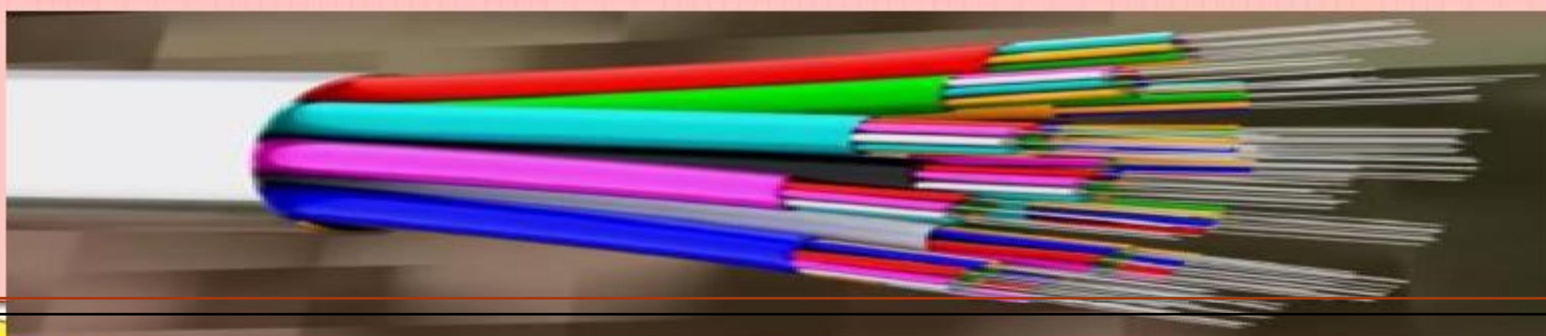
Debre Markos University

Institute of Technology

School of Electrical and Computer Engineering

Optics and Optical Communication System(ECEg-4302)



Course Contents

1) Introduction to Optical Communication Systems
2) Optical Transmitters And Receivers
3) Light Wave Systems
4) Light Signal Amplifiers Circuits
5) Light Signal Dispersion Compensation

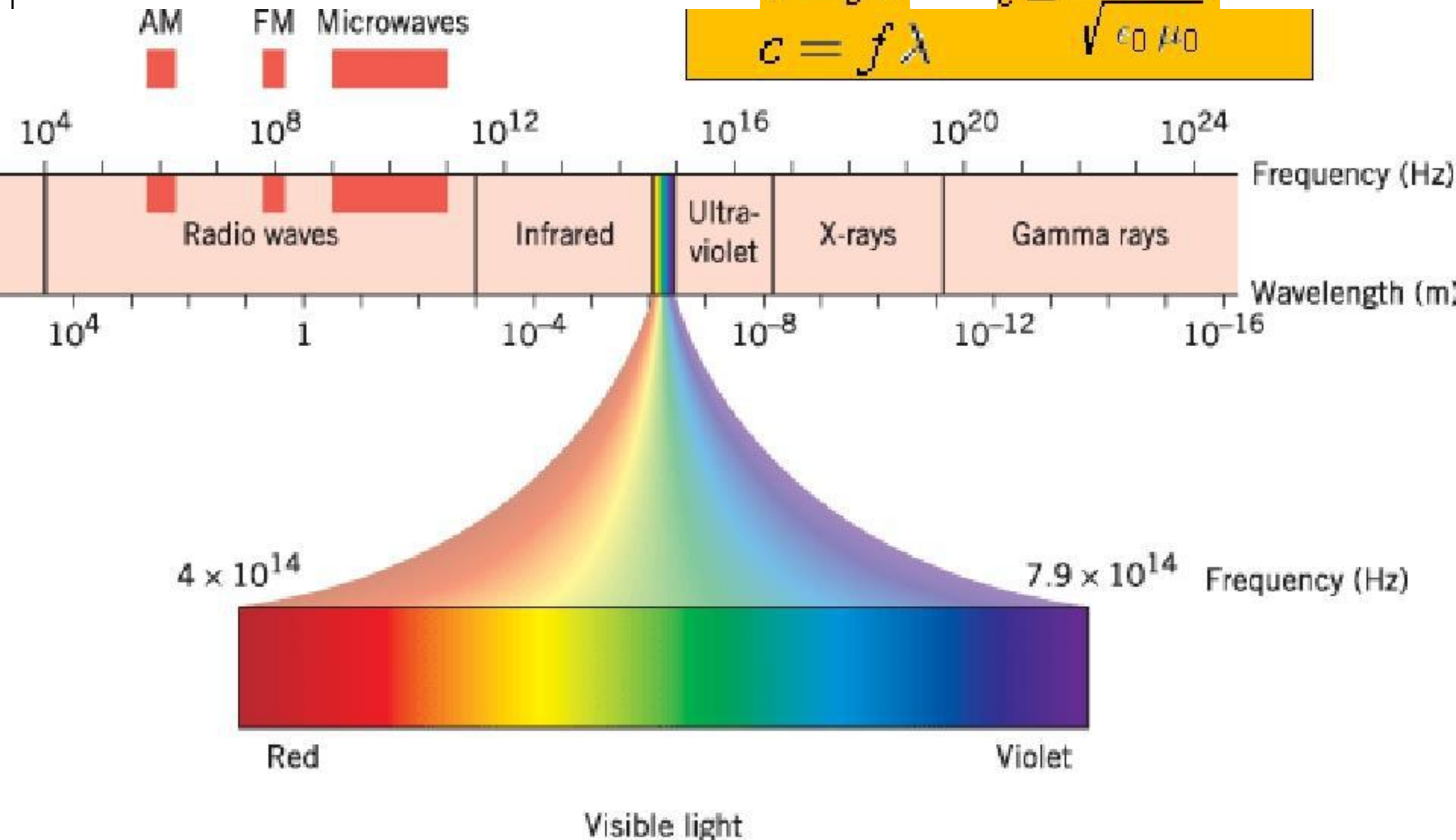
FIBER-OPTIC COMMUNICATION

- is a method of transmitting information from one place to another by sending light through an optical fiber.
- The light forms an electromagnetic carrier wave that is modulated to carry information.

Electromagnetic Spectrum

$$v = f\lambda \qquad c = \frac{1}{\sqrt{\epsilon_0 \mu_0}}$$

$$c = f\lambda$$



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- The process of communicating using fiber-optics involves the following basic steps:
  - Creating the optical signal using a transmitter,
  - relaying the signal along the fiber, ensuring that the signal does not become too distorted or weak,
  - and receiving the optical signal and converting it into an electrical signal.

First generation

The first generation of lightwave systems uses GaAs semiconductor laser and operating region was near 0.8 µm. Other specifications of this generation are as under:

- i) Bit rate : 45 Mb/s
- ii) Repeater spacing : 10 km

Second Generation

- Bit rate : 100 Mb/s to 1.7 Gb/s
- ii) Repeater spacing : 50 km
- iii) Operation wavelength : 1.3 µm

Third Generation

- Bit rate : 10 Gb/s ii)
- Repeater spacing : 100 km
- iii) Operating wavelength : 1.55 µm

- ## Fourth Generation

Fourth generation uses WDM technique.

- Bit rate : 10 Tb/s
- Repeater spacing : > 10,000 km
- Operating wavelength : 1.45 to 1.62 μm

- ## Fifth Generation

Fifth generation uses Roman amplification technique and optical solitaires.

- Bit rate : 40 - 160 Gb/s
- Repeater spacing : 24000 km - 35000 km
- Operating wavelength : 1.53 to 1.57 μm

Evolution of Fiber

- 1609-Galileo uses optical telescope
- 1626-Snell formulates law of refraction
- 1668-Newton invents reflection telescope
- 1840-Samuel Morse Invents Telegraph
- 1841-Daniel Colladon-Light guiding demonstrated in water jet
- 1870-Tyndall observes light guiding in a thin water jet
- 1873-Maxwell electromagnetic waves
- 1876-Elisha Gray and Alexander Bell Invent Telephone
- 1877-First Telephone Exchange

Continued

- 1880-Bell invents Photophone
- 1888-Hertz Confirms EM waves and relation to light
- 1880-1920 Glass rods used for illumination
- 1897-Rayleigh analyzes waveguide
- 1899-Marconi Radio Communication
- 1902-Marconi invention of radio detector
- 1910-1940 Vacuum Tubes invented and developed
- 1930-Lamb experiments with silica fiber
- 1931-Owens-Fiberglass
- 1936-1940 Communication using a waveguide

Continued

- 1951-Heel, Hopkins, Kapany image transmission using fiber bundles
- 1958-59 Kapany creates optical fiber with cladding
- 1961-66 Kao, Snitzer et al conceive of low loss single mode fiber communications and develop theory
- Late 1980s-Single mode transmission at 1.55 µm -0.2 dB/km
- 1989-Erbium doped fiber amplifier
- 1 Q 1996-8 Channel WDM
- 4th Q 1996-16 Channel WDM
- 1Q 1998-40 Channel WDM

OPTICAL FIBER

- Fiber optics (optical fibers) are long, thin strands of very pure glass about the size of a human hair
- They are arranged in bundles called optical cables and used to transmit signals over long distances.
- Fiber optic data transmission systems send information over fiber by turning electric signals into light

Advantages of Optical Fiber

- Thinner
- Less Expensive
- Higher Carrying Capacity
- Less Signal Degradation
- Non-Flammable
- Light Weight

Continued

- Much Higher Bandwidth (Gbps)
- Immunity to Noise
- Safety
- High Security
- Less Loss
- Reliability
- Flexibility

Disadvantages of fiber optics

- Disadvantages include the cost of interfacing equipment necessary to convert electrical signals to optical signals.
- Splicing fiber optic cable is also more difficult.
- expensive over short distance
- requires highly skilled installers
- adding additional nodes is difficult

Areas of Application

- Telecommunications
- Local Area Networks
- Cable TV
- CCTV
- Optical Fiber Sensors

Fiber Optic Cable

- relatively new transmission medium used by telephone companies in place of long-distance trunk lines
- also used by private companies in implementing local data networks
- require a light source with injection laser diode (ILD) or light-emitting diodes (LED)

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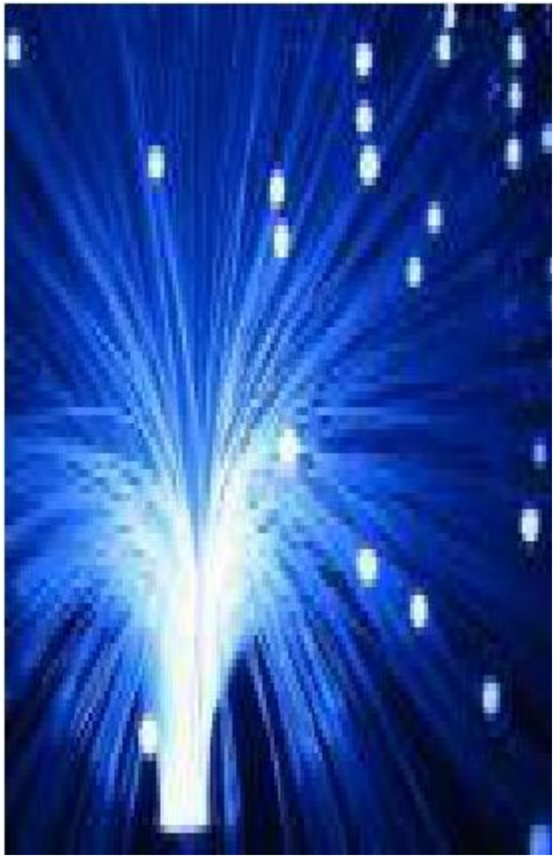
A thin glass cable approximately a little thicker than a human hair surrounded by a plastic coating and packaged into an insulated cable.

A photo diode or laser generates pulses of light which travel down the fiber optic cable and are received by a photo receptor.



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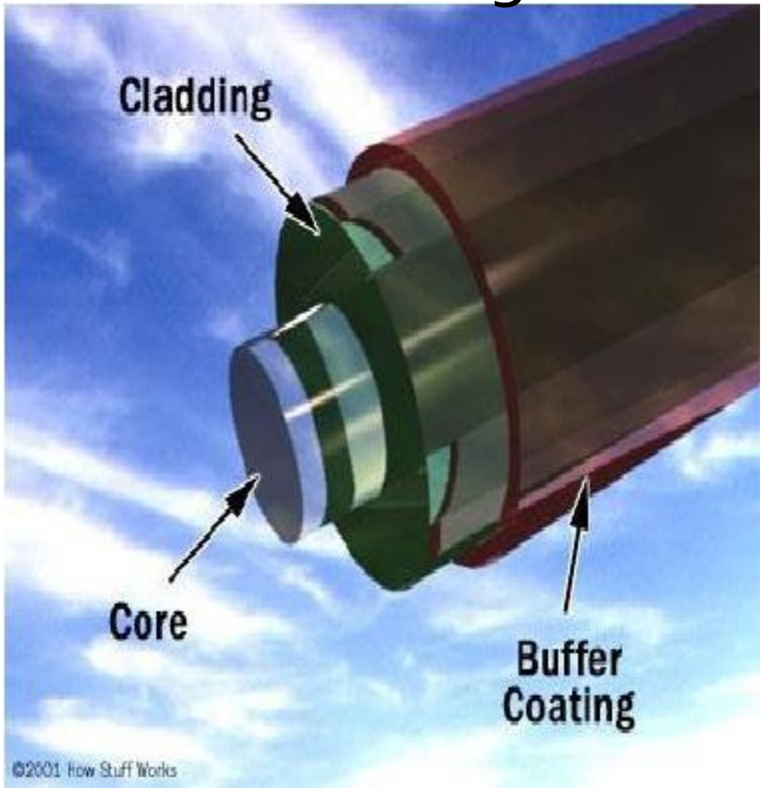
- Optical fiber consists of
  - core,
  - cladding and ,
  - a protective outer coating, which guides light along the core by total internal reflection.

OPTICAL FIBER CONSTRUCTION

- **Core** – thin glass center of the fiber where light travels
- **Cladding**
  - outer optical material surrounding the core
- **Buffer Coating**
  - Plastic coating that protects the fiber



Modes of Fiber

- The **mode** of a fiber refers to the number of paths for the light rays within the cable.
- According to modes optic fibers can be classified into two types.

  i) Single-mode optical fibers and

  ii) Multi-mode optical fibers

- **Single-mode fibers** – used to transmit one signal per fiber (used in telephone and cable TV)
- They have small cores necessitates more expensive components and interconnection methods,
- but allows much longer, higher-performance links

MODE OF PROPAGATION

- **Single-mode fibers** – used to transmit one signal per fiber (used in telephone and cable TV)
- They have small cores necessitates more expensive components and interconnection methods,
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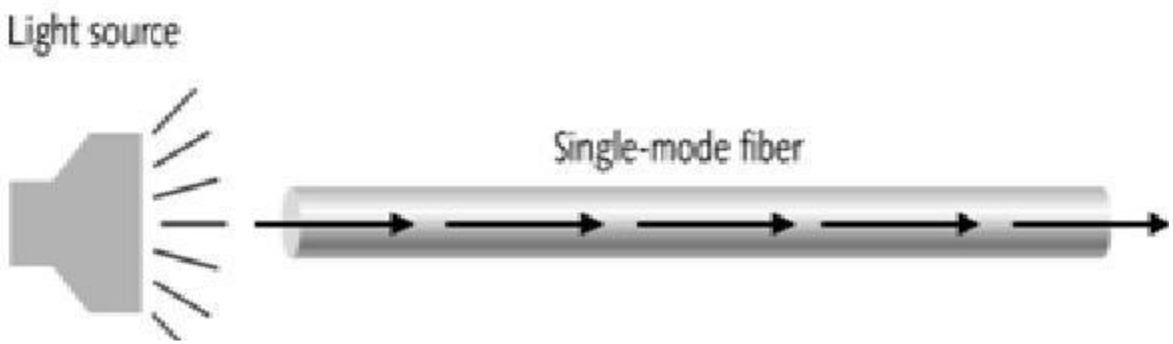
- **Single-mode fiber**
  - Carries light pulses along single path
  - The core diameter is almost equal to the wave length of the emitted light
    - so that it propagates along a single path.



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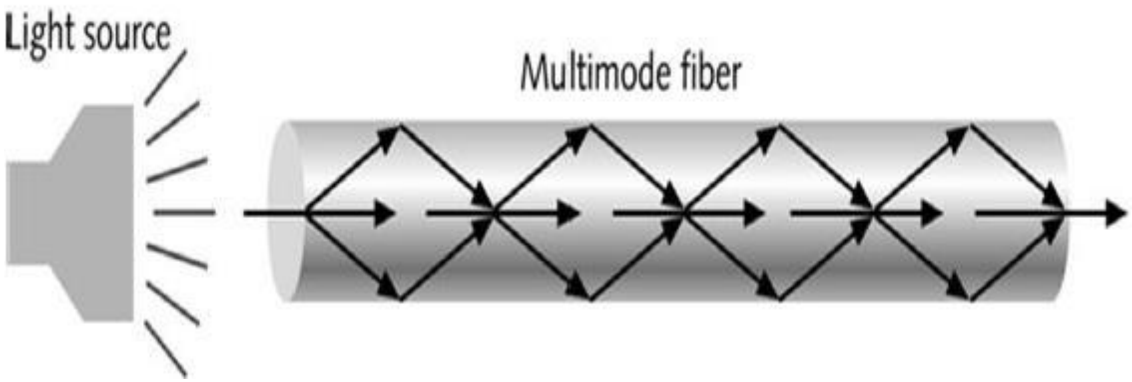
- **Multi-mode fibers** – used to transmit many signals per fiber (used in computer networks)
- Many pulses of light generated by LED travel at different angles



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- Multimode fiber has
  - a larger core allowing less precise,
  - cheaper transmitters and receivers to connect to it as well as cheaper connectors
- However, multi-mode fiber introduces multimode distortion which often limits the bandwidth and length of the link.
- because of its higher dopant content, multimode fiber is usually more expensive and exhibits higher attenuation.

INDEX OF REFRACTION

- In optics the **refractive index** or **index of refraction n** of an optical medium is a dimensionless number that describes how light, or any other radiation, propagates through that medium.
- Refraction occurs when light ray passes from one medium to another i.e. the light ray changes its direction at interface.
- It is defined as

$$n = c / v$$

where *c* is the speed of light in vacuum and **v** is the speed of light in the substance.

Continued

- For example, the refractive index of water is 1.33, meaning that light travels 1.33 times faster in a vacuum than it does in water.
- The refractive index determines how much light is bent, or refracted, when entering a material

Snell’s Law

- Snell’s law states how light ray reacts when it meets the interface of two media having different indexes of refraction.

$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{n_2}{n_1} \rightarrow \begin{array}{ll} \text{if } n_2 > n_1 & \theta_2 < \theta_1 \\ \text{if } n_1 > n_2 & \theta_2 > \theta_1 \end{array}$$

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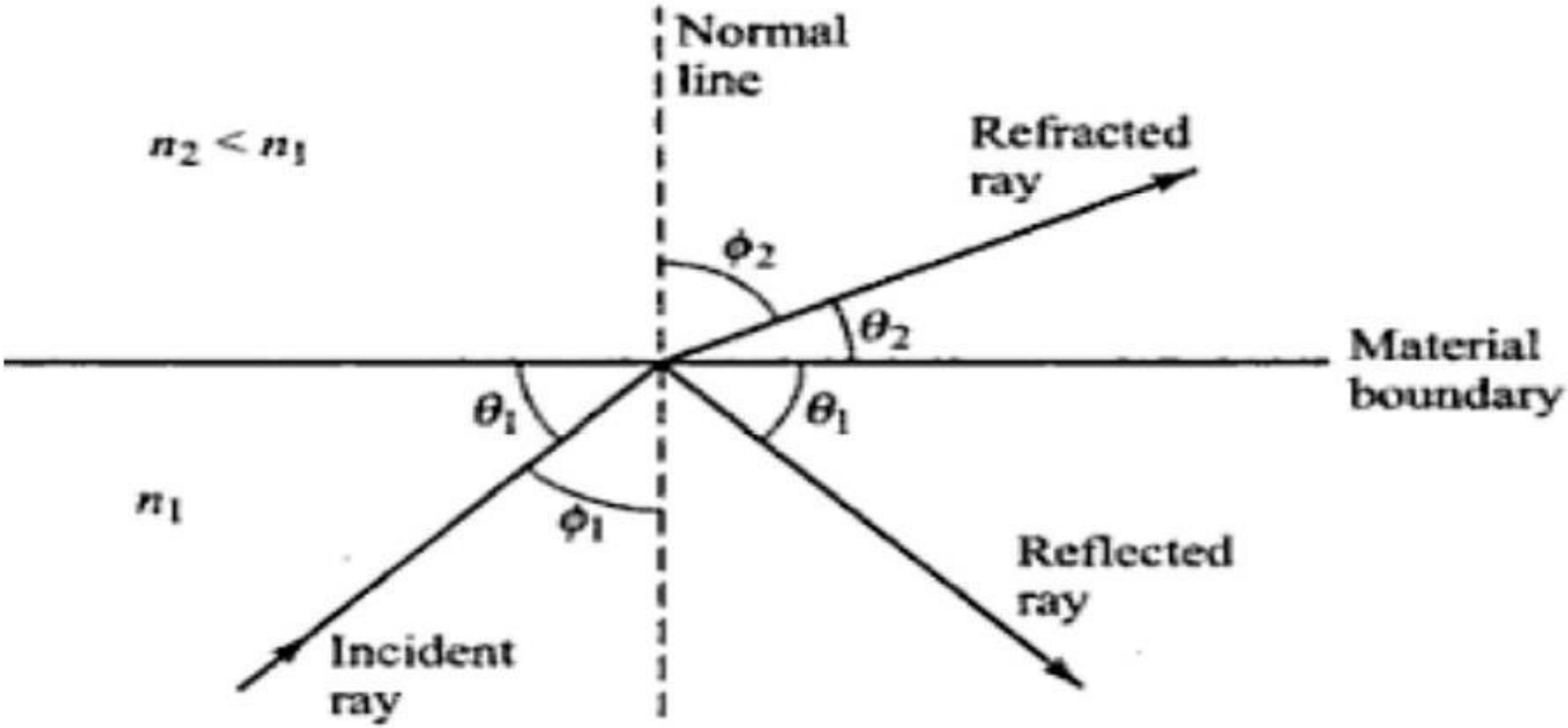
Normal line
Refracted ray
$n_2 < n_1$
ϕ_2
θ_2
Material boundary
θ_1
θ_1
n_1
ϕ_1
Reflected ray
Incident ray

Critical angle, θc

- The minimum angle of incidence at which a light ray strike the interface of two media and
- result in an angle of refraction of 90° or greater
- When a ray of light goes from a material into an optically less dense material like air
- The angle of refraction can become 90° and the ray of light travels along the boundary between the two material
- When this happens the angle of incidence is called the critical angle

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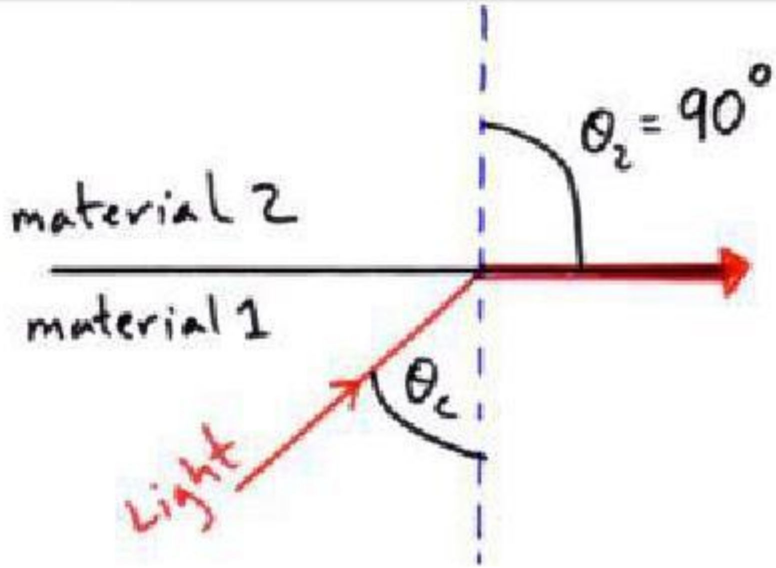


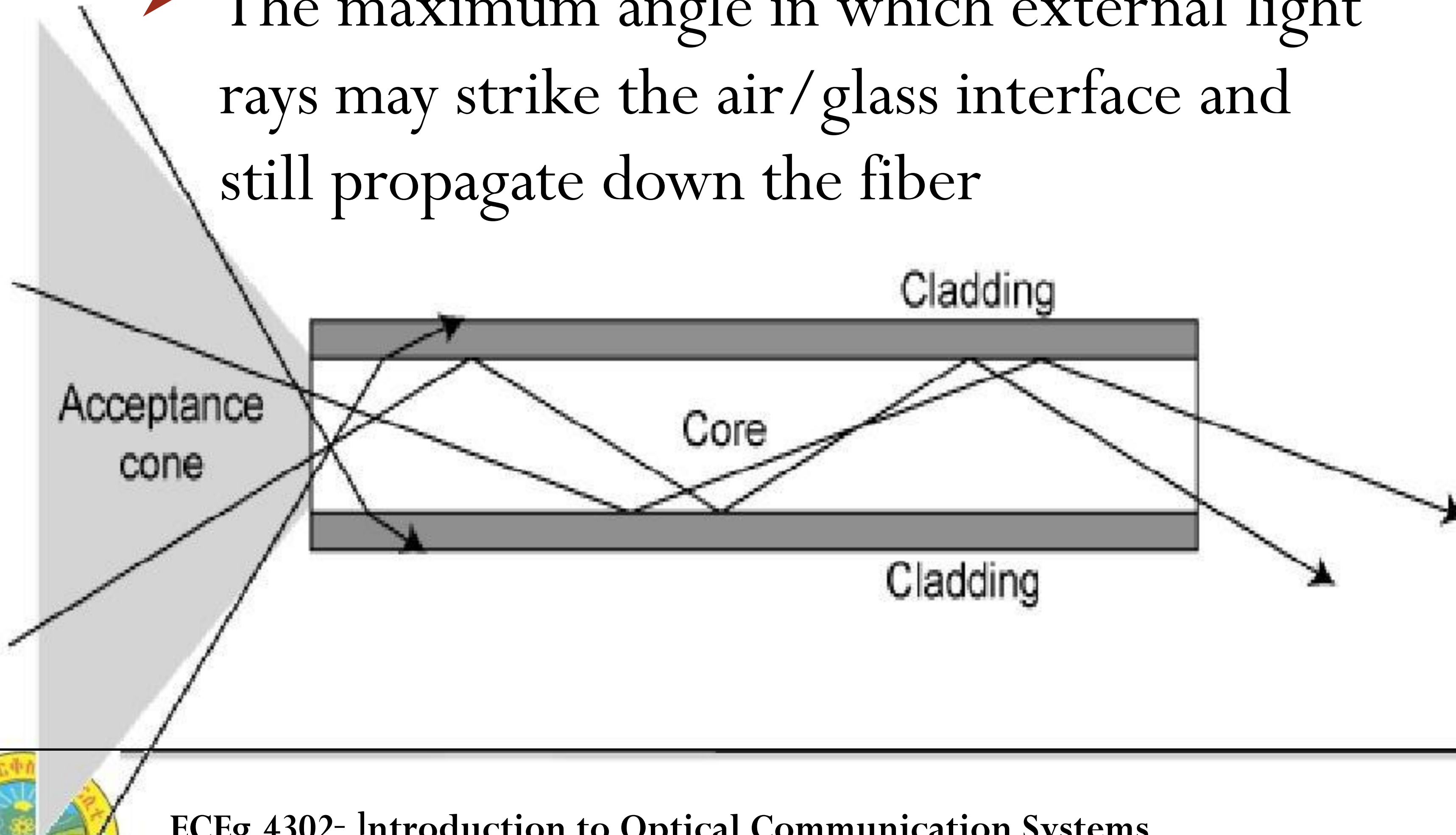
- If the incident angle is greater than the critical angle then light reflects at the boundary between the two material and this is called **Total Internal Reflection**

Cont'd

- When light travelling in a certain medium is reflected off an optically denser material, The process is called ***external reflection***
- Conversly, The reflection of light off of less optically less optically denser material is called ***internal reflection***
- If the light hits the interface at any angle larger than this critical angle, it will not pass through to the second medium at all.
- Instead, all of it will be reflected back into the first medium, a process known as ***total internal reflection***.

Acceptance angle /cone half-angle

- The maximum angle in which external light rays may strike the air/glass interface and still propagate down the fiber



Continued

- θin (max) = sin-1 $\sqrt{n_1^2 - n_2^2},$
- Where,
- θin (max) – acceptance angle (degrees)
- n1 – refractive index of glass fiber core
- n2 – refractive index of quartz fiber cladding

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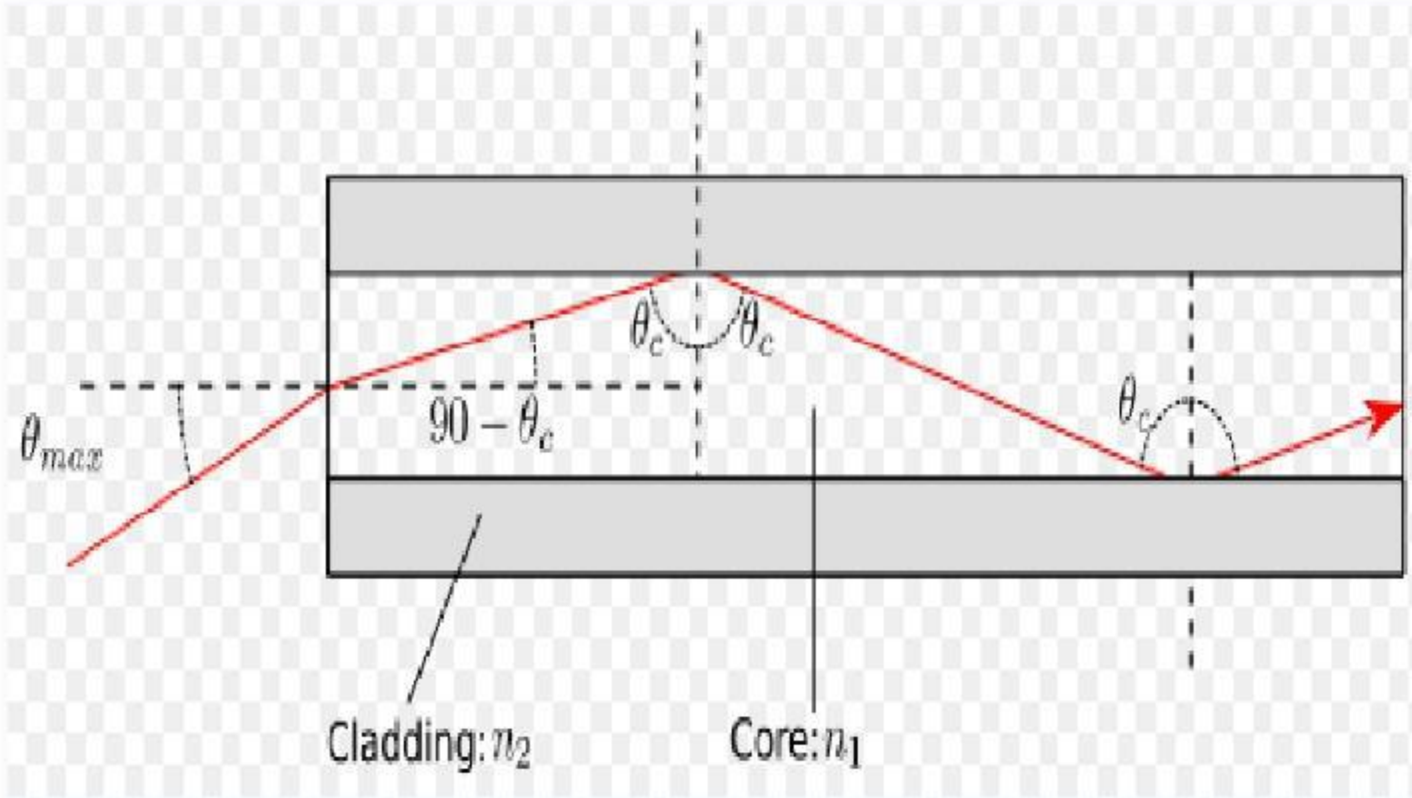
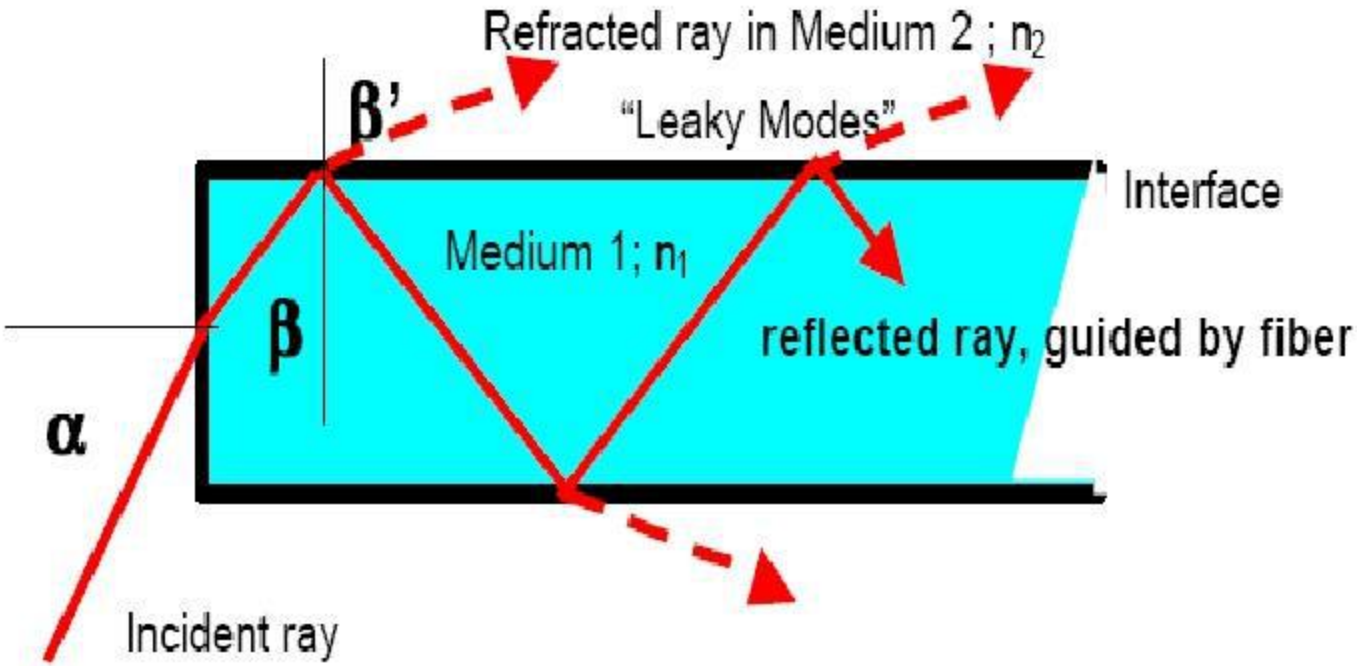

θ_c
θ_c
θ_c
$90 - \theta_c$
θ_{max}
Cladding: n_2
Core: n_1

Continued


Refracted ray in Medium 2 ; n2
β'
"Leaky Modes"
Interface
Medium 1; n1
β
reflected ray, guided by fiber
α
Incident ray

Numerical Aperture (NA)

- Used to describe the light-gathering or light-collecting ability of an optical fiber.
- In optics, the **numerical aperture** (**NA**) of an optical system is a dimensionless number that characterizes the range of angles over which the system can accept or emit light

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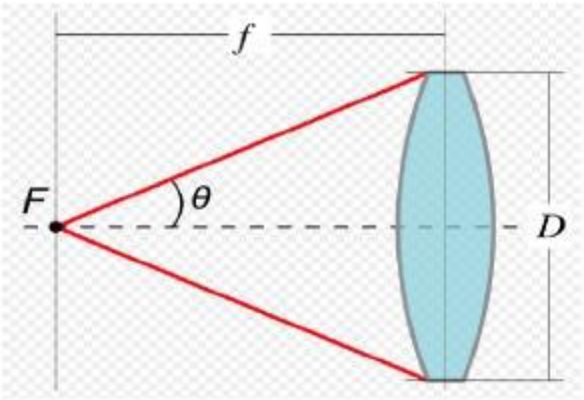
$$\mathrm{NA} = \sqrt{n_1^2 - n_2^2},$$



The numerical aperture in respect to a point P depends on the half-angle θ of the maximum cone of light that can enter or exit the lens.

INDEX PROFILE

- The index profile of an optical fiber is a graphical representation of the magnitude of the refractive index across the fiber
- The refractive index is plotted on the horizontal axis and,
- The radial distance from the core axis is plotted on the vertical axis

Continued

- The boundary between the core and cladding may either be abrupt, in ***step-index fiber***, or gradual, in ***graded-index fiber***.

STEP-INDEX

- A step-index fiber has a central core with a uniform refractive index
- An outside cladding that also has a uniform refractive index surrounds the core;
- however, the refractive index of the cladding is less than that of the central core.

GRADED-INDEX

- Graded Index – Core material has variable index as a function of the radial distance from the center
- This causes light rays to bend smoothly as they approach the cladding, rather than reflecting abruptly from the core-cladding boundary

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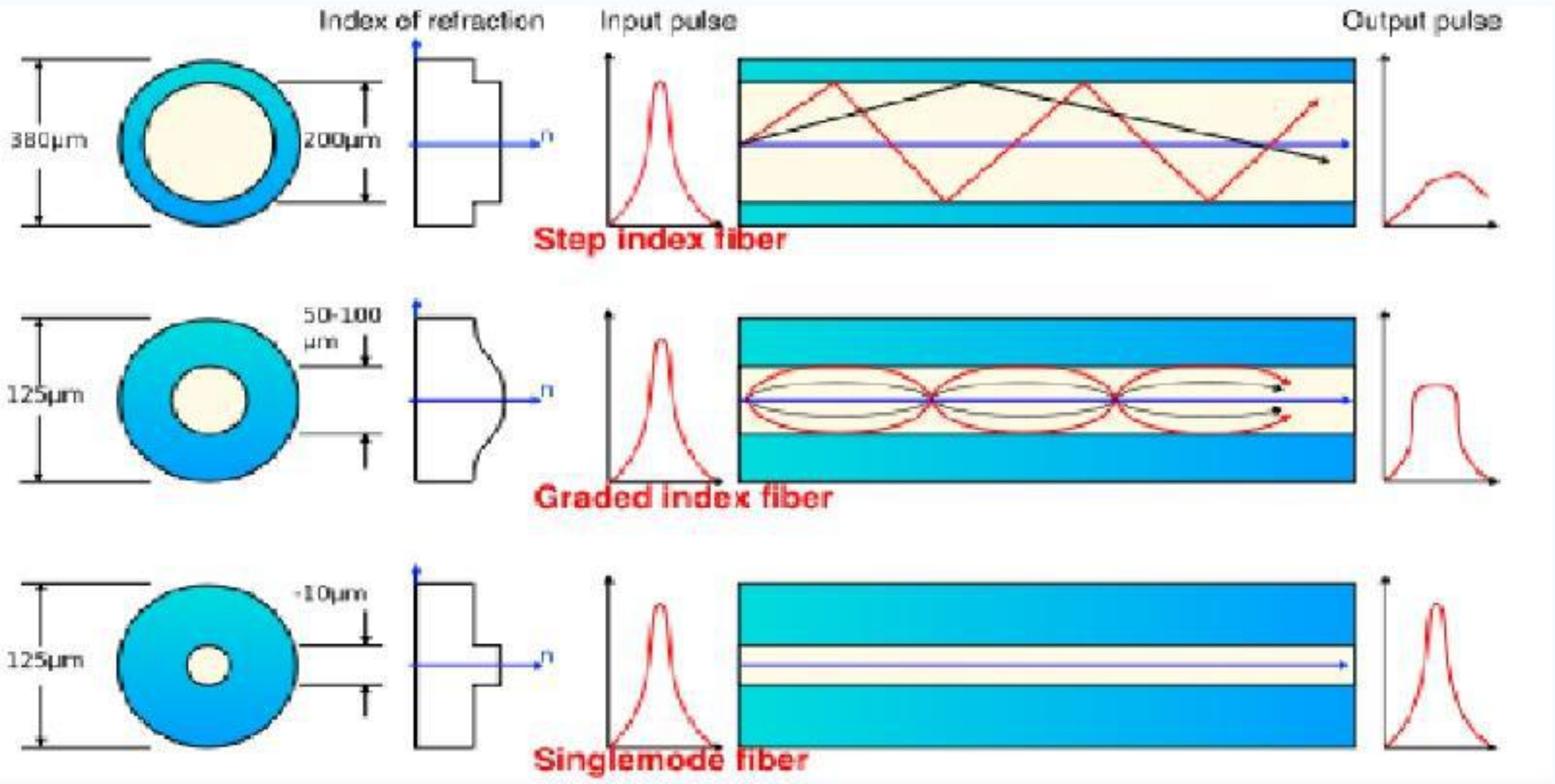

Index of refraction
Input pulse
Output pulse
380μm
200μm
Step index fiber
50-100 μm
125μm
Graded index fiber
~10μm
125μm
Singlemode fiber

Exercises

1. What is the need of fiber optics communication systems?
2. What is the principle operation of fiber optics communication systems?
3. A light ray is incident from medium-1 to medium-2. If the refractive indices of medium-1 and medium-2 are 1.5 and 1.36 respectively then determine the angle of refraction for an angle of incidence of 30^0 ?
4.

Exercise

4. A multimode step index fiber with a core diameter of 80 µm and a relative index difference of 1.5 % is operating at a wavelength of 0. 85 µm. If the core refractive index is 1.48, estimate the normalized frequency for the fiber and number of guided modes.

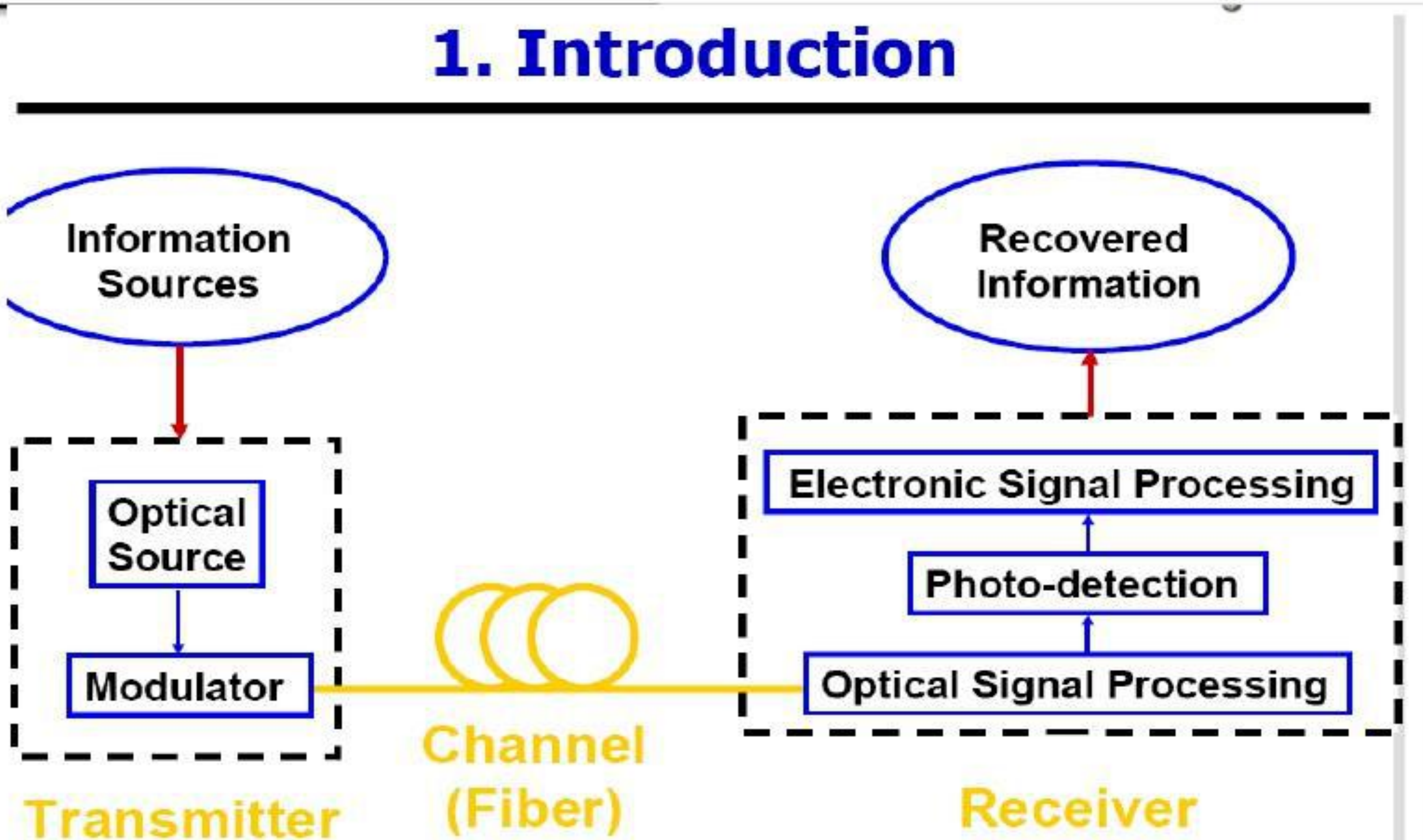
5. A step index multimode fiber with a numerical aperture of a 0.20 supports approximately 1000 modes at an 850 nm wavelength.

   i) What is the diameter of its core?

   ii) How many modes does the fiber support at 1320 nm?

   iii) How many modes does the fiber support at 1550 nm?

Optical Transmitters And Receivers



Optical Transmitters

- Optical Transmitter Functions
  - Coding for error protection
  - Line coding to control transmitted spectrum
  - convert an electrical input signal into the corresponding optical signal
- Fiber-optic communication systems often use semiconductor optical sources such as light-emitting diodes (LEDs) and semiconductor lasers because of several inherent advantages offered by them

Continued

- Some of these advantages are:-
  - compact size
  - high efficiency
  - good reliability
  - right wavelength range
  - small emissive area compatible with fiber core dimensions

Characteristics of Light Source for Communication

- To be useful in an optical link, a light source needs the following characteristics :

i) It must be possible to operate the device continuously at a variety of temperatures for many years.

ii) It must be possible to modulate the light output over a wide range of modulating frequencies.

iii) For fiber links, the wavelength of the output should coincide with one of transmission windows for the fiber type used.

Continued

iv) To couple large amount of power into an optical fiber, the emitting area should be small.

v) To reduce material dispersion in an optical fiber link, the output spectrum should be narrow.

vi) The power requirement for its operation must be low.

vii) The light source must be compatible with the modern solid state devices.

viii) The optical output power must be directly modulated by varying the input current to the device.

ix) Better linearity to prevent harmonics and intermodulation distortion.

Continued

x) High coupling efficiency.

xi) High optical output power.

xii) High reliability.

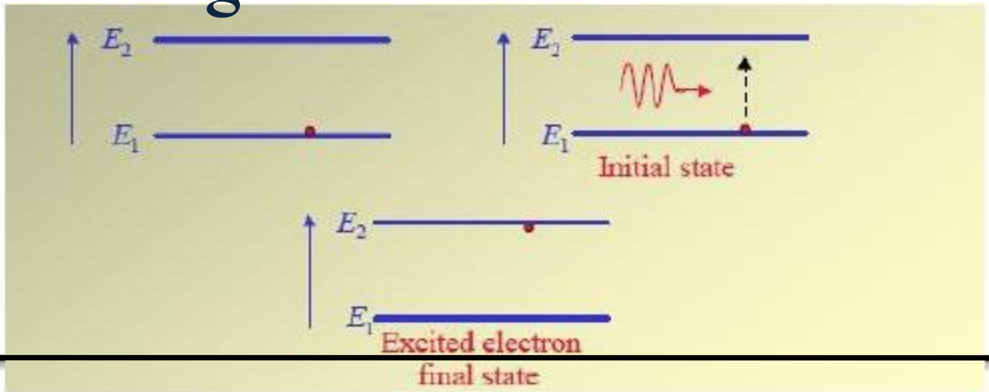
xiii) Low weight and low cost.

Light Sources - Properties

- In order for the light sources to function properly and find practical use, the following requirements must be satisfied:
  - Output wavelength: *must coincide with the loss minima of the fiber*
  - Output power: *must be high, using lowest possible current and less heat*
  - High output directionality
  - Wide bandwidth
  - Low distortion

Absorption

- Under normal conditions, all materials absorb light rather than emit it
- The absorption process can be understood by referring fig below where the energy levels E_1 *and* E_2 correspond to the ground state and the excited state of atoms of the absorbing medium



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- If the photon energy $h\nu$ *of the incident light of frequency* ν *is about the same as the* energy difference $E_g = E_2 - E_1$,
- *the photon is absorbed by the atom, which ends up in* the excited state.
- Incident light is attenuated as a result of many such absorption events occurring inside the medium.

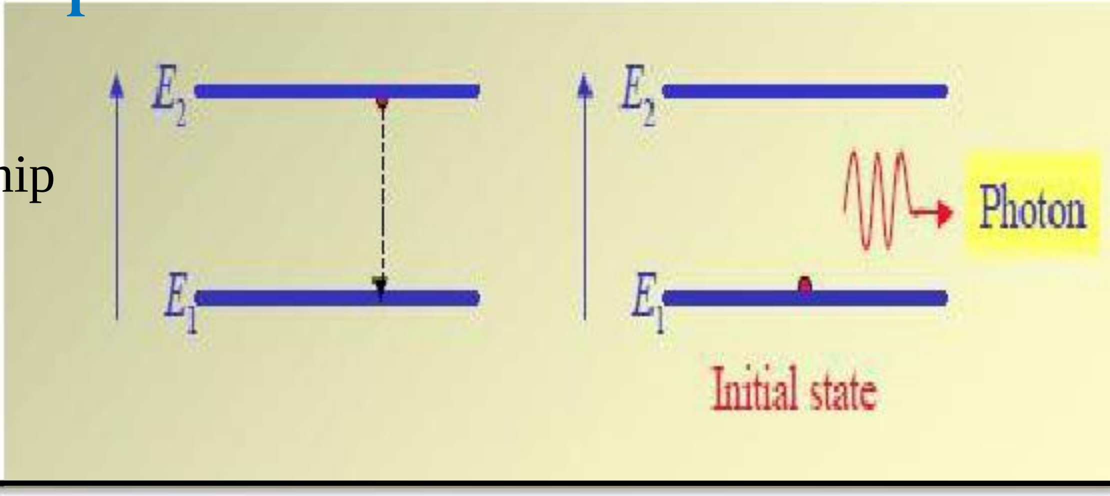
Emission

- The excited atoms eventually return to their normal "ground" state and emit light in the process
- Light emission can occur through two fundamental processes known as
  - *spontaneous emission and*
  - *stimulated emission*

Spontaneous Emission

- E2 is unstable and the excited electron(s) will return back to the lower energy level E1
- As they fall, they give up the energy acquired during absorption in the form of radiation, which is known as the **spontaneous emission process**.

- photons are emitted in random directions with no phase relationship among them.



Stimulated Emission

- But before the occurrence of this spontaneous emission process, if external stimulation (photon) is used to strike the excited atom then, it will stimulate the electron to return to the lower state level.
- By doing so it releases its energy as a new photon. The generated photon(s) is in phase and have the same frequency as the incident photon.
- The result is generation of a coherent light composed of two or more photons

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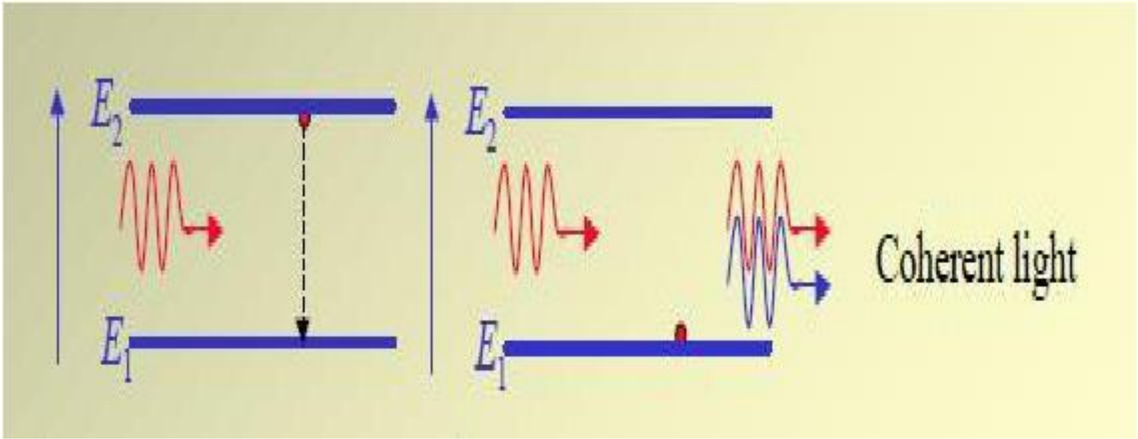


- The remarkable feature of stimulated emission is that the emitted photon matches the original photon not only in energy (or in frequency), but also in its other characteristics, such as the direction of propagation.

Light Sources - Types

- **Light Emitting Diode (LED)**
- **Semiconductor Laser Diode (SLD or LD)**

Light Emitting Diode (LED)

- A forward-biased *p–n junction emits light through spontaneous emission, a phenomenon* referred to as electroluminescence
- In its simplest form, LED is a forward biased *p–n homo junction.*
- *Radiative recombination of electron–hole pairs in the depletion* region generates light;
  - some of it escapes from the device and can be coupled into an optical fiber.
- The emitted light is incoherent with a relatively wide spectral width and a relatively large angular spread.
- In

Power–Current Characteristics

- It is easy to estimate the internal power generated by spontaneous emission
- At a given current *I the carrier-injection rate is I/q*
- *In the steady state, the rate of electron–hole* pairs recombining through radiative and non radiative processes is equal to the carrier-injection rate *I/q*
- *Since the internal quantum efficiency* η_{int} *determines the fraction of* electron–hole pairs that recombine through spontaneous emission, the rate of photon generation is simply $\eta_{int} I/q$

Continued

- *The internal optical power is thus given by*

$$P_{int} = \eta_{int}(\hbar\omega/q)I,$$

- where *hω is the photon energy, assumed to be nearly the same for all photons*

Continued

- *If* *next* is the fraction of photons escaping from the device, the emitted power is given by

$$P_e = \eta_{ext} P_{int} = \eta_{ext}\eta_{int}(\hbar\omega / q)I.$$

Continued

- The quantity η_{ext} is called the *external quantum efficiency*
- *It can be calculated by* taking into account internal absorption and the total internal reflection at the semiconductor–air interface

$$\eta_{ext} = n^{-1}(n+1)^{-2}.$$

- Where n is the refractive index

Continued

- A measure of the LED performance is the total quantum efficiency η_{tot}
- It is defined as the ratio of the emitted optical power *Pe to the applied electrical power,* $P_{ele} = V_0 I$, where V_0 *is the voltage drop across the device*

$$\eta_{tot} = \eta_{ext}\eta_{int}\left(\hbar\omega / qV_0\right).$$

Continued

- Another quantity sometimes used to characterize the LED performance is the *responsivity* defined as the ratio

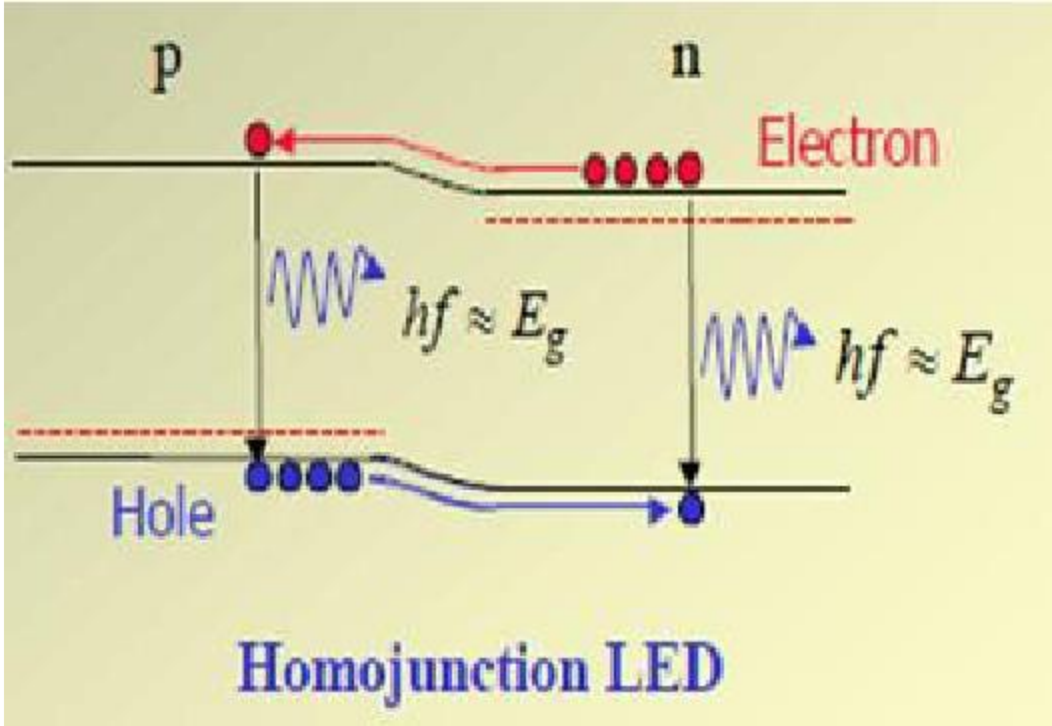
$$R_{LED} = P_e / I$$

$$R_{\mathrm{LED}} = \eta_{\mathrm{ext}} \eta_{\mathrm{int}} (\hbar\omega / q).$$

$$R_{\mathrm{LED}} = \eta_{\mathrm{tot}} V_0.$$

LED - Structure

- Injection of minority carriers across the junction gives rise to efficient Radiative recombination of electrons with holes



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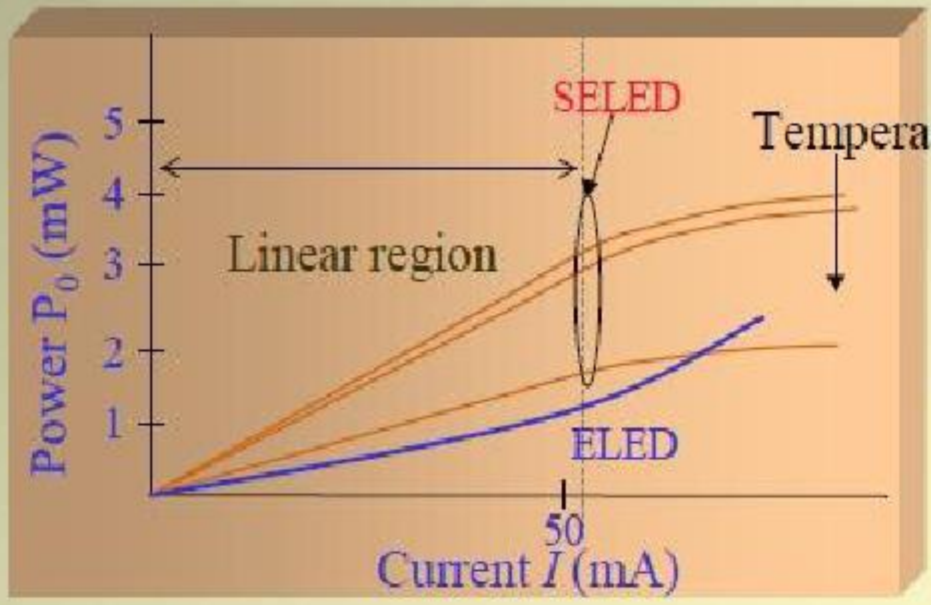
- Depanding on whether the LED emits light from a surface that is parallel to the junction plane or from the edge of the junction region ,the LED types can be classified as follows:
  - surface-emitting and
  - edge-emitting
- Both types can be made using either a *p–n homo-junction* or a hetero-structure design in which the active region is surrounded by *p- and n-type cladding layers.*

Continued

- **Surface Emitting LED (SLED)**
  - Data rates less than 20 Mbps
  - Short optical links with large NA fibers (poor coupling)
  - Coupling lens used to increase efficiency
- **Edge Emitting LED (ELED)**
  - Higher data rate > 100 Mbps
  - Considerable light can be coupled into a fiber of even low numerical aperture
  - The modulation bandwidth of edge-emitting LEDs is generally larger than that of surface-emitting LEDs

LED - Power Vs. Current Characteristics



Since $P \propto I$, then LED can be intensity modulated by modulating the I

Semiconductor Lasers

- Semiconductor lasers emit light through stimulated emission
- As a result of the fundamental differences between spontaneous and stimulated emission, they are not only capable of emitting high powers,
- *But also have other advantages related* to the coherent nature of emitted light
- A relatively narrow angular spread of the output beam compared with LEDs permits high coupling efficiency

LASER - CHARACTERISTICS

- The term Laser stands for **Light Amplification by Stimulated Emission of Radiation**.
- It is coherent in nature i.e. all the wavelengths contained within the Laser light have the same phase
- The main advantage of Laser over other light sources
  - A pumping source(creating more electron-hole pairs) providing power
  - It had well defined threshold current beyond which lasing occurs
  - At low operating current it behaves like LED
  - Most operate in the near-infrared region

Laser Structures

- The simplest structure of a semiconductor laser consists of a thin active layer (thickness∼ *0.1 μm) sandwiched between p-type and n-type cladding layers of another semi*conductor with a higher band gap.
- The resulting *p–n heterojunction is forward-biased* through metallic contacts
- Such lasers are called *broad-area semiconductor lasers since* the current is injected over a relatively broad area covering the entire width of the laser chip (∼ *100 μm).*

Types of laser

- Fabry-Perot (FP)
- Distributed Feedback (DFB)
- Distributed Bragg Reflector (DBR)
- Distributed Reflector (DR)

LED VS LASER

Sr. No.	Parameter	LED	LD (Laser Diode)
1.	Principle of operation	Spontaneous emission	Stimulated emission
2.	Output beam	Non - coherent	Coherent
3.	Spectral width	Broad spectrum (20 nm - 100 nm)	Much narrower (1 - 5 nm)
4.	Data rate	Low	Very high
5.	Transmission distance	Smaller	Greater
6.	Temperature sensitivity	Less sensitive	More temperature sensitive
7.	Coupling efficiency	Very low	High
8.	Compatible fibers	Multimode step index multimode GRIN	Single mode SI Multimode GRIN
9.	Circuit complexity	Simple	Complex
10.	Life time	10^5 hours	10^4 hours
11.	Cost	Low	High

Transmitter Design

- Although an optical source is a major component of optical transmitters, it is not the only component
- Other components include a modulator for converting electrical data into optical form and an electrical driving circuit for supplying current to the optical source
- An external modulator is often used in practice at bit rates of 10 Gb/s or more for avoiding the chirp that is invariably imposed on the directly modulated signal

1.Source–Fiber Coupling

- The design objective for any transmitter is to couple as much light as possible into the optical fiber
- In practice, the coupling efficiency depends on the type of optical source
- (LED versus laser) as well as on the type of fiber (multimode versus single mode)
- The coupling efficiency for LED changes with the numerical aperture, and can become $<1\%$ in the case of single-mode fibers

Continued

- In contrast, the coupling efficiency for edge-emitting lasers is typically 40–50%
- A small piece of fiber is included with the transmitter so that the coupling efficiency can be maximized during packaging; a splice or connector is used to join the pigtail with the fiber cable.

Continued

- Two approaches have been used for source–fiber coupling
- In one approach, known as direct or butt coupling, the fiber is brought close to the source and held in place by epoxy
- In the other, known as lens coupling, a lens is used to maximize the coupling efficiency
- Each approach has its own merits, and the choice generally depends on the design objectives
- An important criterion is that the coupling efficiency should not change with time; mechanical stability of the coupling scheme is therefore a necessary requirement.

Continued

- The coupling efficiency for a fiber of numerical aperture NA is given by $$n_c = (1 - R_f)(\mathrm{NA})^2,$$
- Where Rf is the reflectivity at the fiber front end
- Rf is about 4% if an air gap exists between the source and the fiber but can be reduced to nearly zero by placing an index matching liquid
- The coupling efficiency is about 1% for a surface-emitting LED and roughly 10% for an edge-emitting LED

2. Driving Circuitry

- The purpose of driving circuitry is to provide electrical power to the optical source and to modulate the light output in accordance with the signal that is to be transmitted
- Driving circuits are relatively simple for LED transmitters but become increasingly complicated for high-bit-rate optical transmitters employing semiconductor lasers as an optical source
- The driving circuit is designed to supply a constant bias current as well as modulated electrical signal
- Furthermore, a servo loop is often used to keep the average optical power constant

3. Optical Modulators

- At bit rates of 10 Gb/s or higher, the frequency chirp imposed by direct modulation becomes large enough that direct modulation of semiconductor lasers is rarely used
- For such high-speed transmitters, the laser is biased at a constant current to provide the CW output, and an optical modulator placed next to the laser converts the CW light into a data-coded pulse train with the right modulation format

4. Reliability and Packaging

- An optical transmitter should operate reliably over a relatively long period of time in order to be useful as a major component of light wave systems
- Considerable testing is performed during assembly and manufacture of transmitters to ensure a reasonable lifetime for the optical source
- Both LEDs and semiconductor lasers can stop operating suddenly (catastrophic degradation) or
- May exhibit a gradual mode of degradation in which the device efficiency degrades with aging

Continued

- Attempts are made to identify devices that are likely to degrade catastrophically
- A common method is to operate the device at high temperatures and high current levels
- This technique is referred to as burn-in or accelerated aging and
  - It is based on the assumption that under high-stress conditions weak devices will fail, while others will stabilize after an initial period of rapid degradation

OPTICAL DETECTORS AND RECEIVERS

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

Receiver Functions

- Optical to electronic conversion
- Regeneration of the received signal
- Error detection/correction
- Recoding to match output standard

Photo-detector Requirements

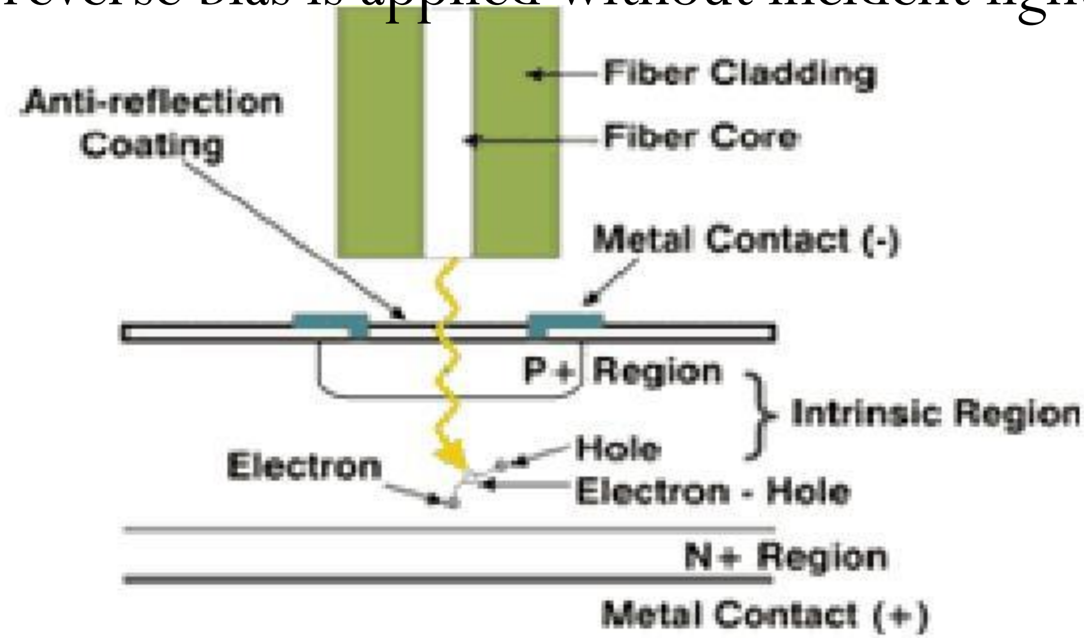
- Good sensitivity (responsivity) at the desired wavelength and poor responsivity elsewhere → wavelength selectivity
- Fast response time → high bandwidth
- Compatible physical dimensions
- Low noise
- Insensitive to temperature variations
- Long operating life and reasonable cost

Photodiodes

- Due to above requirements, only *photodiodes* are used as photo detectors in optical communication systems.
- Positive-Intrinsic-Negative (*pin*) photodiode
- Avalanche Photo Diode (*APD*)
  - An internal gain of *M* due to self multiplication
- Photodiodes are sufficiently *reverse biased* during normal operation → no current flow, the intrinsic region is fully depleted of carriers.

PIN Photodiode.

- Semiconductor positive-negative structure with an intrinsic region sandwiched between the other two regions
- Normally operated by applying a reverse-bias voltage
- Dark current can also be produced which is a leakage current that flows when a reverse bias is applied without incident light



Response time factors.

- Thickness of the active area

  -Related to the amount of time required for the electrons generated to flow out of the detector active area

- Detector RC time constant

  -Depends on the capacitance of the photodiode and the resistance of the load.

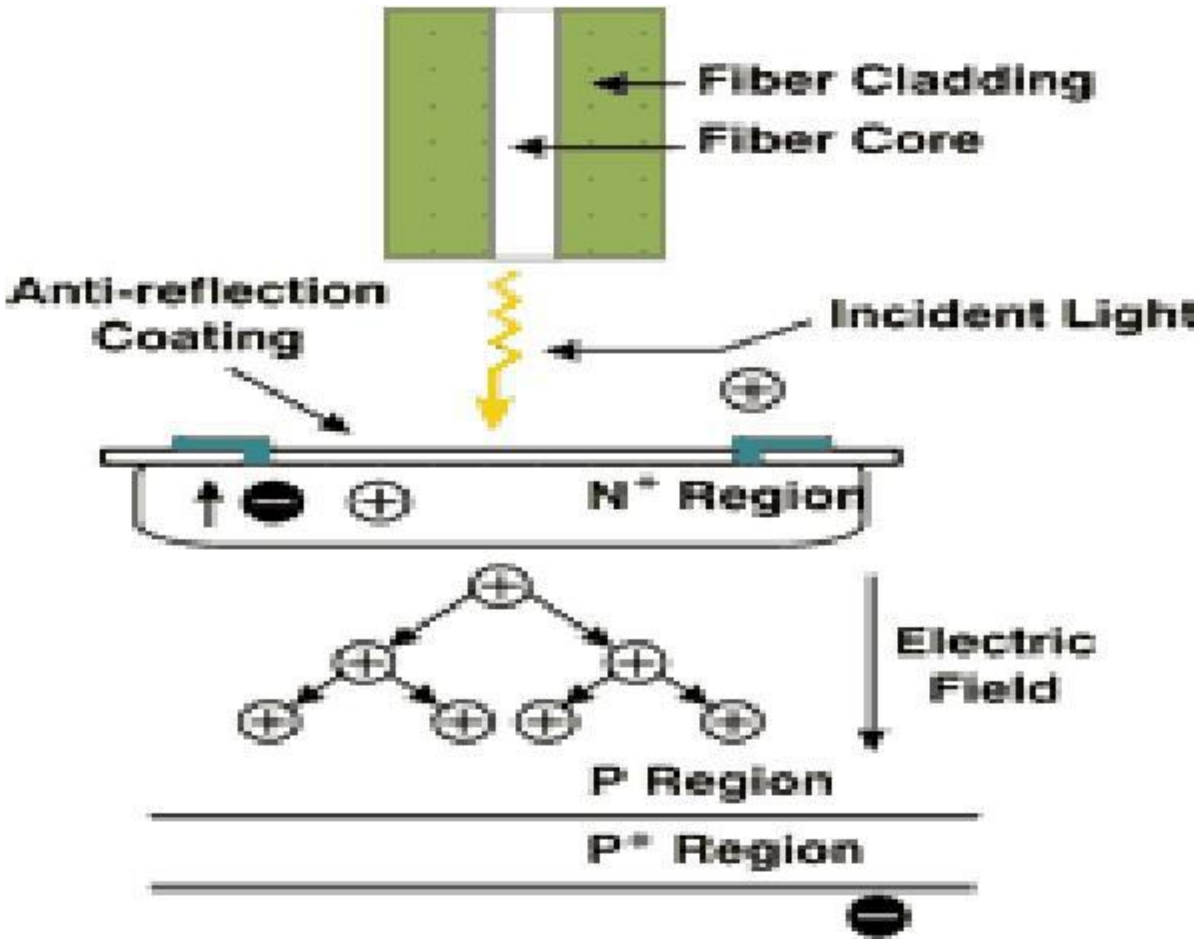
Advantage of PIN photodiodes.

- The output electrical current is linearly proportional to the input optical power making it a highly linear device
- Low bias voltage(<4v)
- Low noise
- Low dark current
- High-speed response

AVALANCHE Photodiodes.

- An APD internally amplifies the photocurrent by an avalanche process when a large reverse-bias voltage is applied across the active region
- The gain of the APD can be changed by changing the reverse-bias voltage.
- APD has an internal gain obtained by having a *high electric field* that energizes photo-generated electrons and holes
- These electrons and holes ionize bound electrons in the valence band upon colliding with them
- This mechanism is known as *impact ionization*
- The newly generated electrons and holes are also accelerated by the high electric field and they gain enough energy to cause further impact ionization
- This phenomena is called the avalanche effect

Continued


Fiber Cladding
Fiber Core
Anti-reflection Coating
Incident Light
N⁺ Region
Electric Field
P Region
P⁺ Region

APD Vs PIN

- APD has high gain due to self multiplying mechanism, used in high end systems
- The tradeoff is the 'excess noise' due to random nature of the self multiplying process.
- APD's need high reverse bias voltage
- Therefore costly and need additional circuitry

Receiver Design

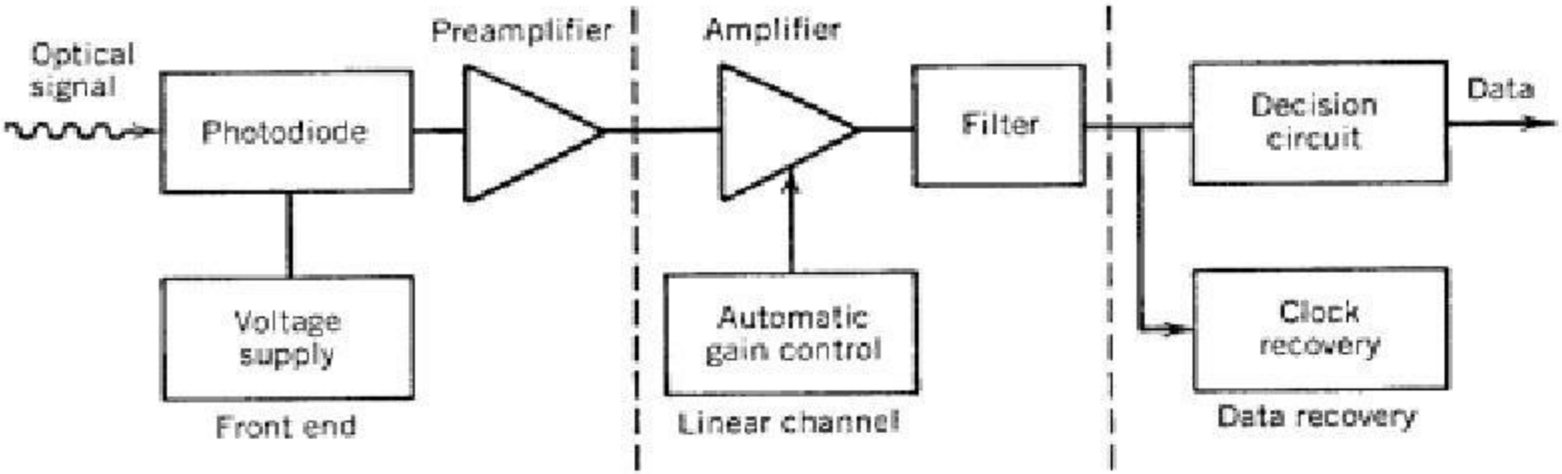


Figure : Diagram of a digital optical receiver showing various components. Vertical dashed lines group receiver components into three sections.

1.Front End

- The front end of a receiver consists of a photodiode followed by a preamplifier
- The optical signal is coupled onto the photodiode by using a coupling scheme similar to that used for optical transmitters
- The photodiode converts the optical bit stream into an electrical time-varying signal
- The role of the preamplifier is to amplify the electrical signal for further processing

Continued

- The design of the front end requires a trade-off between speed and sensitivity
- Since the input voltage to the preamplifier can be increased by using a large load resistor R_L, a high-impedance front end is often used
- A large R_L reduces the thermal noise and improves the receiver sensitivity
- The main drawback of high-impedance front end is its low bandwidth

Continued

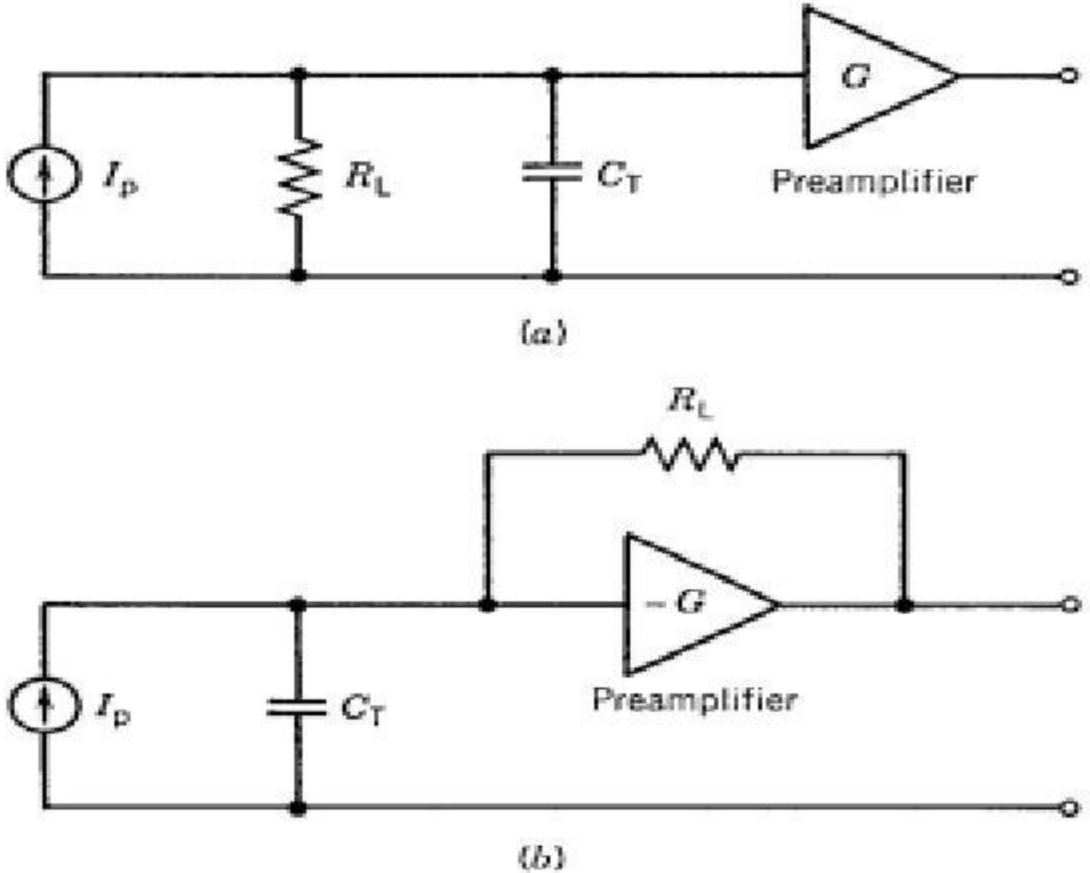


Figure : Equivalent circuit for (a) high-impedance and (b) transimpedance front ends in optical receivers. The photodiode is modeled as a current source in both cases.

Continued

- A high-impedance front end cannot be used if Δf is considerably less than the bit rate
- An equalizer is sometimes used to increase the bandwidth
- The equalizer acts as a filter that attenuates low-frequency components of the signal more than the high-frequency components, thereby effectively increasing the front-end bandwidth
- If the receiver sensitivity is not of concern, one can simply decrease RLto increase the bandwidth, resulting in a low-impedance front end.

Continued

- Transimpedance front ends provide a configuration that has high sensitivity together with a large bandwidth
- Its dynamic range is also improved compared with high-impedance front ends
- The load resistor is connected as a feedback resistor around an inverting amplifier
- Even though RL is large, the negative feedback reduces the effective input impedance by a factor of G, where G is the amplifier gain
- The bandwidth is thus enhanced by a factor of G compared with high impedance front ends
- Transimpedance front ends are often used in optical receivers because of their improved characteristics

2.Linear Channel

- The linear channel in optical receivers consists of
  - a high-gain amplifier (the main amplifier) and
  - a low-pass filter
  - An equalizer is sometimes included just before the amplifier to correct for the limited bandwidth of the front end
  - The amplifier gain is controlled automatically to limit the average output voltage to a fixed level irrespective of the incident average optical power at the receiver

Continued

- The low-pass filter shapes the voltage pulse
- Its purpose is to reduce the noise without introducing much intersymbol interference(ISI)

3.Decision Circuit

- The data-recovery section of optical receivers consists of a decision circuit and a clock recovery circuit
- The purpose of the latter is to isolate a spectral component from the received signal
- This component provides information about the bit slot to the decision circuit and helps to synchronize the decision process
- The decision circuit compares the output from the linear channel to a threshold level, at sampling times determined by the clock-recovery circuit, and decides whether the signal corresponds to bit 1 or bit 0
- The best sampling time corresponds to the situation in which the signal level difference between 1 and 0 bits is maximum

Exercises

1. Describe in detail about the components of fiber optics communication systems
2. Explain The effect of transmitting power in optical communication.

Chapter 3
Light Wave Systems

- System Architectures
- Channel multiplexing
  - Wavelength -Division Multiplexing
  - Time-Division Multiplexing
  - Code-Division Multiplexing
- Coherent Light wave Systems
  - Coherent,
  - homodyne
  - heterodyne

- system performance
- BER in synchronous - and asynchronous- receivers

System Architectures

- From an architectural standpoint, fiber-optic communication systems can be classified into three broad categories:
  - point-to-point links
  - distribution networks, and
  - local-area networks

Point-to-Point Links

- Point-to-point links constitute the simplest kind of light wave systems
- Their role is to transport information, available in the form of a digital bit stream, from one place to another as accurately as possible
- The link length can vary from less than a kilometer to thousands of kilometers, depending on the specific application
- For example, optical data links are used to connect computers and terminals within the same building or between two buildings with a relatively short transmission distance (<10 km)

Distribution Networks

- Many applications of optical communication systems require that information is not only transmitted but is also distributed to a group of subscribers
- Example: local-loop distribution of telephone services and broadcast of multiple video channels over cable television
- Considerable effort is directed toward the integration of audio and video services through a broadband integrated-services digital network (ISDN)
- Such a network has the ability to distribute a wide range of services:
  - telephone, facsimile, computer data, and video broadcasts
- Transmission distances are relatively short (L<50 km), but the bit rate can be as high as 10 Gb/s for a broadband ISDN.

Continued

- Figure 3.1 shows two topologies for distribution networks
- In the case of hub topology, channel distribution takes place at central locations (or hubs)
- Such networks are called metropolitan-area networks (MANs) as hubs are typically located in major cities
- Since the fiber bandwidth is generally much larger than that required by a single hub office, several offices can share a single fiber headed for the main hub
- Telephone networks employ hub topology for distribution of audio channels within a city

Continued

- In the case of bus topology, a single fiber cable carries the multichannel optical signal throughout the area of service
- Distribution is done by using optical taps, which divert a small fraction of the optical power to each subscriber
- The use of optical fiber permits distribution of a large number of channels (100 or more) because of its large bandwidth compared with coaxial cables(about 100 Mb/s) of each video channel unless a compression technique is used

Continued

- A problem with the bus topology is that the signal loss increases exponentially with the number of taps and limits the number of subscribers served by a single optical bus
- Even when fiber losses are neglected, the power available at the Nth tap is given by

$$P_N = P_T C[(1-\delta)(1-C)]^{N-1},$$

- Where P_T is the transmitted power,
- C is the fraction of power coupled out at each tap ,and
- δ accounts for insertion losses, assumed to be the same at each tap

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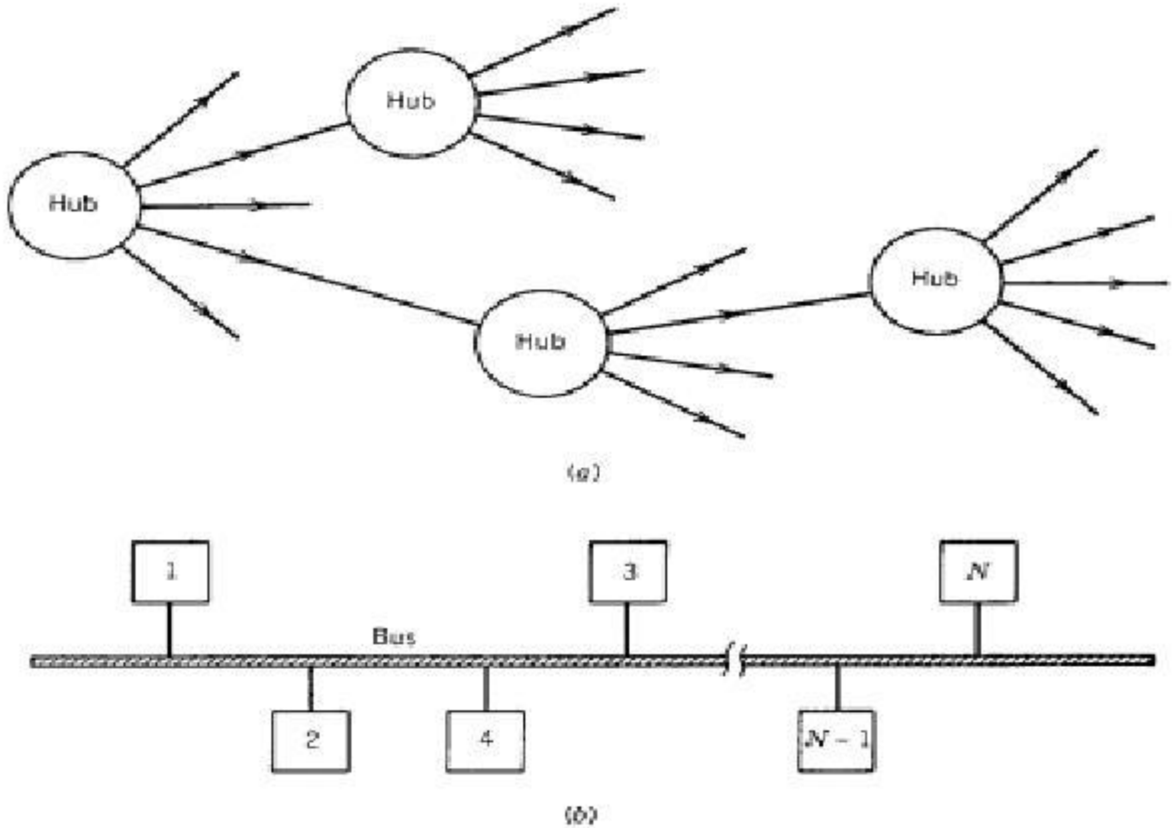

Figure 3.1: (a) Hub topology and (b) bus topology for distribution networks

Local-Area Networks

- Many applications of fiber-optic communication technology require networks in which a large number of users within a local area (e.g., a university campus) are interconnected in such a way that any user can access the network randomly to transmit data to any other user
- Such networks are called local-area networks (LANs)
- Since the transmission distances are relatively short (<10 km), fiber losses are not of much concern for LAN applications
- The major motivation behind the use of optical fibers is the large bandwidth offered by fiber-optic communication systems

Continued

- The system architecture plays an important role for LANs,
- since the establishment of predefined protocol rules is a necessity in such an environment
- Three commonly used topologies are known as bus, ring, and star configurations
- The bus topology is similar to that shown in Fig. 3.1(b)
- Example: A network protocol used to connect multiple computers and used by the Internet

Continued

- Figure 3.2 shows the ring and star topologies for LAN applications
- In the ring topology , consecutive nodes are connected by point-to-point links to form a closed ring
- Each node can transmit and receive the data by using a transmitter–receiver pair, which also acts as a repeater
- A token (a predefined bit sequence) is passed around the ring
- Each node monitors the bit stream to listen for its own address and to receive the data

Continued

- The use of ring topology for fiber-optic LANs has been commercialized with the standardized interface known as the fiber distributed data interface(FDDI)
- It is designed to provide backbone services such as the interconnection of lower-speed LANs or mainframe computers

Continued

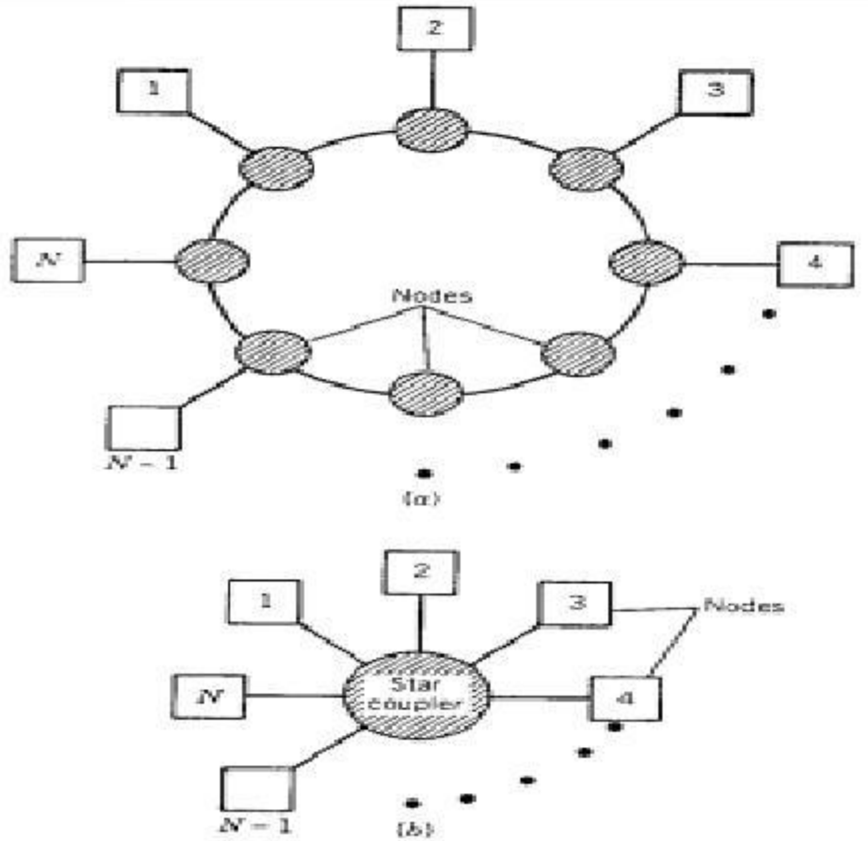

Figure 3.2: (a) Ring topology and (b) star topology for local-area networks

Continued

- In the star topology, all nodes are connected through point-to-point links to a central node called a hub
- Such LANs are further sub classified as active-star or passive-star networks, depending on whether the central node is an active or passive device
- In the active-star configuration, all incoming optical signals are converted to the electrical domain through optical receivers
- The electrical signal is then distributed to drive individual node transmitters
- Switching operations can also be performed at the central node since distribution takes place in the electrical domain

Continued

- In the passive star configuration, distribution takes place in the optical domain devices such as directional couplers
- Since the input from one node is distributed to many output nodes, the power transmitted to each node depends on the number of users
- Similar to the case of bus topology, the number of users supported by passive-star LANs is limited by the distribution losses

Continued

- For an ideal N×N star coupler, the power reaching each node is simply PT/N(if we neglect transmission losses) since the transmitted power PT is divided equally among N users
- For a passive star composed of directional couplers, the power is further reduced because of insertion losses and can be written as

$$P_N = (P_T/N)(1-\delta)^{\log_2 N},$$

- Where δ is the insertion loss of each directional coupler

Multichannel Systems

- In principle, the capacity of optical communication systems can exceed 10 Tb/s because of a large frequency associated with the optical carrier
- In practice, however, the bit rate was limited to 10 Gb/s or less until 1995 **due to the following reasons:**
  - because of the limitations imposed by
    - the dispersive and nonlinear effects and
    - by the speed of electronic components
- Since then, transmission of multiple optical channels over the same fiber has provided a simple way for extending the system capacity to beyond 1 Tb/s

Continued

- Channel multiplexing
  - time domain through time-division multiplexing (TDM)
  - frequency domain through frequency-division multiplexing (FDM)
- The TDM and FDM techniques can also be used in the electrical domain
- To make the distinction explicit, it is common to refer to the two optical-domain techniques as optical TDM (OTDM) and wavelength-division multiplexing(WDM), respectively

Wavelength-Division Multiplexing

- Wavelength-division multiplexing (WDM) is the practice of dividing the wavelength capacity of an optical fiber into multiple channels in order to send more than one signal over the same fiber
- This requires a wavelength division multiplexer in the transmitting equipment and a wavelength division demultiplexer in the receiving equipment
- WDM networks require a variety of passive and active devices to combine, distribute, isolate, and amplify optical power at different wavelengths

Continued

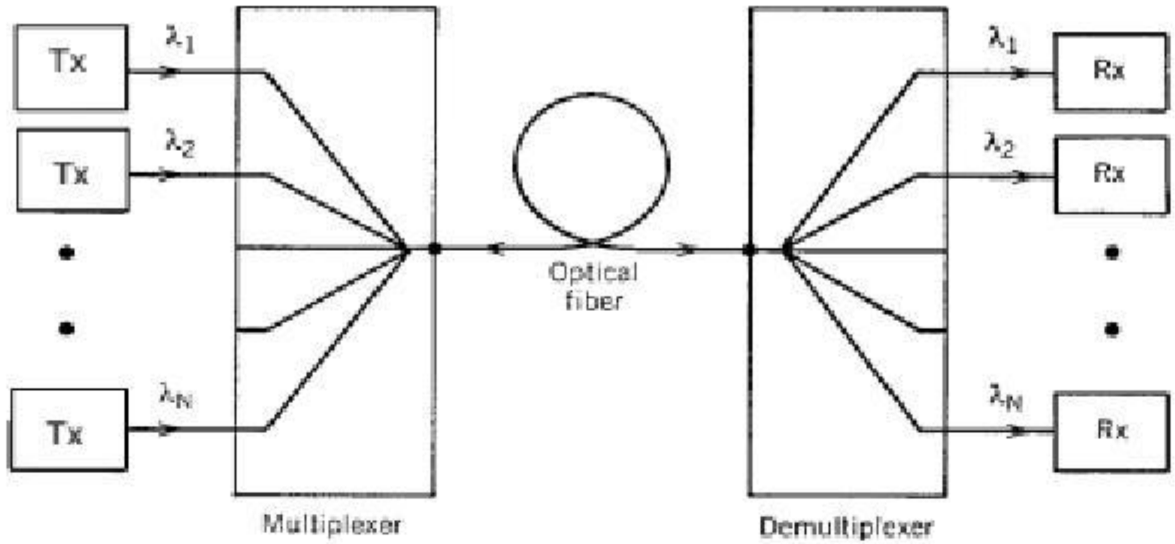

Figure 3.3: Multichannel point-to-point fiber link:Separate transmitter-receiver pairs are used to send and receive the signal at different wavelengths

WDM Components

- tunable optical filters
- multiplexers
- Demultiplexers
- star couplers
- multiwavelength optical transmitters
- add–drop multiplexers

tunable optical filters

- The role of a tunable optical filter in a WDM system is to select a desired channel at the receiver
- The filter bandwidth must be large enough to transmit the desired channel but, at the same time, small enough to block the neighboring channels
- All optical filters require a wavelength-selective mechanism

Tunable optical filter properties

- wide tuning range to maximize the number of channels that can be selected
- negligible crosstalk to avoid interference from adjacent channels
- fast tuning speed to minimize the access time
- small insertion loss
- polarization insensitivity
- stability against environmental changes (humidity, temperature, vibrations, etc.), and
- low cost

Multiplexers and Demultiplexers

- Multiplexers and Demultiplexers are the essential components of a WDM system
- Multiplexers combine the output of several transmitters and launch it into an optical fiber
- Demultiplexers which split the received multichannel signal into individual channels destined to different receivers
- Demultiplexers require a wavelength-selective mechanism
  - can be classified into two broad categories

Continued

- Diffraction-based Demultiplexers
  - use an angularly dispersive element, such as a diffraction grating, which disperses incident light spatially into various wavelength components
- Interference-based Demultiplexers use the folowing devices
  - optical filters
  - directional couplers

Add–Drop Multiplexers

- needed for wide-area and metro-area networks in which one or more channels need to be dropped or added while preserving the integrity of other channels
- Figure 3.4 shows a generic add–drop multiplexer schematically;
- it houses a bank of optical switches between a Demultiplexers–multiplexer pair
- The Demultiplexers separates all channels, optical switches drop, add, or pass individual channels, and the multiplexer combines the entire signal back again

Continued

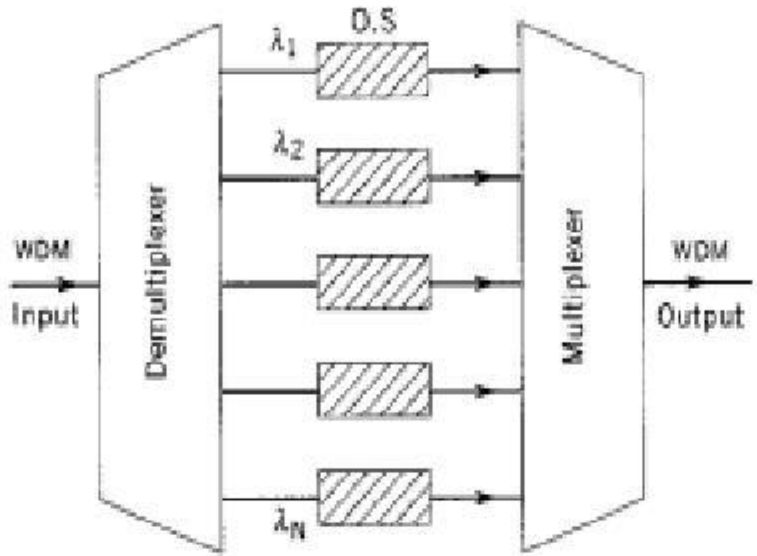

Figure 3.4: A generic add–drop multiplexer based on optical switches

Star Couplers

- The role of a star coupler is to combine the optical signals entering from its multiple input ports and divide it equally among its output ports
- star couplers which mix the output of several transmitters and broadcast the mixed signal to multiple receiver
- The number of input and output ports need not be the same
- For example, in the case of video distribution, a relatively small number of video channels (say 100) may be sent to thousands of subscribers

Continued

- The number of input and output ports is generally the same for the broadcast-and-select LANs in which each user wishes to receive all channels (see Fig. 3.5)
- Such a passive star coupler is referred to as an N×N broadcast star, where N is the number of input (or output) ports

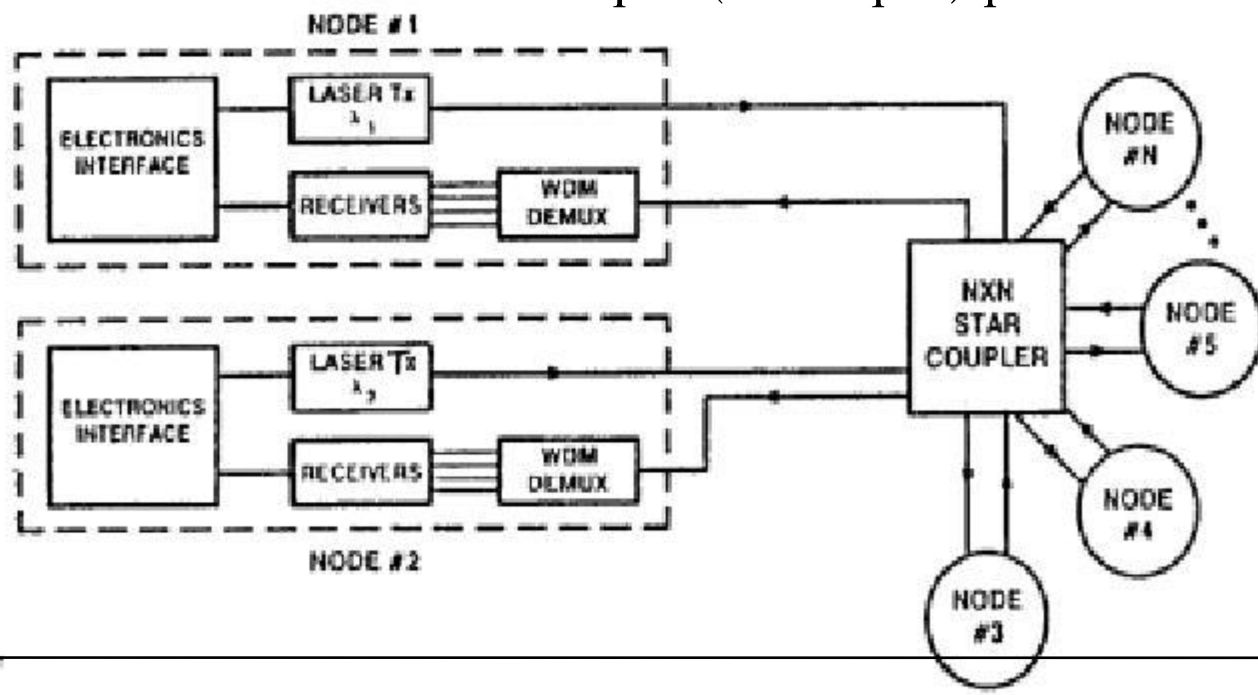

Fig.3.5

Continued

- A reflection star is sometimes used for LAN applications by reflecting the combined signal back to its input ports
- Such a geometry saves considerable fiber when users are distributed over a large geographical area

Optical time division multiplexing

- TDM is commonly performed in the electrical domain to obtain digital hierarchies for telecommunication systems
- In this sense, even single channel lightwave systems carry multiple TDM channels
- The electrical TDM becomes difficult to implement at bit rates above 10 Gb/s because of the limitations imposed by high-speed electronics
- A solution is offered by the optical TDM (OTDM), a scheme that can increase the bit rate of a single optical carrier to values above 1 Tb/s

Continued

- In OTDM lightwave systems, several optical signals at a bit rate B share the same carrier frequency and are multiplexed optically to form a composite bit stream at the bit rate NB, where N is the number of channels
- Figure 3.3 shows the design of an OTDM transmitter based on the delay-line technique
- It requires a laser capable of generating a periodic pulse train at the repetition rate equal to the single-channel bit rate B
- Moreover, the laser should produce pulses of width Tp such that $T_p < T_B = (NB)^{-1}$ to ensure that each pulse will fit within its allocated time slot TB

Continued

- The laser output is split equally into N branches, after amplification if necessary
- A modulator in each branch blocks the pulses representing 0 bits and creates N independent bit streams at the bit rate B
- Multiplexing of N bit streams is achieved by a delay technique that can be implemented optically in a simple manner
- In this scheme, the bit stream in the nth branch is delayed by an amount $(n-1)/(NB)$, where $n=1,\ldots,N$
- The output of all branches is then combined to form a composite signal.

Code-Division Multiplexing

- A multiplexing scheme well known in the domain of wireless communications makes use of the spread-spectrum technique
- It is referred to as code-division multiplexing(CDM) because each channel is coded in such a way that its spectrum spreads over a much wider region than occupied by the original signal
- The term code-division multiple access (CDMA) is often employed in place of CDM to emphasize the asynchronous and random nature of multi user connections

Continued

- Conceptually, the difference between the WDM, TDM, and CDM can be understood as follows:
- The WDM and TDM techniques partition the channel bandwidth or the time slots among users
- In contrast, all users share the entire bandwidth and all time slots in a random fashion in the case of CDM

Coherent Lightwave Systems

- The lightwave systems discussed so far are
  - based on a simple digital modulation scheme
- an electrical bit stream modulates
  - the intensity of an optical carrier inside the optical transmitter and
  - the optical signal transmitted through the fiber link is incident directly on an optical receiver,
- which converts it to the original digital signal in the electrical domain
- Such a scheme is referred to as intensity modulation with direct detection(IM/DD)

Continued

- Many alternative schemes, well known in the context of radio and microwave communication systems , transmit information by modulating the frequency or the phase of the optical carrier and
- detect the transmitted signal by using homodyne or heterodyne detection techniques
- Since phase coherence of the optical carrier plays an important role in the implementation of such schemes,
  - such optical communication systems are called coherent lightwave systems

Continued

- The motivation behind using the coherent communication techniques is two-fold
- First, the receiver sensitivity can be improved by up to 20 dB compared with that of IM/DD systems
- Second, the use of coherent detection may allow a more efficient use of fiber bandwidth by increasing the spectral efficiency of WDM systems

Basic Concepts

- **Local Oscillator**
  - The basic idea behind coherent detection consists of combining the optical signal coherently with a continuous-wave (CW) optical field before it falls on the photo detector(see Fig. 10.1)
  - The CW field is generated locally at the receiver using a narrow line width laser, called the local oscillator (LO)

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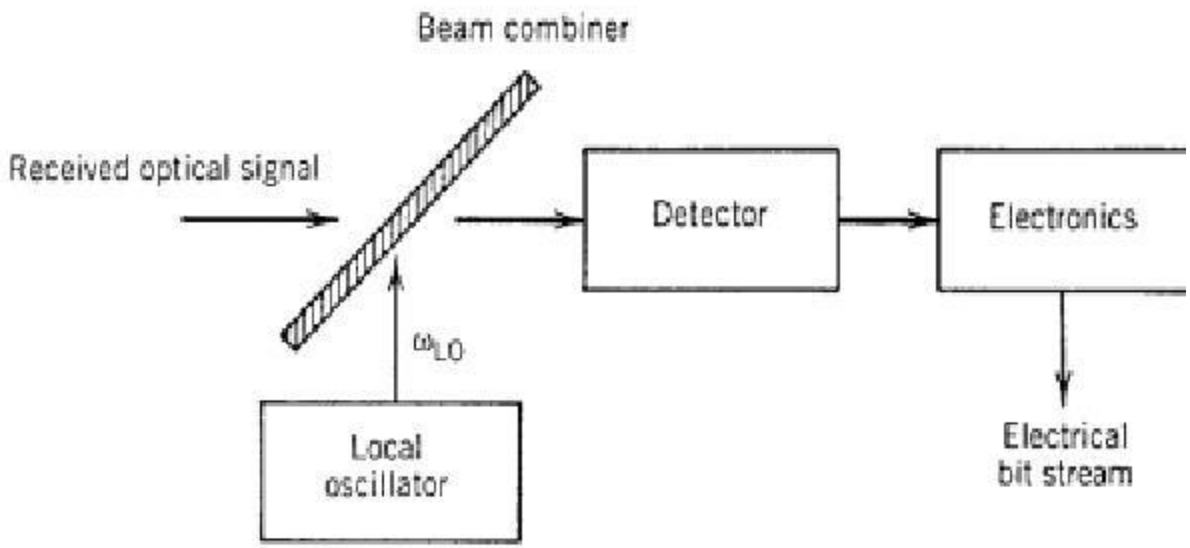


Figure 3.6: Schematic illustration of a coherent detection scheme

Continued

- To see how the mixing of the received optical signal with the LO output can improve the receiver performance, let us write the optical signal using

$$E_s = A_s \exp[-i(\omega_0 t + \phi_s)],$$

  - Where ω_0 is the carrier frequency,
  - A_s is the amplitude, and
  - φ_s is the phase

- The optical field associated with the local oscillator is given by a similar expression

$$E_{LO} = A_{LO} \exp[-i(\omega_{LO} t + \phi_{LO})],$$

- Where A_{LO}, ω_{LO}, and φ_{LO} represent the amplitude, frequency, and phase of the local oscillator, respectively

Continued

- The optical power incident at the photodetector is given by

$$P = K|E_s + E_{LO}|^2$$

  - where K is a constant of proportionality

$$P(t) = P_s + P_{LO} + 2\sqrt{P_s P_{LO}} \cos(\omega_{IF} t + \phi_s - \phi_{LO}),$$

where

$$P_s = KA_s^2, \quad P_{LO} = KA_{LO}^2, \quad \omega_{IF} = \omega_0 - \omega_{LO}.$$

- The frequency $\nu_{IF} \equiv \omega_{IF}/2\pi$ is known as the intermediate frequency(IF)

Continued

- When $\omega_0 \neq \omega_{LO}$, the optical signal is demodulated in two stages; its carrier frequency is first converted to an intermediate frequency ν_{IF} before the signal is demodulated to the baseband
- It is not always necessary to use an intermediate frequency
- In fact, there are two different coherent detection techniques to choose from, depending on whether or not ω_{IF} equals zero
- They are known as homodyne and heterodyne detection techniques

Homodyne Detection

- In this coherent-detection technique, the local-oscillator frequency ω_{LO} is selected to coincide with the signal-carrier frequency ω_0 so that $\omega_{IF} = 0$
- The photocurrent ($I = RP$, where R is the detector responsivity) is given by $$I(t) = R(P_s + P_{LO}) + 2R\sqrt{P_s P_{LO}}\cos(\phi_s - \phi_{LO})$$

Typically, $P_{LO} \gg P_s$, and $P_s + P_{LO} \approx P_{LO}$

- The last term in **the above equation** contains the information transmitted and is used by the decision circuit
- Consider the case in which the local-oscillator phase is locked to the signal phase so that $\varphi_s = \varphi_{LO}$

Continued

- The homodyne signal is then given by

$$I_p(t) = 2R\sqrt{P_s P_{LO}}.$$

Advantages & Disadvantages of Homodyne Detection

- homodyne detection improves the signal-to-noise ratio (SNR) by a large factor than direct-detection
- it is possible to transmit information by modulating the phase or frequency of the optical carrier
- A disadvantage of homodyne detection also results from its phase sensitivity
- Since the last term in the above equation contains the local-oscillator phase φ_{LO} explicitly, clearly φ_{LO} should be controlled
- Ideally, φ_s and φ_{LO} should stay constant except for the intentional modulation of φ_s

Continued

- In practice, both φ_s and φ_{LO} fluctuate with time in a random manner
- However, their difference $\varphi_s - \varphi_{LO}$ can be forced to remain nearly constant through an optical phase-locked loop
- The implementation of such a loop is not simple and makes the design of optical homodyne receivers quite complicated
- In addition, matching of the transmitter and local-oscillator frequencies puts stringent requirements on the two optical sources
- These problems can be overcome by the use of heterodyne detection

Heterodyne Detection

- In the case of heterodyne detection the local-oscillator frequency ω_{LO} is chosen to differ from the signal-carrier frequency ω_0 such that the intermediate frequency ω_{IF} is in the microwave region (ν_{IF} ~1 GHz)
- the photocurrent is now given by

$$I(t) = R(P_s + P_{LO}) + 2R\sqrt{P_s P_{LO}}\cos(\omega_{IF}t + \phi_s - \phi_{LO}).$$

- Since $P_{LO} >> P_s$ in practice, the direct-current (dc) term is nearly constant and can be removed easily using band pass filter

Continued

- The heterodyne signal is then given by the alternating-current (ac)

$$I_{ac}(t) = 2R\sqrt{P_s P_{LO}}\cos(\omega_{IF}t + \phi_s - \phi_{LO})$$

- Similar to the case of homodyne detection, information can be transmitted through amplitude, phase, or frequency modulation of the optical carrier

Continued

- More importantly, the local oscillator still amplifies the received signal by a large factor, there by improving the SNR
- However, the SNR improvement is lower by a factor of 2 (or by 3 dB) compared with the homodyne case
- This reduction is referred to as the heterodyne detection penalty
- The origin of the 3-dB penalty can be seen by considering the signal power (proportional to the square of the current)
- Because of the ac nature of Iac, the average signal power is reduced by a factor of 2

Continued

- The advantage gained at the expense of the 3-dB penalty is that the receiver design is considerably simplified because an optical phase-locked loop is no longer needed
- Fluctuations in both φ_s and φ_{LO} still need to be controlled using narrow-linewidth semiconductor lasers for both optical sources
- The heterodyne-detection scheme quite suitable for practical implementation in coherent lightwave systems

Sensitivity Degradation

- Many physical mechanisms degrade the receiver sensitivity in practical coherent systems:
  - phase noise
  - intensity noise
  - polarization mismatch
  - fiber dispersion

Phase Noise

- An important source of sensitivity degradation in coherent lightwave systems is the phase noise associated with the transmitter laser and the local oscillator
- The reason is from the current generated at the photodetector for homodyne and heterodyne receivers
- In both cases, phase fluctuations lead to current fluctuations and degrade the SNR
- Both the signal phase φ_s and the local-oscillator phase φ_{LO} should remain relatively stable to avoid the sensitivity degradation
- A measure of the duration over which the laser phase remains relatively stable is provided by the coherence time

Continued

- As the coherence time is inversely related to the laser linewidth $\Delta\nu$, it is common to use the linewidth to bit rate ratio ,$\Delta\nu/B$, to characterize the effects of phase noise on the performance of coherent lightwave systems
- Since both φ_s and φ_{LO} fluctuate independently, $\Delta\nu$ is actually the sum of the linewidth $\Delta\nu_T$ and $\Delta\nu_{LO}$ associated with the transmitter and the local oscillator, respectively
- The quantity $\Delta\nu=\Delta\nu_T+\Delta\nu_{LO}$ is often called the IF linewidth

Continued

- Considerable attention has been paid to calculate the BER in the presence of phase noise and to estimate the dependence of the power penalty on the ratio $\Delta\nu/B$
- The tolerable value of $\Delta\nu/B$ for which the power penalty remains below 1 dB depends on the modulation format as well as on the demodulation technique
- In general, the linewidth requirements are most stringent for homodyne receivers
- Although the tolerable linewidth depends to some extent on the design of phase-locked loop, typically $\Delta\nu/B$ should be $< 5\times10^{-4}$ to realize a power penalty of less than 1 dB

Continued

- The linewidth requirements are relaxed considerably for heterodyne receivers, especially in the case of asynchronous demodulation with the ASK or FSK modulation format
- For synchronous heterodyne receivers $\Delta\nu/B<5\times10-3$ is required
- In contrast, $\Delta\nu/B$ can exceed 0.1 for asynchronous ASK and FSK receivers
- The reason is related to the fact that such receivers use an envelope detector that throws away the phase information

Continued

- The effect of phase fluctuations is mainly to broaden the signal bandwidth
- The signal can be recovered by increasing the bandwidth of the bandpass filter (BPF)
- In principle, any linewidth can be tolerated if the BPF bandwidth is suitably increased
- An alternative approach solves the phase-noise problem by designing special receivers known as phase-diversity receivers
- Such receivers use two or more photodetectors whose outputs are combined to produce a signal that is independent of the phase difference $\varphi_{IF} = \varphi_s - \varphi_{LO}$

Chapter Four

Light Signal Amplifier Circuits

Signal Reshaping and Amplification

- In long distance communications, whether going through wire, fiber or wave, the signal carrying the information experience:
  - Power loss
  - Pulse broadening which requires amplification and signal reshaping.
- In fibre optics communications, these can be done in two ways:
- Opto-electronic conversion
  - Optical signal is:
    - Received and transformed to an electronic signal
    - Amplified in electronic domain
    - Converted back into optical signal at same wavelength

Continued

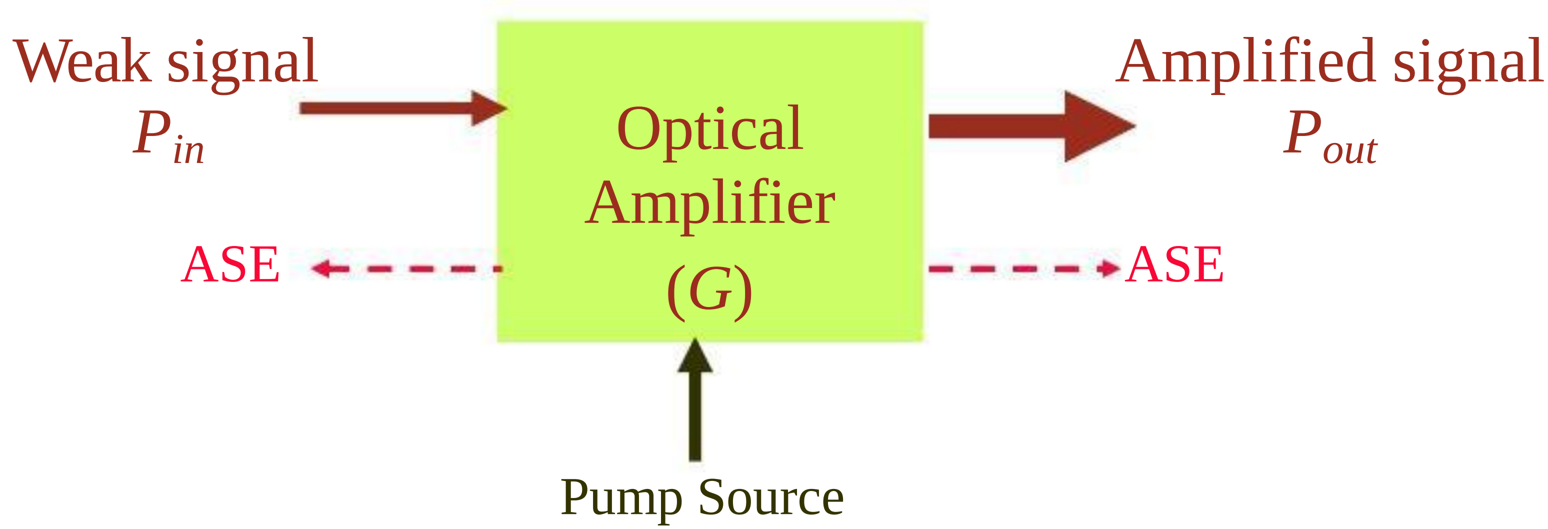
- All optical Amplifier
  - A communication that works completely in the optical domain
  - It amplifies the signal without conversion to electrical form
  - It uses optical switches connected by optical fibers
- Depending on its nature, a signal can also be regenerated
- A digital signal is made of 1's and 0's: it is possible to reconstruct the signal and amplify it at the same time
- An analog signal however, cannot be reconstructed because nobody knows what the original signal looked like

Why the Need for Optical Amplification

- Semiconductor devices can convert an optical signal into an electrical signal, amplify it and reconvert the signal back to an optical signal
- However, this procedure has several disadvantages:
  - Costly
  - Require a large number over long distances
  - Noise is introduced after each conversion in analog signals (which cannot be reconstructed)
  - Restriction on bandwidth, wavelengths and type of optical signals being used, due to the electronics
- By amplifying signal in the optical domain many of these disadvantages would disappear!

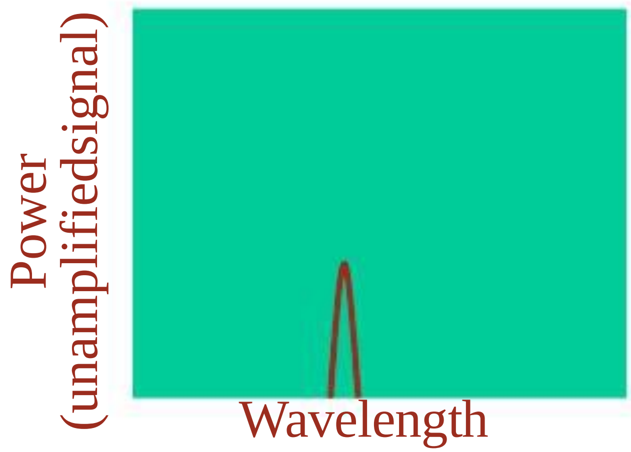
Optical Amplification

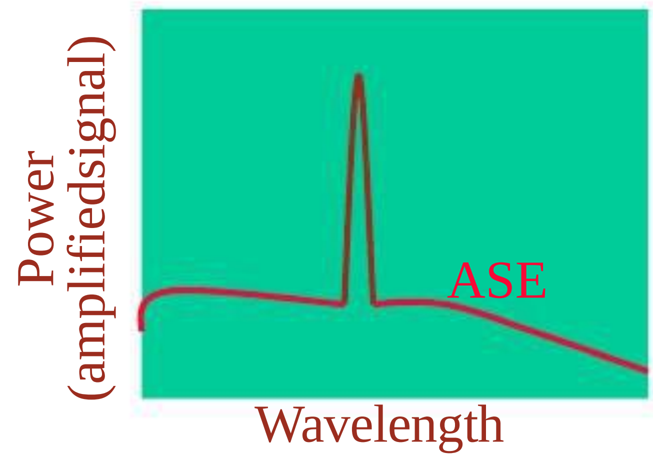
- Amplification gain: Up to a factor of 10,000 (+40 dB)
- In WDM: Several signals within the amplifier's gain (G) bandwidth are amplified, but not to the same extent
- It generates its own noise source known as Amplified Spontaneous Emission (ASE) noise



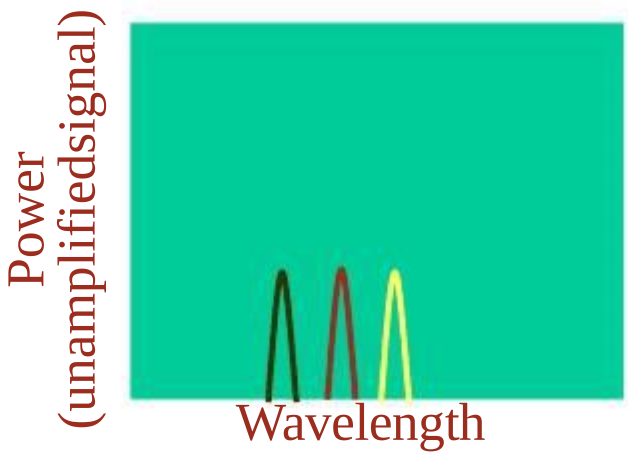
Optical Amplification - Spectral Characteristics

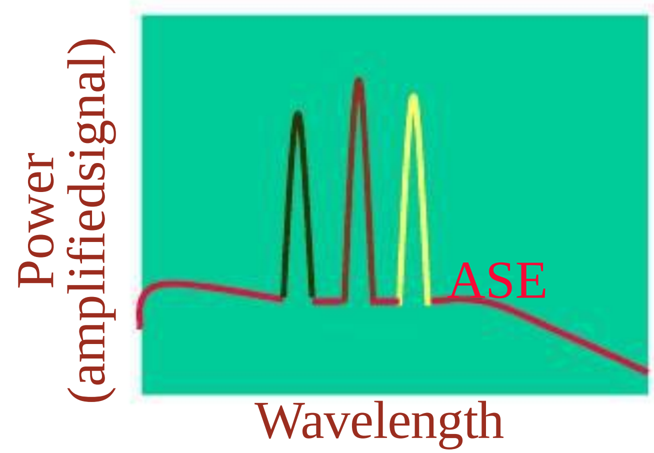
Single channel





WDM channels





Continued

- An optical amplifier is characterized by:
  - Gain– ratio of output power to input power (in dB)
  - Gain efficiency– gain as a function of input power(dB/mW)
  - Gain bandwidth– range of wavelengths over which the amplifier is effective
  - Gain saturation– maximum output power, beyond which no amplification is reached
  - Noise– undesired signal due to physical processing in amplifier

Optical Amplification - Noise Figure

- Required figure of merit to compare amplifier noise performance
- Defined when the input signal is coherent

$$\textbf{Noise Figure (NF)} = \frac{\textbf{Input signal-to-noise ratio}\ (SNR_i)}{\textbf{Output signal-to-noise ratio}\ (SNR_o)}$$

- NF is a positive number, nearly always > 2 (I.e. 3 dB)
- Good performance: when NF ~ 3 dB
- NF is one of a number of factors that determine the overall BER of a network.

Types of Optical Amplifiers

There are mainly two types:

- Semiconductor Laser (optical) Amplifier (SLA)/ (SOA)
- Fiber amplifiers
  - Erbium Doped Fibre Amplifier (EDFA)
  - Fiber Raman Amplifier (FRA)

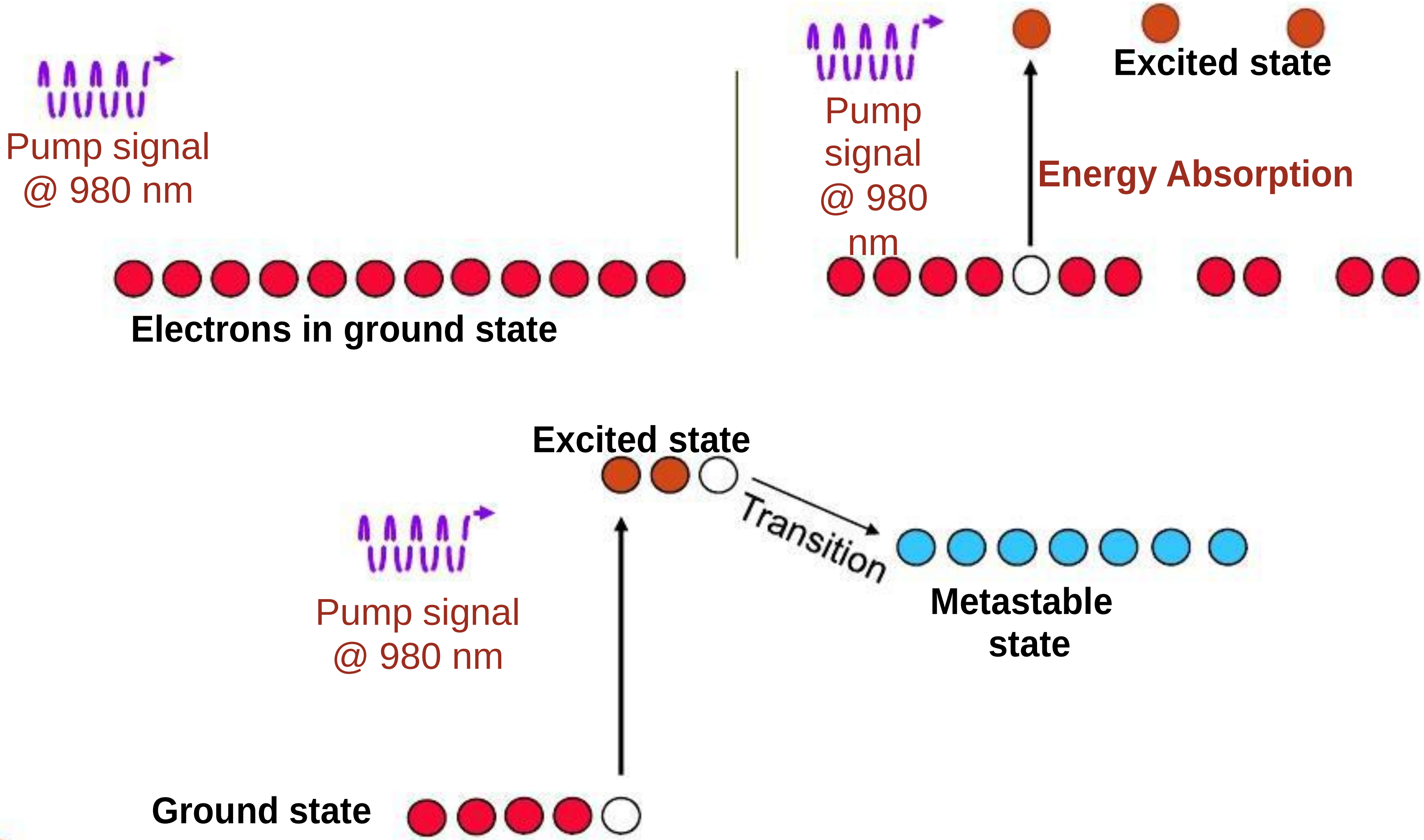
Semi Conductor Optical Amplifier (SOA)

- Semiconductor optical amplifiers (SOAs) are essentially laser diodes, with or without end mirrors, which have fiber attached to both ends
- They amplify any optical signal that comes from either fiber and transmit an amplified version of the signal out of the second fiber

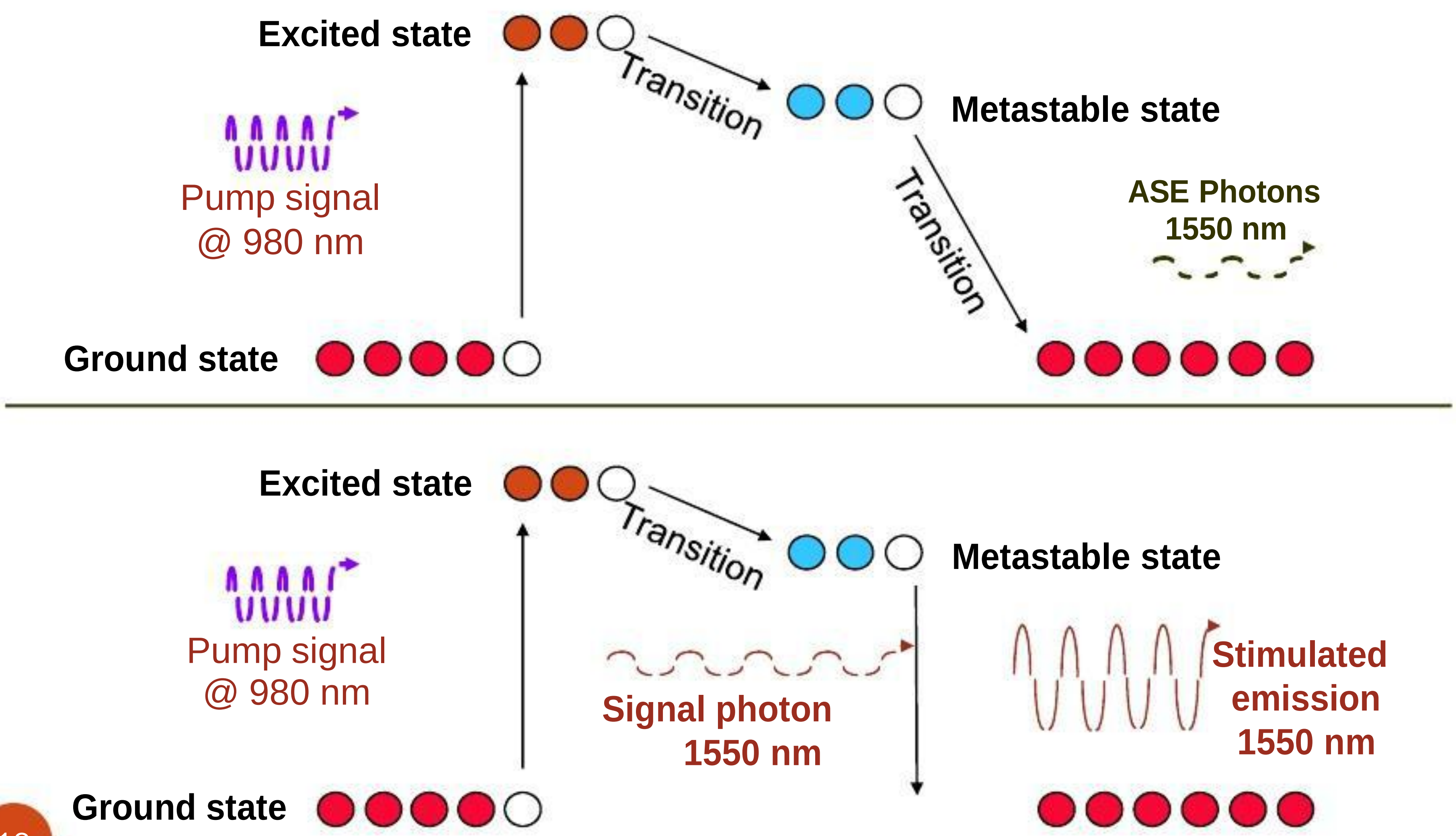
Problems:

- Poor noise performance: they add a lot of noise to the signal!
- Matching with the fibre is also a problem!
- However, they are small and cheap!

SLA - Principle Operation



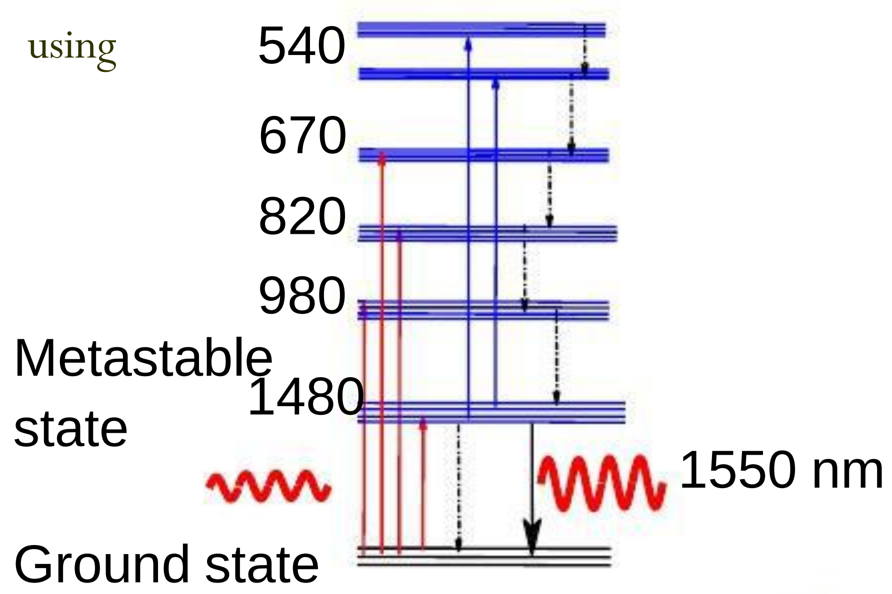
SLA - Principle Operation



Erbium Doped Fibre Amplifier (EDFA)

- EDFA is an optical fibre doped with erbium.
  - Erbium is a rare-earth element which has some interesting properties for fibre optics communications.
  - Photons at 1480 or 980 nm activate electrons into a metastable state
  - Electrons falling back emit light at 1550 nm.
  - By one of the most extraordinary coincidences, 1550 nm is a low-loss wavelength region for silica optical fibers.
  - This means that we could amplify a signal by using stimulated emission.

- EDFA is a low noise light amplifier



Continued

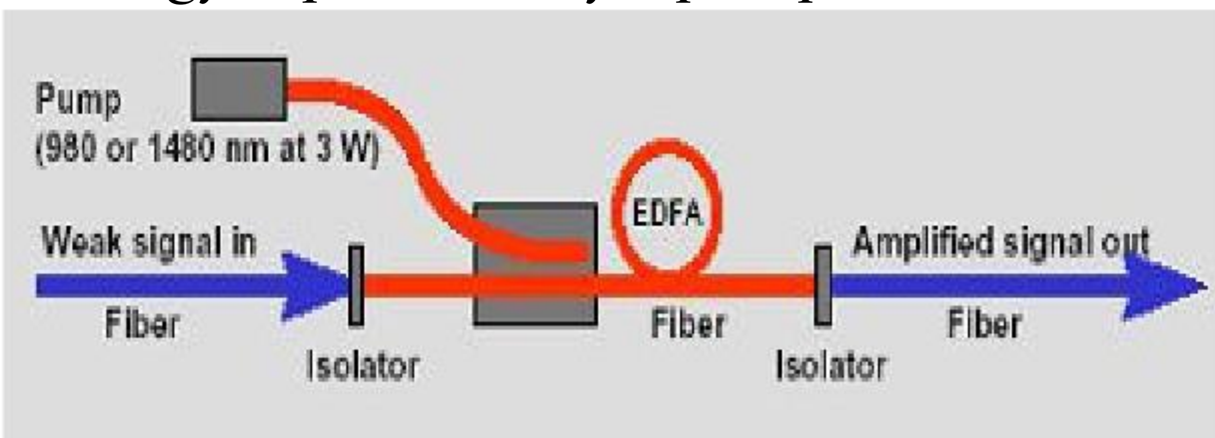
- An erbium-doped fiber amplifier consists of:
  - A length of silica fiber, whose core is doped with rare earth element erbium
  - A pump laser of 980 nm or 1480 nm
  - Wavelength multiplexers or couplers/isolators

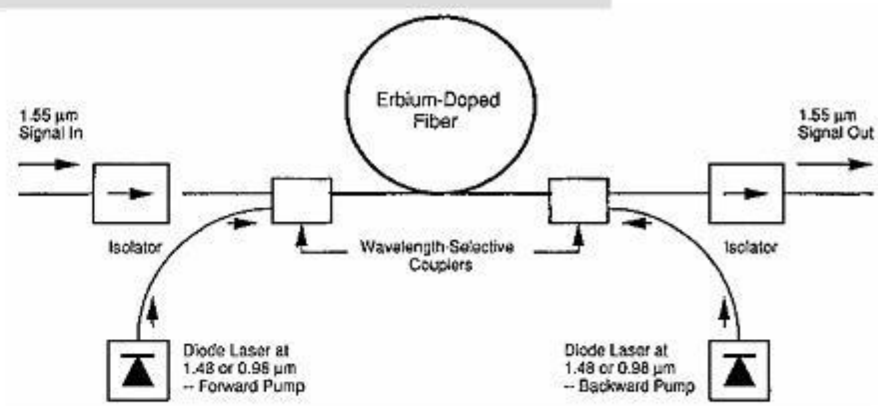
Combination of several factors has made EDFA an attractive choice:

- Availability of compact and reliable high-power semiconductor pump lasers
- It is an all fiber device, easy to couple light in and out of fiber
- Simplicity of device
- It introduces no crosstalk when amplifying WDM signals

Continued

- EDFA is a fiber segment, a few meters long, heavily doped with erbium
- Energy is provided by a pump laser beam





SOA vs EDFA

- They are not a good as EDFAs for use as amplifiers
- SOAs introduce severe crosstalk when they are used in WDM systems
- Gains and output powers achievable with EDFAs are higher
- Coupling losses and the polarization-dependent losses are also lower with EDFAs since the amplifier is also a fiber
- Due to the higher input coupling loss, SOAs have higher noise figures relative to EDFAs
- The SOA requires very high-quality antireflective coatings on its facets (reflectivity of less than 10-4)which is not easy to achieve

RAMAn AMPLIFIER

- A fiber-based Raman amplifier uses stimulated Raman scattering(SRS) occurring in silica fibers when an intense pump beam propagates through it
- SRS differs from stimulated emission in one fundamental aspect
  - Where as in the case of stimulated emission an incident photon stimulates emission of another identical photon without losing its energy,
  - in the case of SRS the incident pump photon gives up its energy to create another photon of reduced energy at a lower frequency (inelastic scattering); the remaining energy is absorbed by the medium in the form of molecular vibrations (optical phonons)

Properties of Rama Amplifiers

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

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Difficulties with Raman Amplifiers

- The Pump and amplified signals are at different wavelengths Therefore the signal and the pump pulses will separate due to dispersion (waveguide dispersion)after a certain propagation **distance**
- A second problem is that the pump power decreases along the fiber length due to linear absorption and scattering – Raman gain is greater at the input end
- A final problem results from amplifying spontaneous Raman photons
- This occurs when the pump power is increased to offset attenuation

Losses and spontaneous Raman photons are coupled in to the guided mode all along the length of the fiber.This increases noise

Continued

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

Exercises

1. What are the advantages of optical fiber amplifiers in fiber optics communication link?
2. Compare and contrast the different types of optical amplifiers

Chapter Five
Light Signal Degradation and Dispersion Compensation Techniques

- Light signal degradation
  - Signal attenuation
  - Signal dispersion
- Dispersion compensation technique

Light signal degradation

- Transmission over fiber is limited by the attenuation and dispersion
- The signal degradation is due to signal attenuation and signal dispersion

Signal Attenuation

- One of the important property of optical fiber is signal attenuation. It is also known as fiber loss or signal loss.
- The signal attenuation of fiber determines the maximum distance between transmitter and receiver.
- The attenuation also determines the number of repeaters required, maintaining repeater is a costly affair.
- Attenuation is a measure of decay of signal strength or loss of light power that occurs as light pulses propagate through the length of the fiber.

Causes of Attenuation

- The Basic attenuation mechanisms in a fiber:

1. Absorption:
   - It is related to the fiber material.
2. Scattering:
   - It is associated both with the fiber material
   - and with the structural imperfections in the optical waveguide.
3. Radiative losses/ Bending losses:
   - It originates from perturbation (both microscopic and macroscopic) of the fiber geometry.

Attenuation Units

- As attenuation leads to a loss of power along the fiber, the output power is significantly less than the couples power. Let the couples optical power is P(0) i.e. at origin (z = 0).
- Then the power at distance z is given by

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

where, α_P is fiber attenuation constant (per km).

$$\alpha_P = \frac{1}{z}\ln\left[\frac{p(0)}{p(z)}\right]$$

$$\boxed{\alpha_{dB/km} = 10.\frac{1}{z}\log\left[\frac{P(0)}{P(z)}\right]}$$

$$\alpha_{dB/km} = 4.343\alpha_P \quad \text{per km}$$

This parameter is known as fiber loss or fiber attenuation.

Continued

- **Example:** For a 30 km long fiber attenuation 0.8 dB/km at 1300nm. If a 200 µwatt power is launched into the fiber, find the output power.

Solution

$z = 30$ km , $\alpha_{dB/km} = 0.8$ dB/km, $P(0) = 200\ \mu W$

Attenuation in optical fiber is given by,

$$\alpha_{dB/km} = 10.\frac{1}{z}\log\left[\frac{P(0)}{P(z)}\right]$$

$$0.8 = 10 \times \frac{1}{30}\log\left[\frac{200\ \mu W}{P(z)}\right]$$

$$P(z) = 0.7962\ \mu W$$

Dispersion

- Dispersion is the spreading of a light pulse as it travels along an optical fiber.
- It occurs because the speed of light through a fiber depends on its wavelength and the propagation mode.
- Dispersion limits digital transmission speed by causing pulses to overlap, so they cannot be distinguished.
- The bit rate must be low enough to ensure that pulses do not overlap.
- A lower bit rate means that the pulses are farther apart and, therefore, that greater dispersion can be tolerated.

Continued

- Dispersion is caused by difference in the propagation times of light rays that takes different paths during the propagation.
- he light pulses travelling down the fiber encounter dispersion effect because of this the pulse spreads out in time domain.
- Dispersion limits the information bandwidth. The distortion effects can be analyzed by studying the group velocities in guided modes.

Continued

Dispersion is generally divided into three categories:

- ✓ Intermodal Delay or(Modal Dispersion)
- ✓Intra modal Dispersion or Chromatic Dispersion
  - Material Dispersion
  - Waveguide Dispersion
- ✓Polarization –Mode Dispersion

Modal Dispersion

- Modal dispersion is defined as pulse spreading caused by the time delay between lower-order modes and higher-order modes.
- Modal dispersion is problematic in multimode fiber, causing bandwidth limitation.
- This signal distortion mechanism is a result of each mode having a different value of the group velocity at a single frequency.

Group Velocity: It is the speed at which energy in a particular mode travels along the fiber.

- T

Continued

- Modal dispersion is given by,

$$\Delta t_{modal} = \frac{n_1 Z}{c}\left(\frac{\Delta}{1-\Delta}\right)$$

where Δtmodal = Dispersion, n1 = Core refractive index Z= Total fiber length, c = Velocity of light in air

Δ= Fractional refractive index

The modal dispersion Δtmodal describes the optical pulse spreading due to modal effects optical pulse width can be converted to electrical rise time through the relationship.

$$t_{r\,mod} = 0.44\,(\Delta t_{modal})\pi r^2$$

Material Dispersion

- Material dispersion exists due to change in index of refraction for different wavelengths.
- It is due to the wavelength dependency on the index of refraction of glass i.e. refractive index of the core varies as a function of wavelength.
- R.M.S pulse broadening due to material dispersion is given by,

$$\sigma m = \sigma \, LM$$

- The material dispersion for unit length (L = 1) is given by

$$D_{mat} = \frac{-\lambda}{c} \times \frac{d^2 n}{d\lambda^2}$$

c = Light velocity, λ = Center wavelength

$\frac{d^2 n}{d\lambda^2}$ = Second derivative of index of refraction w.r.t wavelength

Waveguide Dispersion

- Waveguide dispersion is caused by the difference in the index of refraction between the core and cladding, resulting in a ‘drag’ effect between the core and cladding portions of the power.
- Waveguide dispersion is significant only in fibers carrying fewer than 5-10 modes. Since multimode optical fibers carry hundreds of modes, they will not have observable waveguide dispersion.
- It is due to the physical structure of the waveguide.
- In a simple step-index profile fiber, waveguide dispersion is not a major factor, but in fibers with more complex index profiles, waveguide dispersion can be more significant.

Polarization mode dispersion

- It is due to slightly different velocity for each polarization mode because of the lack of perfectly symmetric & an isotropicity of the fiber.
- Different frequency component of a pulse acquires different polarization state (such as linear polarization and circular polarization). This results in pulse broadening is kno**w as polarization mode dispersion (PMD).**
- PMD is the limiting factor for optical communication system at high data rates. The effects of PMD must be compensated.

Dispersion Compensation Techniques

- In order to remove the spreading of the optical or light pulses, the dispersion compensation is the most important feature required in optical fiber communication system.
- The most commonly employed techniques for dispersion compensation are as follows:
  - ✓ Dispersion Compensating Fibers (DCF)
  - ✓ Electronic dispersion compensation (EDC)
  - ✓ Fiber Bragg Grating (FBG)
  - ✓ Digital filters

Dispersion Compensating Fibers (DCF)

- DCF is a loop of fiber having negative dispersion equal to the dispersion of the transmitting fiber.
- It can be inserted at either beginning (pre-compensation techniques) or end (post-compensation techniques) between two optical amplifiers.
- But it gives large footprint and insertion losses

Electronic dispersion compensation (EDC)

- Electronic equalization techniques are used in this method. Since there is direct detection at the receiver, linear distortions in the optical domain, e.g. chromatic dispersion, are translated into non linear distortions after optical-to-electrical conversion.
- It is due to this reason that the concept of nonlinear cancellation and nonlinear channel modeling is implemented.
- For this mainly feed forward equalizer (FFE) and decision feedback equalizers (DFE) structures are used.
- EDC slows down the speed of communication since it slows down the digital to analog conversion

Fiber Bragg Grating (FBC)

- Optical Fiber Bragg Grating (FBG) has recently found a practical application in compensation of dispersion-broadening in long-haul communication.
- In this, Chirped Fiber Grating (CFG) is preferred.
- CFG is a small all-fiber passive device with low insertion loss that is compatible with the transmission system and CFG's dispersion can be easily adjusted.
- CFG should be located in-line for optimum results.
- This is a preferred technique because of its advantages including small footprint, low insertion loss, dispersion slope compensation and negligible non-linear effects. But the architectures using FBG is complex

Digital Filters

- Digital filters using Digital Signal Processing (DSP) can be used for compensating the chromatic dispersion.
- They provide fixed as well as tunable dispersion compensation for wavelength division multiplexed system.
- Popularly used filter is lossless all-pass optical filters for fiber dispersion compensation, which can approximate any desired phase response while maintaining a constant, unity amplitude response
- Other filters used for dispersion compensation are bandpass filter, Gaussian filters, Super-Gaussian filters, butterworth filters and microwave photonic filter

Assignment

1. The input power to an optical fiber is 3 mW while the power measured at the output end is 4 μW. If the fiber attenuation is 0.5 dB/km, calculate the length of the fiber.
2. An LED operating at 850 nm has a spectral width of 45 nm. What is the pulse spreading in ns/km due to material dispersion?
3. What are the loss or signal attenuation mechanism in a fiber and discuss the cause of each loss with its types?
4. Describe the fiber soliton and soliton communication systems?

Assignment

4. What are the different factors or the considerations for the evaluation of fiber optic link design?

5. A fiber optic link of overall length 10km with a rate of 20 mbps requires the LED average power of 0.1 mw at 85μm with fiber attenuation of 2.5 dB/km and it needs splicing at every 2 km with a loss of 0.3 dB per splice connector loss is 1.5dB by considering the the receiver power of -46 dBm and the predicted safety margin is 6 dB

   Find the link power budget

6. Describe the fiber soliton and soliton communication systems?

THANK YOU