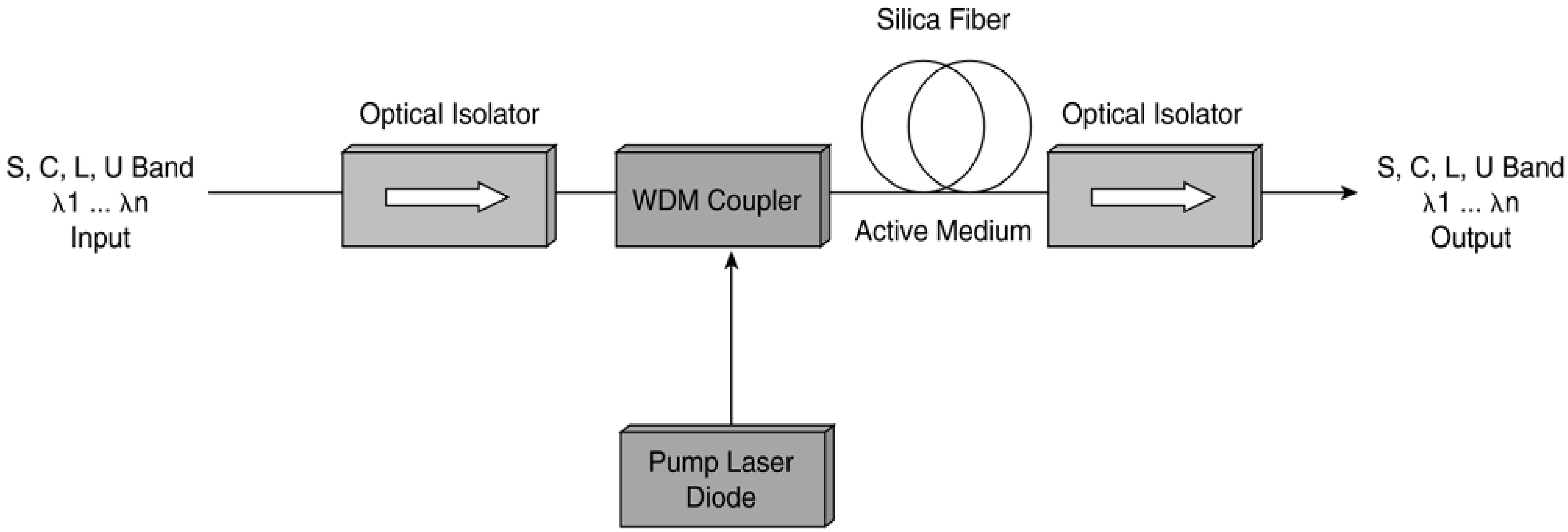
- They are highly polarisation sensitive.

- They can produce severe crosstalk when multiple optical channels are amplified.

- This latter characteristic makes them unusable as amplifiers in WDM systems but gives them the ability to act as wavelength changers and as simple logic gates in optical network systems.

Raman Fiber Amplifiers

The gain spectra for Raman amplification is quite broad (150 to 200 nm) and covers the entire operating S-, C-, L-, and U-bands

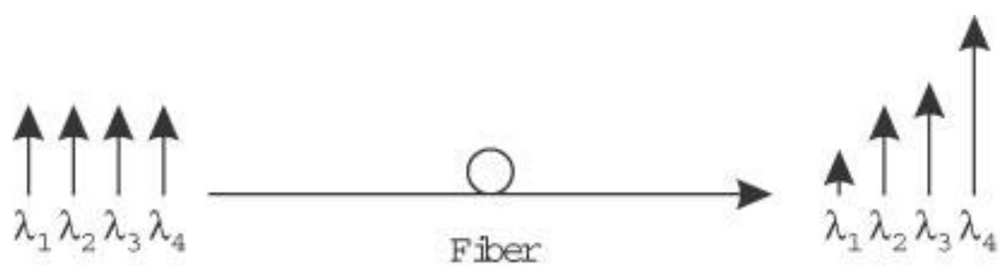


The pumping can be done in forward (co-propagating) and in reverse (counter-propagating) direction.

20- to 35-dB gain with 800 mW to 1W pump power

Recall: SRS

- **Stimulated Raman Scattering is an interaction between light waves and the vibrational modes of silica molecules.**
- **If a photon of energy hv1 is incident on a molecule having a vibrational frequency Vm, the molecule can absorb some energy from the photon.**
- **In this interaction , the photon is scattered, thereby attaining a lower frequency v2 and a corresponding lower energy hv2.**
- **The modified photon is called a stokes photon.**
- **The optical signal that is injected into the fiber is called the pump wave.**
- **This process generates scattered light at a wavelength longer than that of incident light.**
- **If another signal is present at this longer wavelength, the SRS light will amplify it.**



Broadband Amplification using Raman Amplifiers

- Raman amplification can provides very broadband amplification
- Multiple high-power "pump" lasers are used to produce very high gain over a range of wavelengths.
- 93 nm bandwidth has been demonstrated with just two pumps sources

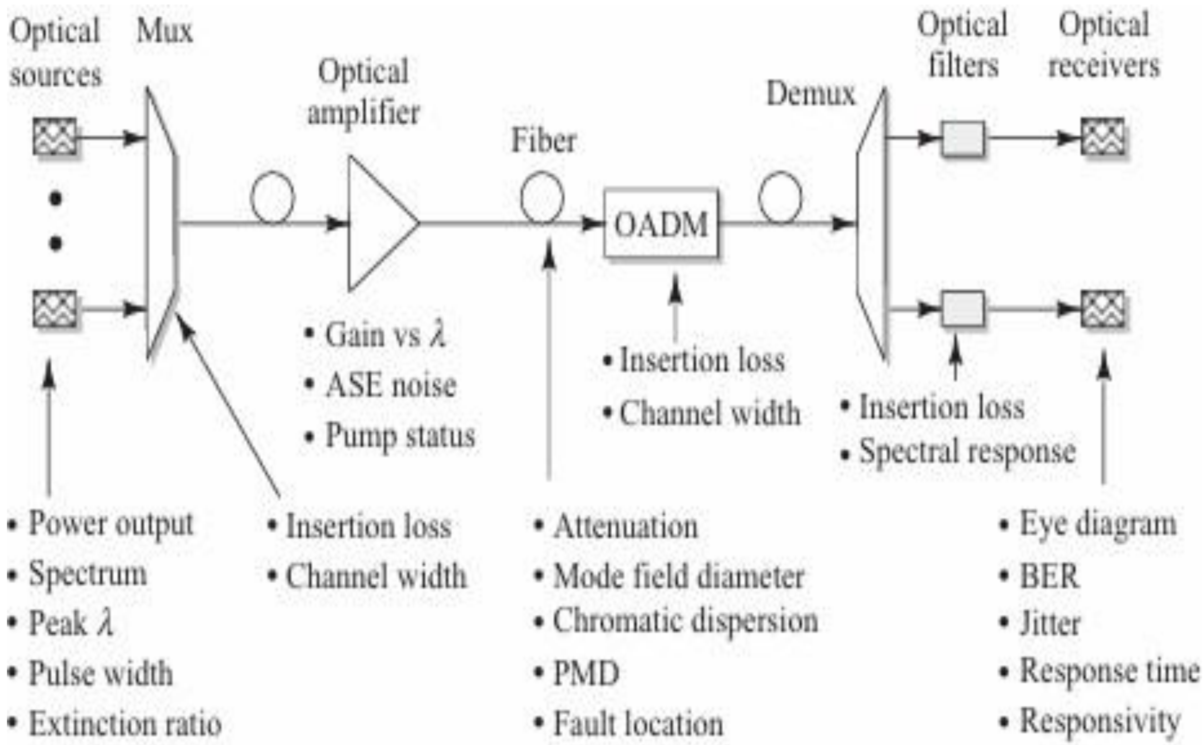
- Advantages
  - Variable wavelength amplification possible
  - Compatible with installed SM fibre
  - Can be used to "extend" EDFAs
  - Can result in a lower average power over a span, good for lower crosstalk
  - Very broadband operation may be possible
- Disadvantages
  - High pump power requirements, high pump power lasers have only recently arrived
  - Sophisticated gain control needed
  - Noise is also an issue

Comparison of different optical amplifiers

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	2×10^{-9}
Size	Rack mounted	Bulk module	Compact
Switchable	No	No	Yes
Cost Factor	Medium	High	Low

Optical Time-Domain Reflectometer (OTDR)

Components of a typical WDM link and some performance-measurement parameters



Optical system test instruments and their functions

Test instrument	*Function*
Test-support lasers (multiple-wavelength or broadband)	Assist in tests that measure the wavelength-dependent response of an optical component or link
Optical spectrum analyzer	Measures optical power as a function of wavelength
Multifunction optical test system	Factory or field instruments with exchangeable modules for performing a variety of measurements
Optical power attenuator	Reduces power level to prevent instrument damage or to avoid overload distortion in the measurements
Conformance analyzer	Measures optical receiver performance in accordance with standards-based specifications
Visual fault indicator	Uses visible light to give a quick indication of a break in an optical fiber
Optical power meter	Measures optical power over a selected wavelength band
BER test equipment	Uses standard eye-pattern masks to evaluate the data-handling ability of an optical link
OTDR (field instrument)	Measures attenuation, length, connector/splice losses, and reflectance levels; helps locate fiber breaks
Optical return loss tester	Measures total reverse power in relation to total forward power at a particular point

Visual Fault Indicator

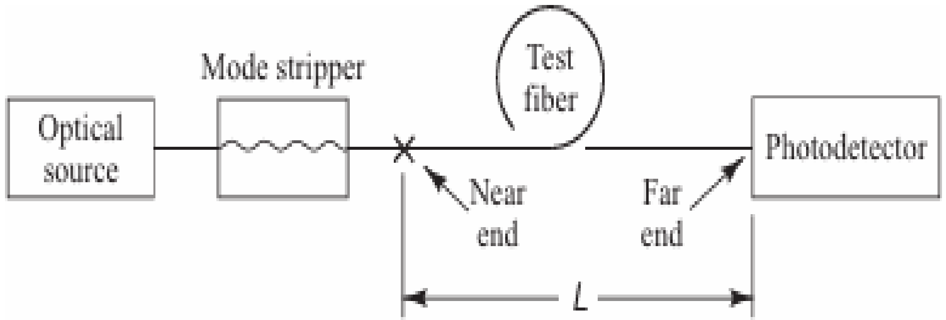
- A visual fault locator (VFL) is a handheld pen-sized instrument that uses a visible laser light source to locate events such as fiber breaks, overly tight bends in a fiber, or poorly mated connectors.
- The source emits a bright beam of red light (e.g., 650 nm) into a fiber, thereby allowing the user to see a fiber fault or a high-loss point as a glowing or blinking red light.
- The VFL is particularly useful for identifying fiber faults within the initial dead zone of an OTDR.

Attenuation Measurements

Three basic methods are available for determining attenuation in fibers.

- The earliest devised and most common approach involves measuring the optical power transmitted through a long and a short length of the same fiber using identical input couplings. This method is known as the cutback technique.
- A less accurate but nondestructive method is the insertion-loss method, which is useful for cables with connectors on them.
- The third technique, which involves the use of an OTDR.

The Cutback Technique



Schematic experimental setup for determining fiber attenuation by the cutback technique. The optical power is first measured at the far end, then the fiber is cut at the near end, and the power output there is measured

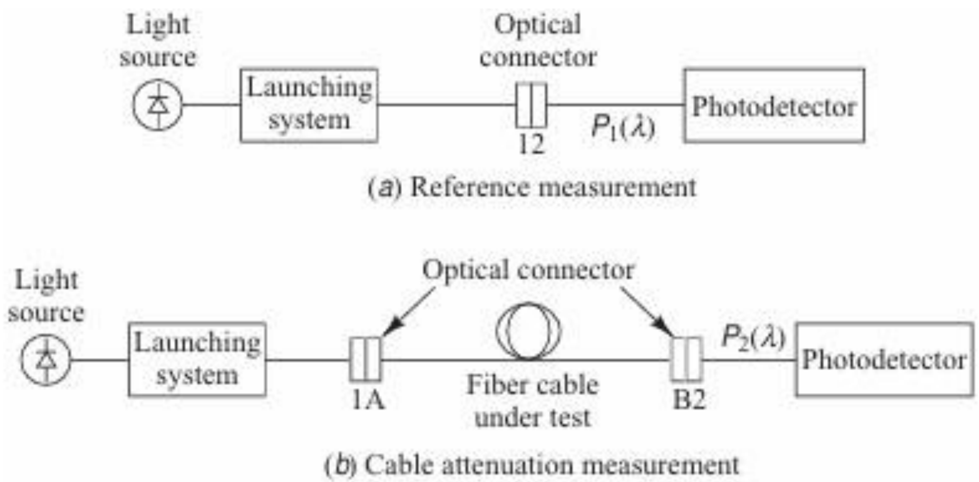
- To find the transmission loss, the optical power is first measured at the output (or far end) of the fiber.
- Then, without disturbing the input condition, the fiber is cut off a few meters from the source, and the output power at this near end is measured.
- If P_F and P_N represent the output powers of the far and near ends of the fiber, respectively, the average loss α in decibels per kilometer is given by

$$\alpha = \frac{10}{L} \log \frac{P_N}{P_F}$$

where L(in kilometers) is the separation of the two measurement points.

Insertion-Loss Method

- For cables with connectors, one cannot use the cutback method. In this case, one commonly uses an insertion-loss technique.
- This is less accurate than the cutback method but is intended for field measurements to give the total attenuation of a cable assembly in dB.



Test setup for using the insertion-loss technique to measure attenuation of cables that have attached connectors

To carry out the attenuation tests, the connector of the short-length launching fiber is attached to the connector of the receiving system and the launch-power level $P_1(\lambda)$ is recorded. Next, the cable assembly to be tested is connected between the launching and receiving systems, and the received-power level $P_2(\lambda)$ is recorded. The attenuation of the cable in decibels is then

$$A = 10\log\frac{P_1(\lambda)}{P_2(\lambda)}$$

This attenuation is the sum of the loss of the cabled fiber and the connector between the launch connector and the cable.

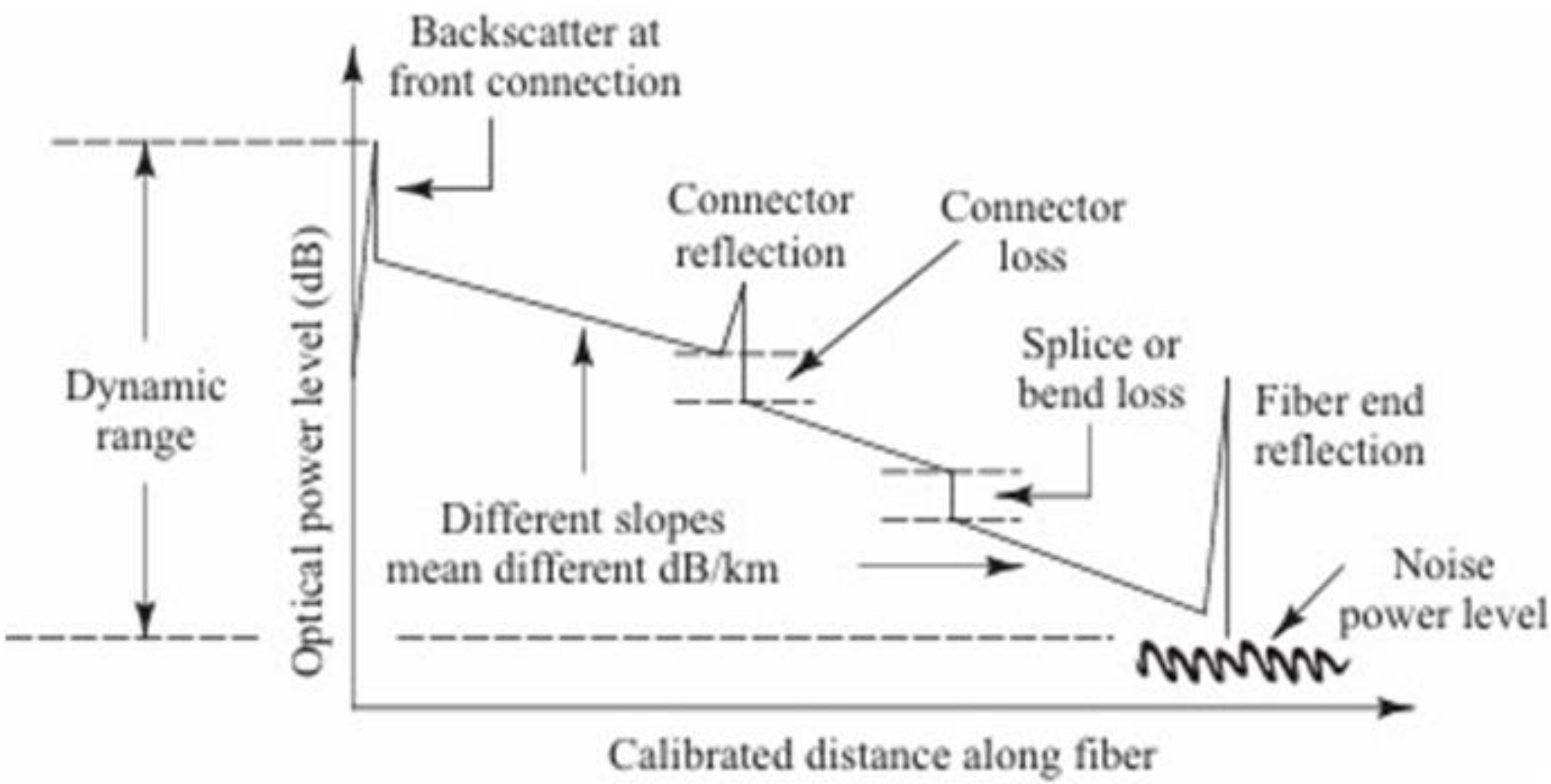
Optical Time-Domain Reflectometer

- An optical time-domain reflectometer (OTDR) is a versatile portable instrument that is used widely to evaluate the characteristics of an installed optical fiber link.
- In addition to identifying and locating faults or anomalies within a link, this instrument measures parameters such as fiber attenuation, length, optical connector and splice losses, and light reflectance levels.

Optical Time-Domain Reflectometer

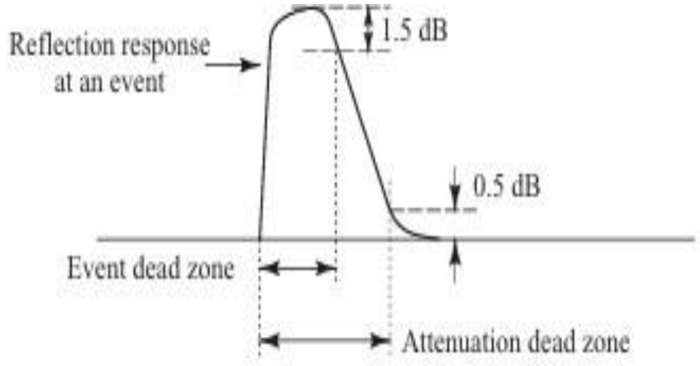
- An OTDR is fundamentally an optical radar.
- The OTDR operates by periodically launching narrow laser pulses into one end of a fiber under test by using either a directional coupler or a circulator.
- The properties of the optical fiber link then are determined by analyzing the amplitude and temporal characteristics of the waveform of the reflected and back-scattered light.

Typical trace as seen on the display screen of an OTDR.



OTDR Dead Zone

- The concept of a dead zone is another important OTDR specification. Dead zone is the distance over which the photodetector in an OTDR is saturated momentarily after it measures a strong reflection.
- An event dead zone specifies the minimum distance over which an OTDR can detect a reflective event that follows another reflective event.
- The attenuation dead zone indicates over which distance the photodetector in an OTDR needs to recover following a reflective event before it is again able to detect a splice.



Two specifications for dead zone are the event dead zone and the attenuation dead zone.

Fiber Fault Location

- To locate breaks and imperfections in an optical fiber, the fiber length L (and, hence, the position of the break or fault) can be calculated from the time difference between the pulses reflected from the front of the fiber and the event location. If this time difference is 't', then the length L is given by,

$$L = \frac{ct}{2n_1}$$

- where n_1 (the core refractive index of the fiber).

- The number "2" in the denominator accounts for the fact that light travels a length L from the source to the break point and then another length L on the return trip.

Optical Return Loss

- Reflections of the light in a backward direction occur at various points in optical links that use laser transmitters.
- This can occur at connectors, fiber ends, optical splitter interfaces, and within the fiber itself due to Rayleigh scattering.
- The percent of power reflected back from a particular point in a light path is called back reflection.

Optical Return Loss

- If it is not controlled, the back reflections can cause optical resonance in the laser source and result in erratic operation and increased laser noise.
- In addition, the back reflections can undergo multiple reflections in the transmission line and increase the bit-error rate when they enter the receiver.
- The ORL is expressed as a ratio of reflected power P_{ref} to incident power P_{inc}

$$\mathrm{ORL} = 10\log(P_{\mathrm{ref}}/P_{\mathrm{inc}})$$

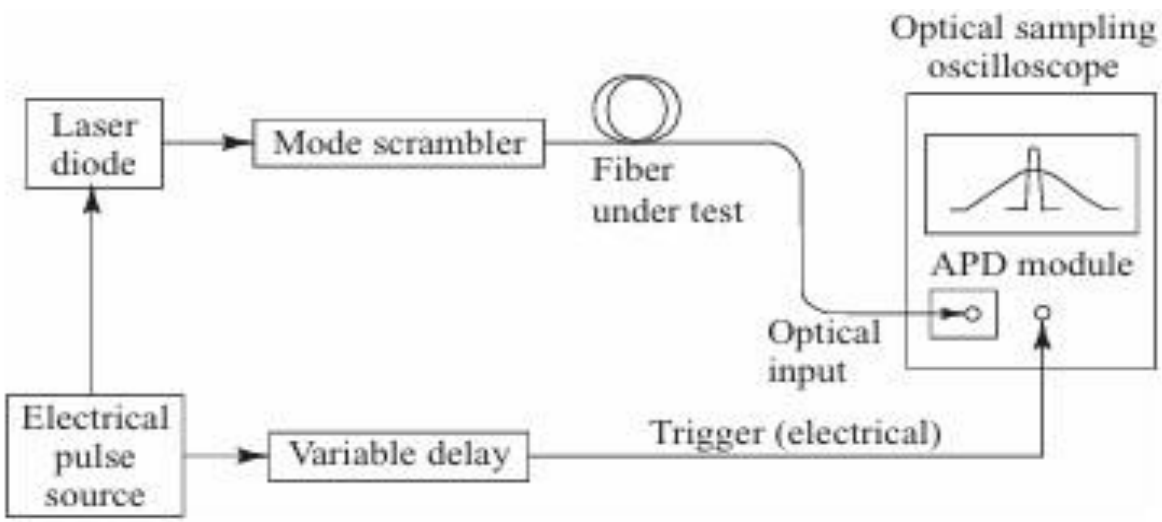
Dispersion Measurements

- Three basic forms of dispersion produce pulse broadening of light wave signals in optical fi bers, thereby limiting the information-carrying capacity.

1. In multimode fibers, intermodal dispersion arises from the fact that each mode in an optical pulse travels a slightly different distance and thus arrives at the fiber end at slightly offset times.
2. Chromatic dispersion stems from the variation in the propagation speed of the individual wavelength components of an optical signal.
3. Polarization-mode dispersion arises from the splitting of a polarized signal into orthogonal polarization modes, each of which has a different propagation speed.

Time-Domain Intermodal Dispersion Measurements

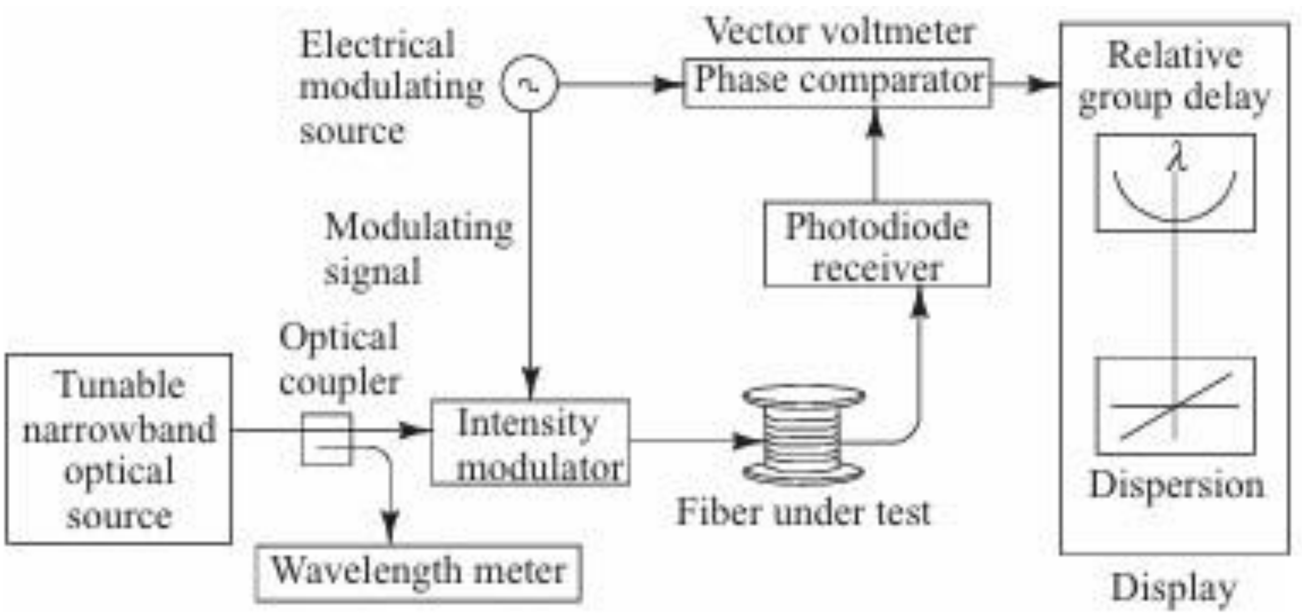
- The simplest approach for making pulse-dispersion measurements in the time domain is to inject a narrow pulse of optical energy into one end of an optical fiber and detect the broadened output pulse at the other end.



Test setup for making pulse-dispersion measurements in the time domain

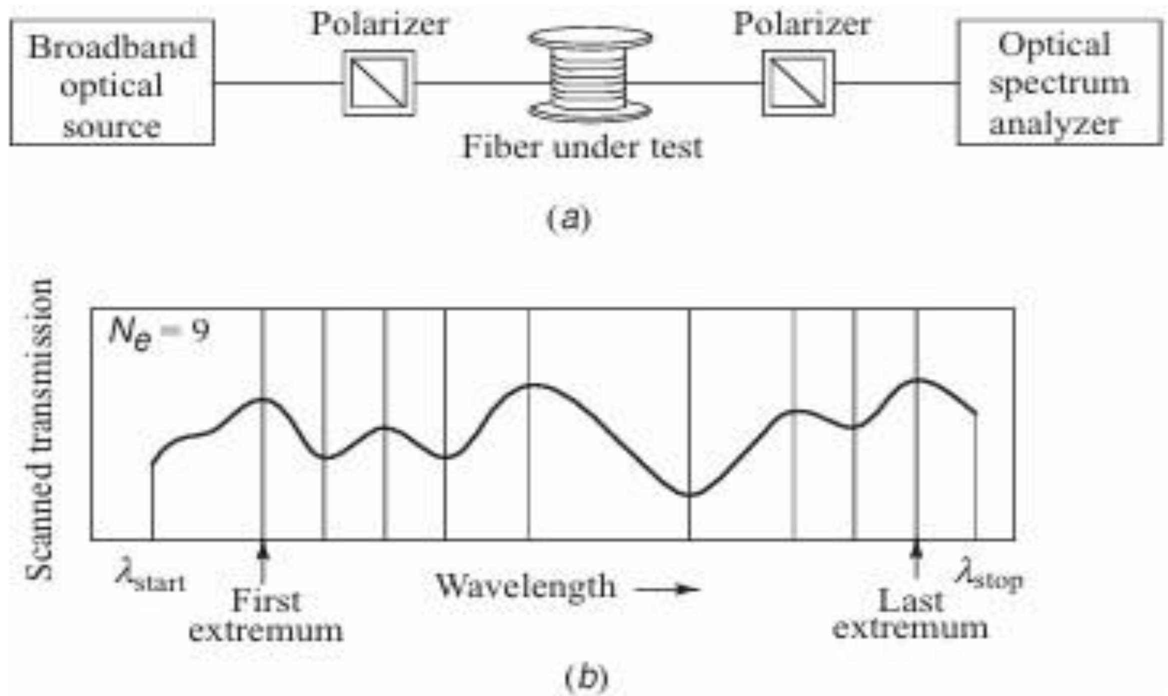
Chromatic Dispersion

- Chromatic dispersion is a primary dispersive mechanism in single-mode fibers.



Test setup and display output for measuring chromatic dispersion by the phase-shift method

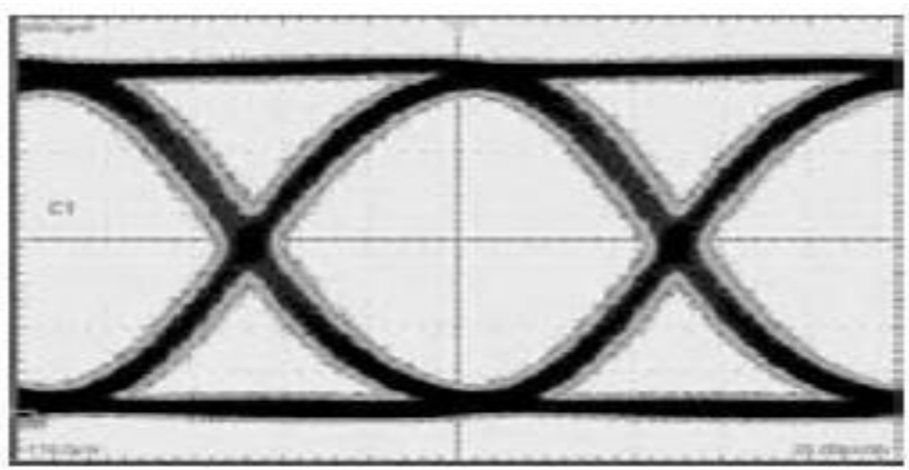
Polarization-Mode Dispersion



(a) Setup for measuring polarization-mode dispersion using an optical spectrum analyzer. (b) Typical OSA trace for PMD showing transmitted power level as a function of wavelength.

Eye Diagram Tests

- The use of an eye diagram is a traditional technique for quickly and intuitively assessing the quality of a received signal.
- Modern bit-error rate (also called bit-error ratio) measurement instruments construct such eye diagrams by generating a pseudorandom pattern of ones and zeros at a uniform rate but in a random manner.
- When the pulses in this pattern are superimposed simultaneously, an eye pattern is formed.
- Signal-distorting effects cause the eye opening to get smaller,



- Stressed Eye

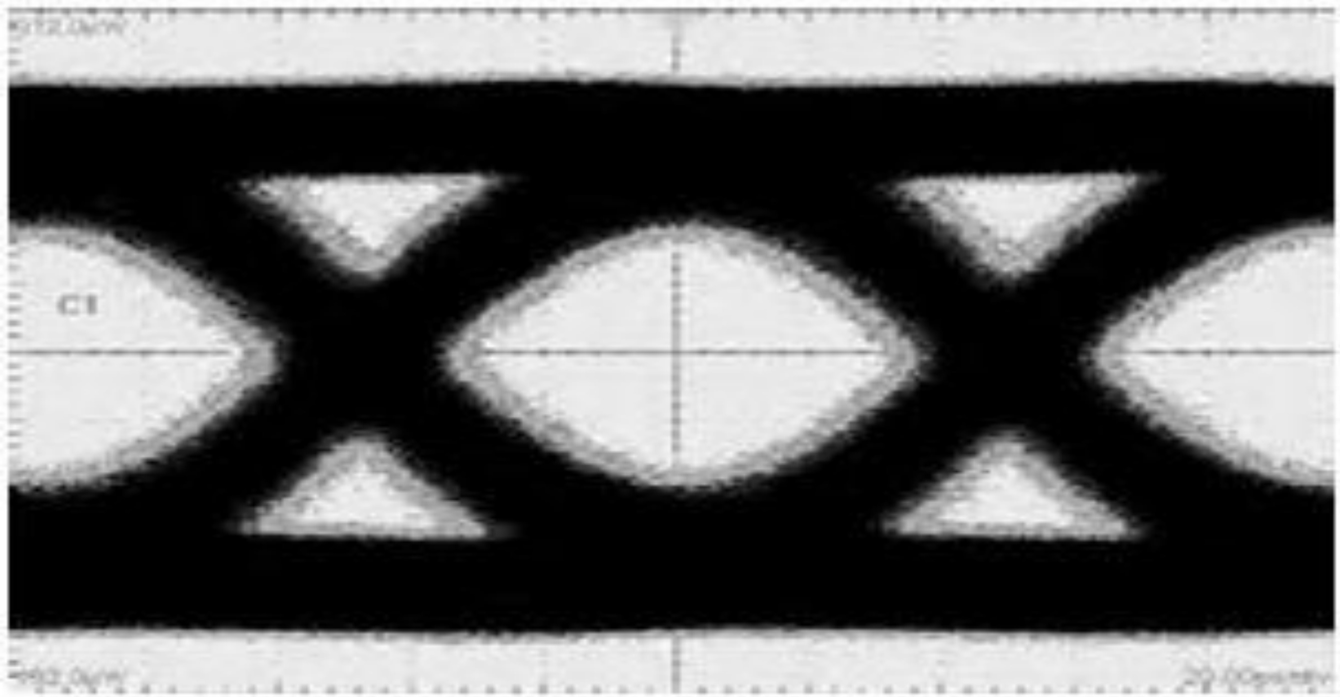


Fig. 14.17 *The inclusion of all possible signal distortion effects results in a stressed eye with only a small opening.*