NEHRU COLLEGE OF ENGINEERING AND RESEARCH CENTRE
(NAAC Accredited)
(Approved by AICTE, Affiliated to APJ Abdul Kalam Technological University, Kerala)

DEPARTMENT OF ELECTRONICS & COMMUNICATION ENGINEERING

COURSE MATERIALS

EC 405:OPTICAL COMMUNICATION

VISION OF THE INSTITUTION

To mould true citizens who are millennium leaders and catalysts of change through excellence in education.

MISSION OF THE INSTITUTION

NCERC is committed to transform itself into a center of excellence in Learning and Research in Engineering and Frontier Technology and to impart quality education to mould technically competent citizens with moral integrity, social commitment and ethical values.

We intend to facilitate our students to assimilate the latest technological know-how and to imbibe discipline, culture and spiritually, and to mould them in to technological giants, dedicated research scientists and intellectual leaders of the country who can spread the beams of light and happiness among the poor and the underprivileged.

ABOUT DEPARTMENT

- Established in: 2002
- Course offered : B.Tech in Electronics and Communication Engineering

  M.Tech in VLSI
- Approved by AICTE New Delhi and Accredited by NAAC
- Affiliated to the University of Dr. A P J Abdul Kalam Technological University.

DEPARTMENT VISION

Providing Universal Communicative Electronics Engineers with corporate and social relevance towards sustainable developments through quality education.

DEPARTMENT MISSION

1) Imparting Quality education by providing excellent teaching, learning environment.

2) Transforming and adopting students in this knowledgeable era, where the electronic gadgets (things) are getting obsolete in short span.

3) To initiate multi-disciplinary activities to students at earliest and apply in their respective fields of interest later.

4) Promoting leading edge Research & Development through collaboration with academia & industry.

PROGRAMME EDUCATIONAL OBJECTIVES

PEOI. To prepare students to excel in postgraduate programmes or to succeed in industry / technical profession through global, rigorous education and prepare the students to practice and innovate recent fields in the specified program/ industry environment.

PEO2. To provide students with a solid foundation in mathematical, Scientific and engineering fundamentals required to solve engineering problems and to have strong practical knowledge required to design and test the system.

PEO3. To train students with good scientific and engineering breadth so as to comprehend, analyze, design, and create novel products and solutions for the real life problems.

PEO4. To provide student with an academic environment aware of excellence, effective communication skills, leadership, multidisciplinary approach, written ethical codes and the life-long learning needed for a successful professional career.

PROGRAM OUTCOMES (POS)

Engineering Graduates will be able to:

1. **Engineering knowledge**: Apply the knowledge of mathematics, science, engineering fundamentals, and an engineering specialization to the solution of complex engineering problems.
2. **Problem analysis**: Identify, formulate, review research literature, and analyze complex engineering problems reaching substantiated conclusions using first principles of mathematics, natural sciences, and engineering sciences.
3. **Design/development of solutions**: Design solutions for complex engineering problems and design system components or processes that meet the specified needs with appropriate consideration for the public health and safety, and the cultural, societal, and environmental considerations.
4. **Conduct investigations of complex problems**: Use research-based knowledge and research methods including design of experiments, analysis and interpretation of data, and synthesis of the information to provide valid conclusions.
5. **Modern tool usage**: Create, select, and apply appropriate techniques, resources, and modern engineering and IT tools including prediction and modeling to complex engineering activities with an understanding of the limitations.
6. **The engineer and society**: Apply reasoning informed by the contextual knowledge to assess societal, health, safety, legal and cultural issues and the consequent responsibilities relevant to the professional engineering practice.
7. **Environment and sustainability**: Understand the impact of the professional engineering solutions in societal and environmental contexts, and demonstrate the knowledge of, and need for sustainable development.
8. **Ethics**: Apply ethical principles and commit to professional ethics and responsibilities and norms of the engineering practice.
9. **Individual and team work**: Function effectively as an individual, and as a member or leader in diverse teams, and in multidisciplinary settings.
10. **Communication**: Communicate effectively on complex engineering activities with the engineering community and with society at large, such as, being able to comprehend and write effective reports and design documentation, make effective presentations, and give and receive clear instructions.
11. **Project management and finance**: Demonstrate knowledge and understanding of the engineering and management principles and apply these to one’s own work, as a member and leader in a team, to manage projects and in multidisciplinary environments.
12. **Life-long learning**: Recognize the need for, and have the preparation and ability to engage in independent and life-long learning in the broadest context of technological change.

PROGRAM SPECIFIC OUTCOMES (PSO)

PSO1: Ability to Formulate and Simulate Innovative Ideas to provide software solutions for Real-time Problems and to investigate for its future scope.

PSO2: Ability to learn and apply various methodologies for facilitating development of high quality System Software Tools and Efficient Web Design Models with a focus on performance optimization.

PSO3: Ability to inculcate the Knowledge for developing Codes and integrating hardware/software products in the domains of Big Data Analytics, Web Applications and Mobile Apps to create innovative career path and for the socially relevant issues.

COURSE OUTCOMES

EC 405

SUBJECT CODE: EC 308	
COURSE OUTCOMES	
C405.1	Know about light transmission through optical fibers and concept of attenuation and dispersion
C405.2	Understand the construction and working of Optical sources- LEDs and LASERs
C405.3	Understand the characteristics of Optical detectors
C405.4	Design and analysis of Optical networks and Optical fiber link design
C405.5	Apply the knowledge of optical amplifiers in the design of optical link & Analyse the performance of optical amplifiers.
C405.6	Describe the principle of FSO,VLC and LiFi & Know the concept of WDM & optical network components

MAPPING OF COURSE OUTCOMES WITH PROGRAM OUTCOMES

CO'S	PO1	PO2	PO3	PO4	PO5	PO6	PO7	PO8	PO9	PO10	PO11	PO12
C405.1	2	1	3	2		3						
C405.2	1	2	2	1	2	2		2				
C405.3	3	2	2	1	2	1					2	1
C405.4	2	2	2	2								1
C405.5	3	3	3	2	2							1
C405.6	2	2	3	2			2					1
C405	3	2	2	2	2	1	2	2			2	1

CO'S	PSO1	PSO2	PSO3
C405.1	2	2	
C405.2	2		
C405.3	3		
C405.4	3		2
C405.5	3	3	2
C405.6	2	3	
C405	3	2	1

SYLLABUS

COURSE CODE	COURSE NAME	L-T-P-C	YEAR OF INTRODUCTION
EC405	OPTICAL COMMUNICATION	3-0-0-3	2016

Prerequisite: EC203 Solid State Devices, EC205 Electronic Circuits

Course objectives:

- To introduce the concepts of light transmission through optical fibers, optical sources and detectors.
- To compare the performance of various optical transmission schemes.
- To impart the working of optical components and the principle of operation of optica amplifiers.
- To give idea on WDM technique.

Syllabus: General light wave system, advantages, classification of light wave systems, fibre types linear and non linear effects in fibres, Fibre materials, fabrication of fibres, Optical sources, LEDs and LDs Optical detectors, Optical receivers, Digital transmission systems, Optical Amplifiers WDM concept, Introduction to free space optics, Optical Time Domain Reflectometer (OTDR).

Expected outcome:

The students will be able to:-

i. Know the working of optical source and detectors.
ii. Compare the performance of various optical modulation schemes.
iii. Apply the knowledge of optical amplifiers in the design of optical link.
iv. Analyse the performance of optical amplifiers.
v. Know the concept of WDM
vi. Describe the principle of FSO and LiFi.

Text Books:

1. Gerd Keiser, Optical Fiber Communications, 5/e, McGraw Hill, 2013.
2. Mishra and Ugale, Fibre optic Communication, Wiley, 2013.

References:

1. Chakrabarthi, Optical Fibre Communication, McGraw Hill, 2015.
2. Hebbar, Optical fibre communication, Elsevier, 2014
3. John M Senior- Optical communications, **3/e**, Pearson, 2009.
4. Joseph C. Palais, Fibre Optic Communications, 5/e Pearson, 2013.
5. Keiser, Optical Communication Essentials (SIE), 1/e McGraw Hill Education New Delhi, 2008.

Course Plan			
Module	**Course contents**	**Hours**	**End Sem. Exam Marks**
I	General light wave system, advantages, classification of light wave systems. Fibres: types and refractive index profiles, mode theory of fibres: modes in SI and GI fibres, linear and non linear effects in fibres, dispersion, Group Velocity Dispersion, modal, wave guide and Polarization, Modes, Dispersion, attenuation- absorption, bending and scattering losses.	8	**15%**
II	Fibre materials, fabrication of fibres, photonic crystal fibre, index guiding PCF, photonic bandgap fibre, fibre cables. Optical sources, LEDs and LDs, structures, characteristics, modulators using LEDs and LDs. coupling with fibres, noise in Laser diodes, Amplified Spontaneous Emission noise, effects of Laser diode noise in fibre communications	7	**15%**
FIRST INTERNAL EXAM			
III	Optical detectors, types and characteristics, structure and working of PIN and AP, noise in detectors, comparison of performance. Optical receivers, Ideal photo receiver and quantum limit of detection.	6	**15%**
IV	Digital transmission systems, design of IMDD links- power and rise time budgets, coherent Systems, sensitivity of a coherent receiver, comparison with IMDD systems. Introduction to soliton transmission, soliton links using optical amplifiers, GH effect, soliton-soliton interaction, amplifier gain fluctuations, and design guide lines of soliton based links.	8	**15%**
SECOND INTERNAL EXAM			
V	Optical Amplifiers ,basic concept, applications, types, doped fibre amplifiers, EDFA, basic theory, structure and working, Semiconductor laser amplifier, Raman amplifiers, TDFA, amplifier configurations, performance comparison.	6	**20%**
VI	The WDM concept, WDM standards, WDM components, couplers, splitters, Add/ Drop multiplexers, gratings, tunable filters, system performance parameters. Introduction to optical networks. Introduction to free space optics, LiFi technology and VLC. Optical Time Domain Reflectometer (OTDR) – fault detection, length and refractive index measurements.	7	**20%**
END SEMESTER EXAM			

Question Paper Pattern

The question paper shall consist of three parts. Part A covers modules I and II, Part B covers modules III and IV, and Part C covers modules V and VI. Each part has three questions uniformly covering the two modules and each question can have maximum four subdivisions. In each part, any two questions are to be answered. Mark patterns are as per the syllabus with 50% for theory and 50% for logical/numerical problems, derivation and proof.

QUESTION BANK

MODULE I				
Q:NO:	**QUESTIONS**	**CO**	**KL**	**PAGE NO:**
1	.Define Reflection, Refraction and Total internal reflection.	CO1	K2	4
2	.A silica optical fiber with 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 surface,(b) The NA for the fiber (c) The acceptance angle air for the fiber.	CO1	K5	8
3	Draw the basic diagram of general light wave system and explain it.	CO1	K3	12
4	. A typical refractive index difference for an optical fiber designed for an optical fiber designed for long distance transmission is 1%. Estimate the NA and 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 with in the fiber.	CO1	K5	16
5	List out the advantages of optical light wave system and explain it.	CO1	K2	23
6	Differentiate between graded index and step index fibers.	CO1	K3	30
7	Describe about signal degradation in optical fibers.	CO1	K2	31
8	Define snells law and also explain NA and acceptance angle	CO1	K2	33
9	Derive V number of the optical fiber.	CO1	K2	35
10	Discuss transmission media alternative to the optical communication.	CO1	K2	37
11	Write short notes on intra modal and intermodal dispersion	CO1	K2	40
MODULE II				
1	. Compare LED & LASER Diode considering different	CO2	K3	49

	parameters			
2	List out the requirements to be satisfied by a fiber material to use that material for optical fiber explain with example.	CO2	K2	51
3	Discuss the modulation characteristics of LASER diode	CO2	K2	52
4	Describe about Super luminescent LED and explain its working.	CO2	K2	53
5	Discuss the structure and explain the operation of LASER	CO2	K2	54
6	Explain about photonic crystal fibers and also explain index guiding PCF & photonic bandgap fiber.	CO2	K2	62
7	Briefly describe effects of LASER diode noise in fiber communications.	CO2	K2	65
8	Illustrate about fabrication of fibers	CO2	K2	66
9	Explain the classification of lasers.	CO2	K2	68
10	Discuss different types of LED structures with neat diagram.	CO2	K2	70
11	Explain different types of fiber materials.	CO2	K2	72
MODULE III				
1	Explain the structure of avalanche photo diode.	CO3	K1	85
2	Explain the structure of PIN photo diode	CO3	K3	87
3	List out the performance parameters of optical detectors.	CO3	K2	89
4	Explain types of noises in detectors.	CO3	K3	90
5	Explain about optical receivers and also explain quantum limit of detection.	CO3	K2	91
6	Explain PIN photo diode & avalanche photo diode.	CO3	K2	94
7	Compare PN,PIN & Avalanche photo diode	CO3	K2	95
8	What is ideal photo receiver ?Draw the equivalent circuit of optical fiber receiver and explain it	CO3	K3	96
9	What is receiver sensitivity?	CO3	K2	97
10	What are the characteristics of optical detectors?	CO3	K3	98

MODULE IV				
1	Explain about coherent system.	CO4	K3	99
2	What do you mean by intensity modulation?explain	CO4	K2	102
3	Compare coherent & IMDD system.	CO4	K2	103
4	Explain about soliton transmission .	CO4	K2	105
5	Describe briefly about coherent system and intensity modulation system.	CO4	K2	107
6	Explain about soliton-soliton interaction and GH effect	CO4	K2	110
7	.Explain in detail about design of IMDD links ,Power & rise time budget calculation	CO4	K3	111
8	List out the limitations of soliton.	CO4	K3	113
9	What are the design criterias used for link design.	CO4	K2	114
10	Write a short notes on soliton-soliton interaction	CO4	K2	116
11	Describe about GH effect.	CO4	K1	121
12	Describe about soliton transmission.	CO4	K2	122
MODULE V				
1	Explain the basic concept of optical amplifiers	CO5	K3	126
2	Draw the neat diagram of EDFA and explain its working	CO5	K2	135
3	Describe about Raman amplifier.	CO5	K3	138
4	Briefly explain the principle of Raman amplifier with proper diagram	CO5	K3	141
5	Explain about TDFA	CO5	K2	143
6	Explain in detail about semiconductor laser amplifiers.	CO5	K3	146
7	Explain TDFA & EDFA	CO5	K3	147
8	Explain in detail amplifier configuration used in EDFA	CO5	K2	149
9	Explain in detail about semiconductor laser amplifiers.	CO5	K2	151

MODULE VI				
1	Describe about WDM	CO6	K3	153
2	Explain about WDM standards	CO6	K2	154
3	Draw the neat diagram of optical coupler and OADM and explain it working	CO6	K2	156
4	Explain about FSO and what are its limitations.	CO6	K2	157
5	Explain in detail about visible light communication and also explain applications of VLC	CO6	K3	158
6	Explain in detail about wavelength division multiplexing.	CO6	K2	162
7	Draw the block diagram & explain optical time domain reflectometer . How it can be used for measurement of refractive index profile.	CO6	K2	170
9	Write notes on SONET & SDH	CO6	K3	171

APPENDIX 1

CONTENT BEYOND THE SYLLABUS

S:NO;	TOPIC	PAGE NO:
1	OPTO ELECTRONIC DEVICES	180

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MODULE I
INTRODUCTION TO LIGHT WAVE SYSTEMS

Light wave systems represent a natural extension of microwave communication systems in as much as information is transmitted over an electromagnetic carrier in both types of systems. The major difference from a conceptual standpoint is that, whereas carrier frequency is typically ~1 GHz for microwave systems, it increases by five orders of magnitude and is typically ~100 THz in the case of light-wave systems. This increase in carrier frequency translates into a corresponding increase in the system capacity. Indeed, whereas microwave systems rarely operate above 0.2 Gb/s, commercial lightwave systems can operate at bit rates exceeding 1 Tb/s. Although the optical carrier is transmitted in free space for some applications related to satellites and space research, terrestrial lightwave systems often employ optical fibers for information transmission. Such fiber-optic communication systems have been deployed worldwide since 1980 and constitute the backbone behind the Internet. One can even claim that the lightwave technology together with advances in microelectronics was responsible for the advent of the "information age" by the end of the twentieth century.

Before optical communication the most of the communication was in radio and microwave domain which has frequency range orders of magnitude lower than the optical see Fig for the electromagnetic spectrum.

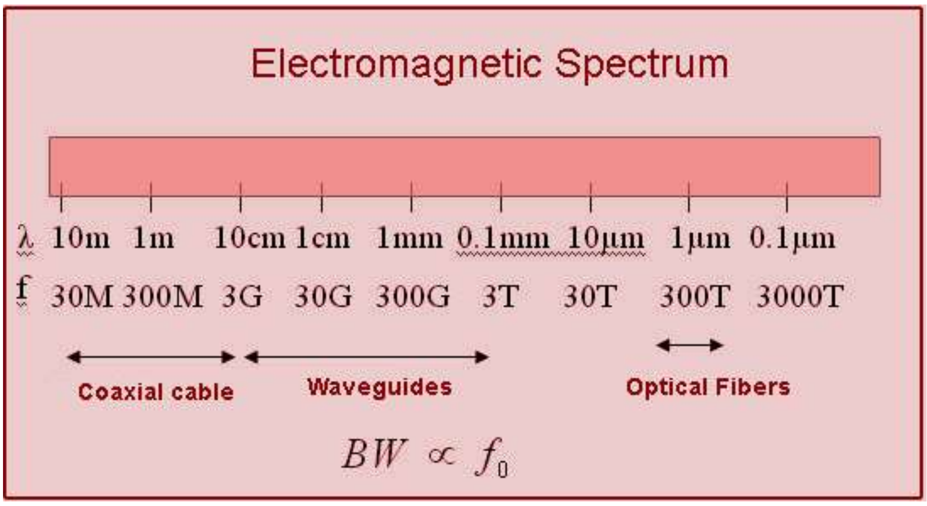


Fig 1.1 EM spectrum

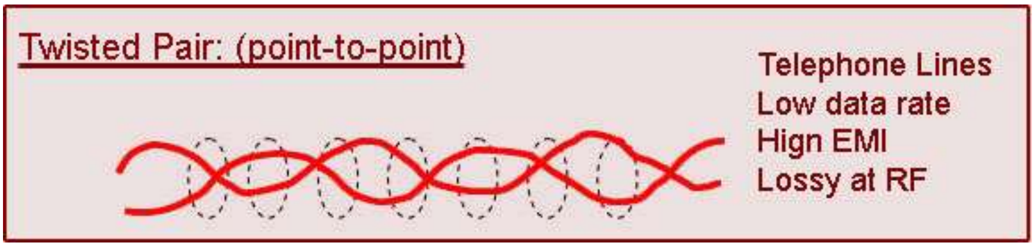
For good communication a system needs to have following things.

(1) **Bandwidh (BW)**
(2) **Good signal to noise ratio (SNR) i.e. low loss**

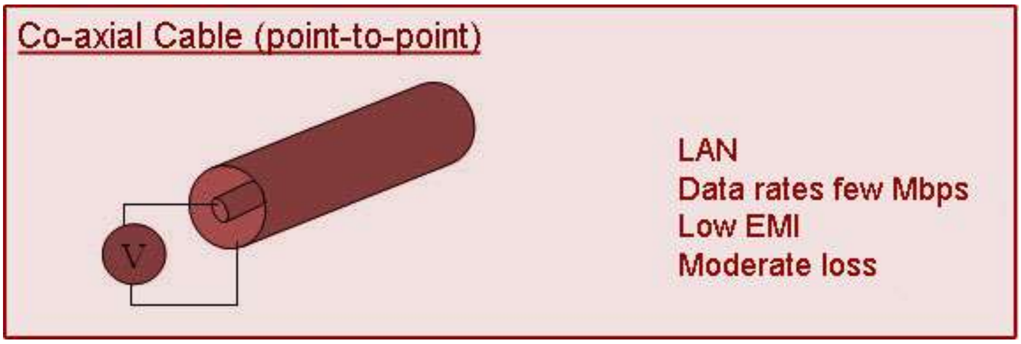
- Since the bandwidth of a system is more or less proportional to the frequency of operation, use of higher frequency facilitates larger BW.
- The BW at optical frequencies is expected to be 3 to 4 orders of magnitude higher than that at the microwave frequencies (1GHz to 100GHz).

TRANSMISSION MEDIA ALTERNATIVE TO THE OPTICAL COMMUNICATION

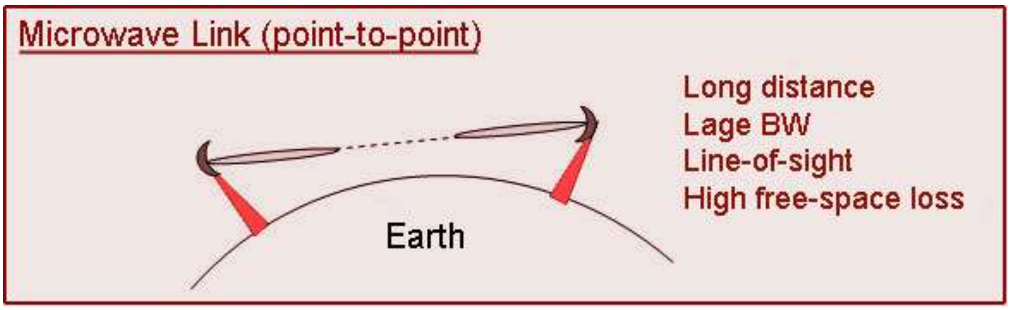
There are various wired and wireless media used for long and short distance communication. Their broad characteristics are summarized in the following.



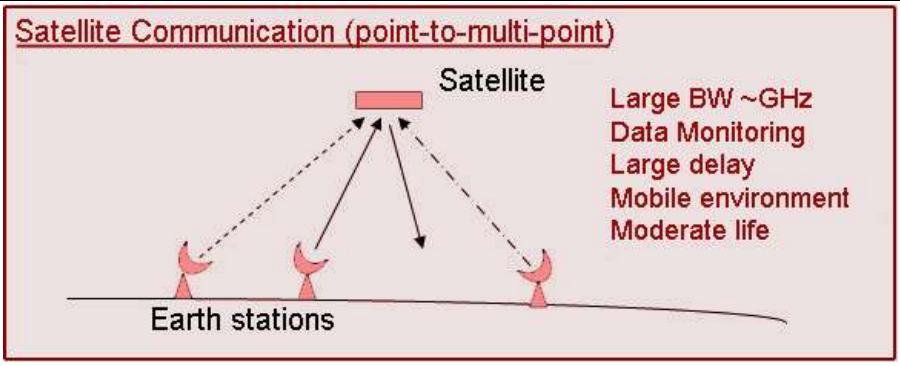
(a)



(b)



(c)



(d)

Fig 1.2 Transmission Media Alternative To The Optical Communication

The first two media have a very limited bandwidth.
Microwave links and Satellite communication has comparable bandwidths as in principle their mode of operation is same but the spatial reach of satellite is far greater. Before Fiber optic communication became viable, satellite communication was the only choice for long distance communication.

Comparison of Satellite and Optical communication

Satellite vs Fiber Optics

Satellite	Fiber Optics
Point to Multi-point	Point to point
BW ~ GHz	BW ~ THz
Maintenance free	Needs Maintenance
Short life ~7-8 Yr	Long life
No upgradeability	Upgradeable
Mobile, air, sea	On ground only

The two modes of transmission have their own merits and limitations. The two can infact play a complementary role. We therefore conclude that Satellite and Optical communication will co-exist due their complementary nature.

LIGHT PROPAGATION

The transmission of light along an optical fiber follows two theories: ray theory and mode theory.

RAY THEORY

This theory describes light as a simple ray. Ray theory is used to approximate the light acceptance and guiding properties of the optical fiber. The rays can be propagated by three paths along an optical fiber; these are the meridional, skew, and axial rays.

Different Rays

The rays approaching from within the cone of acceptance are successfully propagated along the Fiber. The exact path taken by the ray depends on the position and the angle at which the ray strikes the core. There are three possible paths: skew, meridional, and axial rays as shown in Fig.

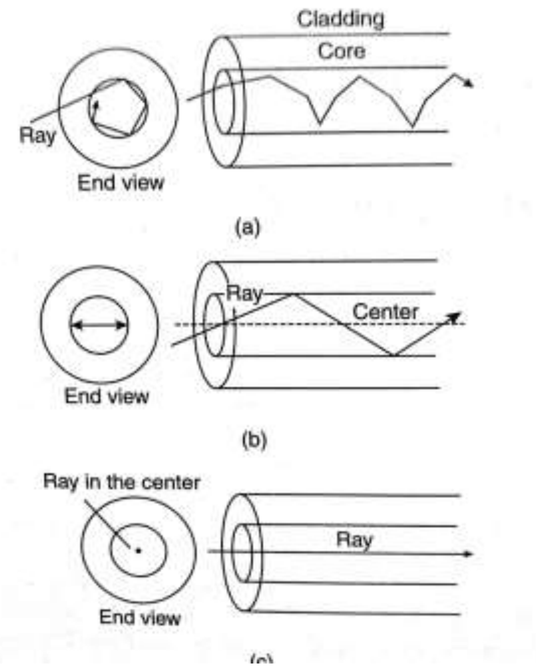


Fig 1.3 : (a) Skew Ray (b) Meridional Ray (C) Axial Ray

The skew my never passes through the center of the core. It reflects off the core-cladding interface and bounces around the outside of the core. It moves forward in a path similar to a spiral staircase as shown in Fig. 1.3(a).

The meridional ray passes through center of the core and is then reflected from the parallel surfaces of core and passes through the center. In the end view it appears as a horizontal line as shown in Fig.1.3(b). It should be noted that the axial ray travels straight through the center of the core as shown in Fig.1.3(c).

We can explain the basic transmission properties of optical fiber using these rays. Meridional rays are of two types: bound and unbound rays. Bound rays propagate through the fiber by TIR. They remain in the core and propagate along the axis of the fiber. Unbound rays are refracted out of the fiber core into the cladding as shown in Fig.

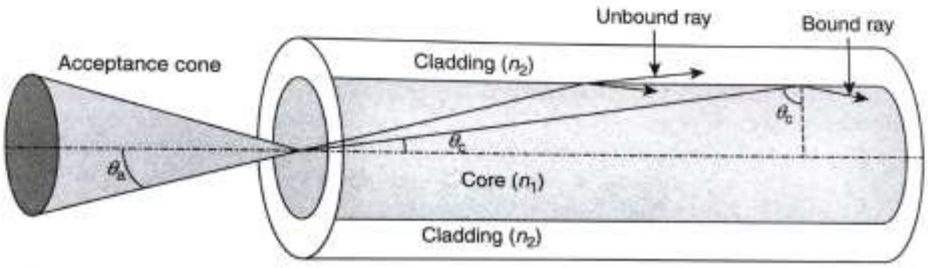


Fig 1.4 : Acceptance cone

LIGHT PROPAGATION BY TIR

In a perfect core-cladding interface, the bound rays remain in the core. A part of bound rays will be refracted out of the cladding due to imperfections at the core-cladding boundary. Light rays refracted into cladding will eventually escape from the fiber.

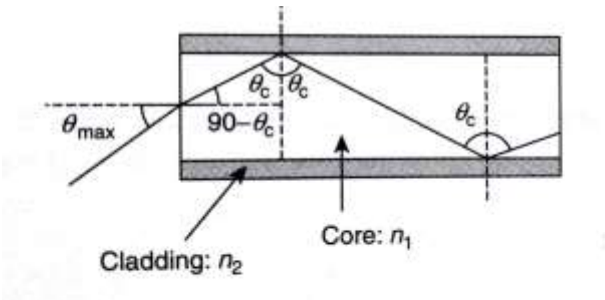


Fig 1.5 : Light Propagation By TIR

Metidional rays follow the laws of reflection and refraction. Bound rays propagate along the fiber due to TIR. Rays that enter the fiber must intersect the core-cladding interface at an angle greater than the critical angle θ_C. Only the rays that enter the fiber and strike the interface at angles greater than θ_C will be propagated along the fiber.

In order to be transmitted, the light ray incident on the fiber core must be within the acceptance cone defined by the acceptance angle. This is the angle over which light rays entering the fiber Will be guided along its core. The acceptance angle is normally measured in terms of NA. NA is a measurement of the ability of an optical fiber to capture light. It is a dimensionless quantity that specifies the angular range over Which an optical fiber can accept light. In an optical system, NA is given by

$$NA = n_0 \sin(\theta_A) \quad \text{...............} \mathbf{(1)}$$

where no is the index of refraction of the surrounding medium and θ_A is half angle of the maximum cone of the light that can enter the optical system.
When a light ray is incident from a medium of refractive index n_0 to the core of index n_1, Snell's law at a medium-core interface gives

$$n_0 sin\theta_i = n_1 sin\theta_r \quad ....(2)$$

Where θ_i is the angle of incidence at the core and θ_r is the angle of refraction at medium core interface. From Fig 1.5 using trigonometry, we get
$sin\theta_r = \sin(90 - \theta_c)=\cos\theta_c$
Where $\theta_c = sin^{-1}\left(\frac{n_2}{n_1}\right)$ is the critical angle of TIR
Substituting for θ_r in snell's law we get

$$\frac{n_0}{n_1}\sin\theta_i = \cos\theta_c \quad ....(3)$$

Squiring both sides we get

$$\frac{{n_0}^2}{{n_1}^2} sin^2\theta_i = cos^2\theta_c = 1 - sin^2\theta_c = 1 - \frac{{n_0}^2}{{n_1}^2} \quad ....(4)$$

Thus

$$n_0\sin\theta_i = \sqrt{{n_1}^2 - {n_2}^2} \quad ....(5)$$

From Eqn 1 & 5

$$\textbf{NA} = \sqrt{{n_1}^2 - {n_2}^2} \quad ....(6)$$

Where n1 is the refractive index of fiber and n2 is the refractive index of the cladding. Core-cladding index difference Δ is also called fractional refractive index change is given by

$$\Delta = \frac{{n_1}^2 - {n_2}^2}{2{n_1}^2} \approx \frac{n_1 - n_2}{n_1} \quad .... (7)$$

$$\textbf{NA} = \sqrt{{n_1}^2 - {n_2}^2} = n_1\sqrt{2\Delta} \quad .... (8)$$

The relationship between acceptance angle ,indices of refraction of core (n_{core}), the cladding $(n_{cladding})$, The surrounding medium n_o and NA is given by

$$\text{NA}= n_0\sin\theta_a = \sqrt{{n_{core}}^2 - {n_{cladding}}^2} \quad .... (9)$$

Usually the surrounding medium is air so no = 1, therefore

$$\textbf{NA} = \sin\theta_a \quad .... (10)$$

The acceptance angle of fiber is given by

$$\theta_a = sin^{-1}(NA) \quad .... (11)$$

FIBER AS A DIELECTRIC WAVEGUIDE (MODE THEORY)

MODES. - A set of guided electromagnetic waves is called the **modes** of an optical fiber.

The mode theory, along with the ray theory, is used to describe the propagation of light along an optical fiber. The mode theory uses electromagnetic wave behaviour to describe the propagation of light along a fiber. A set of guided electromagnetic waves is called the **modes** of the fiber.

PLANE WAVES. - The mode theory suggests that a light wave can be represented as a plane wave. A **plane wave** is described by its direction, amplitude, and wavelength of propagation. A plane wave is a wave whose surfaces of constant phase are infinite parallel planes normal to the direction of propagation.

The planes having the same phase are called the wave fronts. The wavelength of the plane wave is given by:

$$Wavelength\ \lambda = \frac{C}{f \times n}$$

where *c* is the speed of light in a vacuum, *f* is the frequency of the light, and n is the index of refraction of the plane-wave medium. Figure 1.6 shows the direction and wavefronts of plane-wave propagation. Plane waves, or wavefronts, propagate along the fiber similar to light rays. However, not all wavefronts incident on the fiber at angles less than or equal to the critical angle of light acceptance propagate along the fiber. Wavefronts may undergo a change in phase that prevents the successful transfer of light along the fiber.

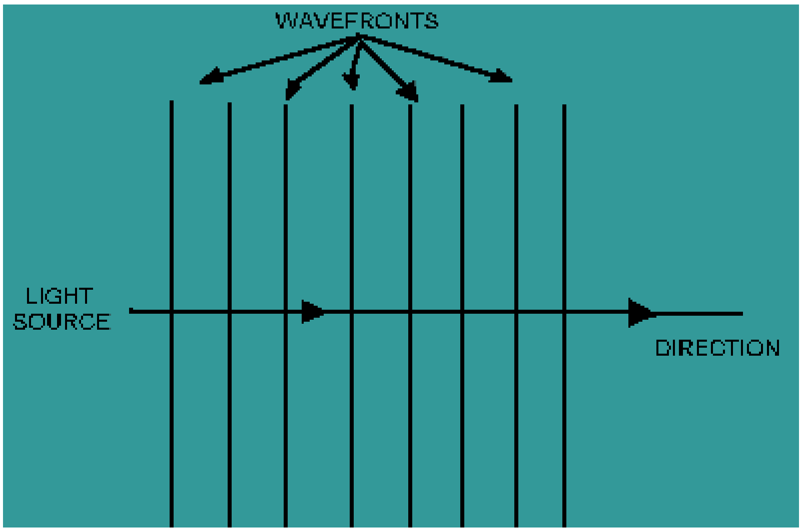


Figure 1.6 . - Plane-wave propagation .

Wavefronts are required to remain in phase for light to be transmitted along the fiber. Consider the wavefront incident on the core of an optical fiber as shown in figure 1.6(b). Only those wavefronts incident on the fiber at angles less than or equal to the critical angle may propagate along the fiber. The wavefront undergoes a gradual phase change as it travels down the fiber. Phase changes also occur when the wavefront is reflected. The wavefront must remain in phase after the wavefront transverses the fiber twice and is reflected twice. The distance transversed is shown between point A and point B on figure 1.6(b).. The reflected waves at point A and point B are in phase if the total amount of phase collected is an integer multiple of 2π ; radian. If propagating wavefronts are not in phase, they eventually disappear. Wavefronts disappear because of **destructive interference**. The wavefronts that are in phase interfere with the wavefronts that are out of phase. This interference is the reason why only a finite number of modes can propagate along the fiber.

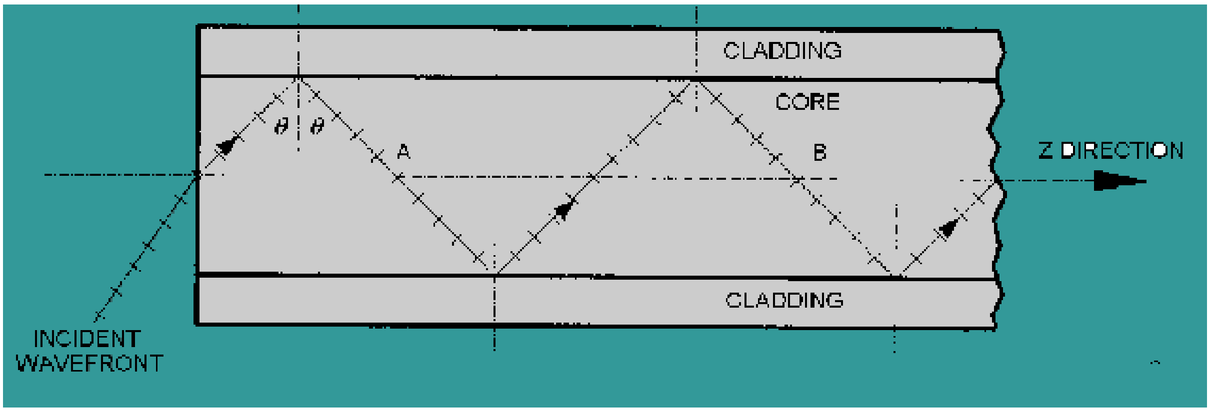
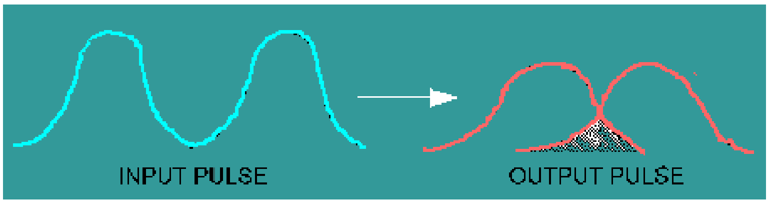


Figure 1.6(b). - Wavefront propagation along an optical fiber .

The plane waves repeat as they travel along the fiber axis. The direction the plane waves travel is assumed to be the z direction as shown in figure **1.6(b)**.. The plane waves repeat at a distance equal to lambda. Plane waves also repeat at a periodic frequency β is defined as the **propagation constant** along the fiber axis. As the wavelength (λ ,lambda;) changes, the value of the propagation constant must also change.

For a given mode, a change in wavelength can prevent the mode from propagating along the fiber. The mode is no longer bound to the fiber. The mode is said to be cut off. Modes that are bound at one wavelength may not exist at longer wavelengths. The wavelength at which a mode ceases to be bound is called the **cutoff wavelength** for that mode. However, an optical fiber is always able to propagate at least one mode. This mode is referred to as the fundamental mode of the fiber. The fundamental mode can never be cut off. The wavelength that prevents the next higher mode from propagating is called the cutoff wavelength of the fiber. An optical fiber that operates above the cutoff wavelength (at a longer wavelength) is called a single mode fiber. An optical fiber that operates below the cutoff wavelength is called a multimode fiber. In a fiber, the propagation constant of a plane wave is a function of the wave's wavelength and mode. The change in the propagation constant for different waves is called **dispersion**. The change in the propagation constant for different wavelengths is called **chromatic**

dispersion. The change in propagation constant for different modes is called **modal dispersion**. These dispersions cause the light pulse to spread as it goes down the fiber



Maxwell's equations describe electromagnetic waves or modes as having two components. The two components are the electric field, E(x, y, z), and the magnetic field, H(x, y, z). The electric field, E, and the magnetic field, H, are at right angles to each other. Modes traveling in an optical fiber are said to be transverse.

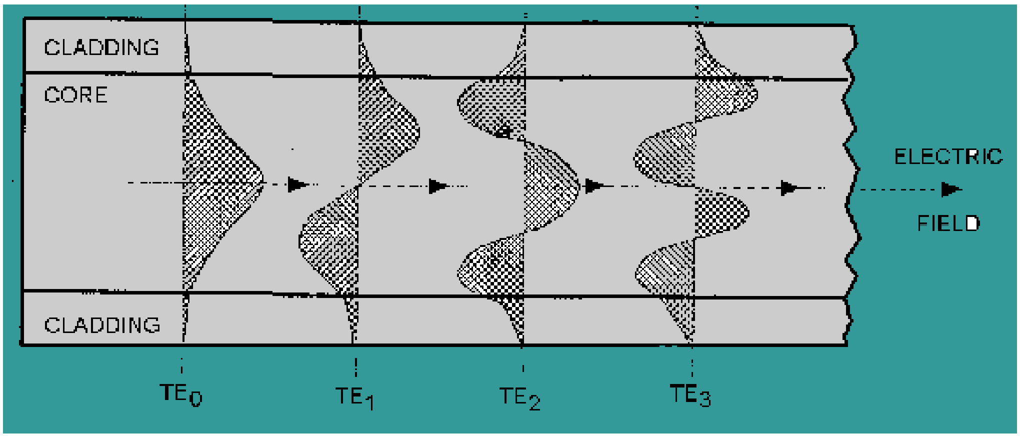


Figure . Transverse electric (TE) mode field patterns

The transverse modes, shown in figure, propagate along the axis of the fiber. The mode field patterns shown in figure are said to be transverse electric (TE). In TE modes, the electric field is perpendicular to the direction of propagation.

The magnetic field is in the direction of propagation. Another type of transverse mode is the transverse magnetic (TM) mode. TM modes are opposite to TE modes. In TM modes, the magnetic field is perpendicular to the direction of propagation. The electric field is in the direction of propagation.

The TE mode field patterns shown in figure indicate the **order** of each mode. The order of each mode is indicated by the number of field maxima within the core of the fiber. For example, TE_0 has one field maxima. The electric field is a maximum at the center of the waveguide and decays toward the core-cladding boundary. TE_0 is considered the fundamental mode or the lowest order standing wave. As the number of field maxima increases, the order of the mode is higher. Generally, modes with more than a few (5-10) field maxima are referred to as high-order modes.

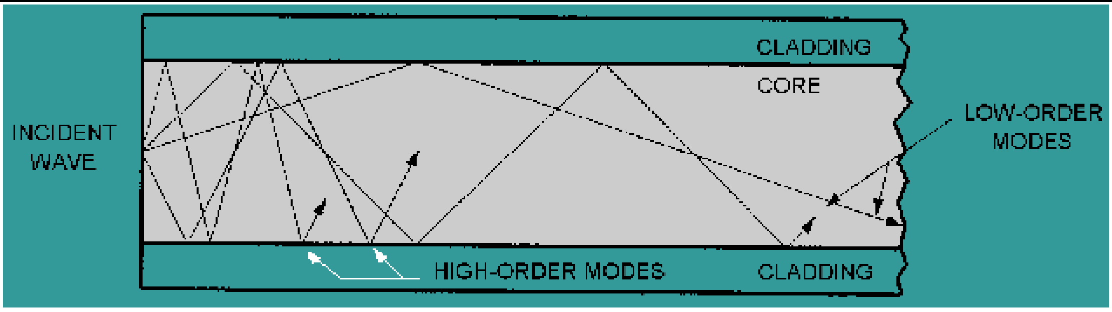


Figure - Low-order and high-order modes.

The order of the mode is also determined by the angle the wave front makes with the axis of the fiber. Figure illustrates light rays as they travel down the fiber. These light rays indicate the direction of the wave fronts. High-order modes cross the axis of the fiber at steeper angles.

Notice that the modes are not confined to the core of the fiber. The modes extend partially into the cladding material. Low-order modes penetrate the cladding only slightly. In low-order modes, the electric and magnetic fields are concentrated near the center of the fiber. However, high-order modes penetrate further into the cladding material. In high-order modes, the electrical and magnetic fields are distributed more toward the outer edges of the fiber.

This penetration of low-order and high-order modes into the cladding region indicates that some portion is refracted out of the core. The refracted modes may become trapped in the cladding due to the dimension of the cladding region. The modes trapped in the cladding region are called **cladding modes**. As the core and the cladding modes travel along the fiber, mode coupling occurs. **Mode coupling** is the exchange of power between two modes. Mode coupling to the cladding results in the loss of power from the core modes.

In addition to bound and refracted modes, there are leaky modes.

Leaky modes are similar to leaky rays. **Leaky modes** lose power as they propagate along the fiber. For a mode to remain within the core, the mode must meet certain boundary conditions. A mode remains bound if the propagation constant beta; meets the following boundary condition:

$$\frac{2\pi n_2}{\lambda} < \beta < \frac{2\pi n_1}{\lambda}$$

where n_1 and n_2 are the index of refraction for the core and the cladding, respectively. When the propagation constant becomes smaller than $\frac{2\pi n_2}{\lambda}$; power leaks out of the core and into the cladding. Generally, modes leaked into the cladding are lost in a few centimeters. However, leaky modes can carry a large amount of power in short fibers.

NORMALIZED FREQUENCY(V Number)

Electromagnetic waves bound to an optical fiber are described by the fiber's normalized frequency. The **normalized frequency** determines how many modes a fiber can support. Normalized frequency is a dimensionless quantity.

Normalized frequency is also related to the fiber's cutoff wavelength. Normalized frequency (V) is defined as:

$$V = \frac{2\pi}{\lambda} \times a \times \sqrt{{n_1}^2 - {n_2}^2} = \frac{2\pi}{\lambda} \times a \ \times n_1\sqrt{2\Delta}$$

where n_1 is the core index of refraction, n_2 is the cladding index of refraction, a is the core diameter, and λ; is the wavelength of light in air.

$V = \sqrt{U^2 + W^2}$ ……………………………………….(1)

Where U is the Propagation parameter and W is the cladding decay parameter. U and V is given by

$$U = a\sqrt{{n_1}^2k^2 - \beta^2}$$

$$W = a\sqrt{\beta^2 - {n_2}^2k^2}$$

Where $\boldsymbol{a}$ is the radious of the core ,$\boldsymbol{n_1}$ is the refractive index of the core ,$\boldsymbol{n_2}$ is the refractive index of the cladding, β is the propagation constant, and $k = \frac{2\pi}{\lambda}$; Now

$$V^2 = U^2 + W^2$$

$$= a^2({n_1}^2k^2 - \beta^2) + a^2(\beta^2 - {n_2}^2k^2)$$

$$= a^2{n_1}^2k^2 - a^2\beta^2 + a^2\beta^2 - a^2{n_2}^2k^2$$

$$= a^2k^2({n_1}^2 - {n_2}^2)$$

This implies $V = ak\sqrt{{n_1}^2 - {n_2}^2}$ But **NA =** $\sqrt{{n_1}^2 - {n_2}^2}$

There fore $V = ak \times NA$

$$V = \frac{2\pi}{\lambda} \times a \times NA = \frac{2\pi}{\lambda} \times a \ \times n_1\sqrt{2\Delta}$$

The number of modes that can exist in a fiber is a function of V. As the value of V increases, the number of modes supported by the fiber increases. Optical fibers, single mode and multimode, can support a different number of modes.

Number of modes in step index fiber $M = \frac{V^2}{2}$

number of modes in Multimode graded index fiber

$$Mg = \left\{\frac{\alpha}{\alpha + 2}\right\}\left(\frac{V^2}{2}\right)$$

.ADVANTAGES OF OPTICAL COMMUNICATION

- Ultra high bandwidth (THz)
- Low loss (0.2 dB/Km)
- Low EMI
- Security of transmission
- Low manufacturing cost
- Low weight, low volume
- Point to Point Communication
- The optical transmission medium is the best in a sense that it has ultra wide bandwidth and very low attenuation.

CLASSIFICATION OF FIBER-OPTIC COMMUNICATION SYSTEMS

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 is the simplest form in fiber-optic communication systems. Their main role is to transport information, in the form of digital bit stream, from one place to another with high accuracy. The length of the link can vary from less than a kilometer to thousands of kilometers, depending on the application required.

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). They are used mainly due to their immunity to electromagnetic interference, rather than their low loss and wide bandwidth.

On the other hand, undersea lightwave systems are used for high-speed transmission across continents with a link length of several thousands of kilometers. There is a need for low losses and a large bandwidth, in order to reduce the operating cost

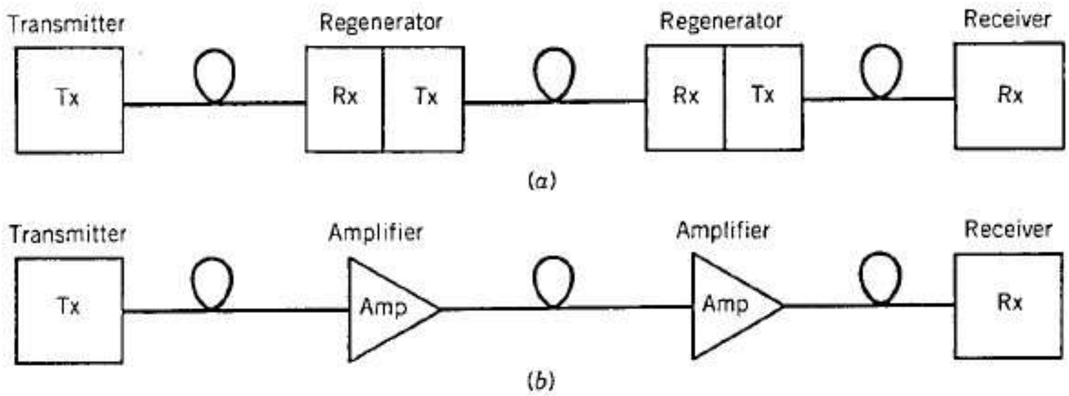


Fig 1.14 Point to point link

The figure about shows the point-to-point fiber links with periodic loss compensation through (a) regenerators and (b) optical amplifiers. A regenerator consists of a receiver followed by a transmitter. Compensation is required when the link length exceeds a certain value, depending on the operating wavelength, to prevent the signal from coming too weak to be detected reliably.

Distribution Networks

In the case of distribution networks, information is not only transmitted, but is also distributed to a group of subscribers. Examples include local-loop distribution of telephone services and broadcast of multiple video channels over cable television. Such networks have the ability to distribute a wide range of services, including telephone, facsimile, computer data, and video broadcasts. Transmission distances are relatively short (< 50 km), but the bit rate can be as high as 10 Gb/s for a broadband ISDN.

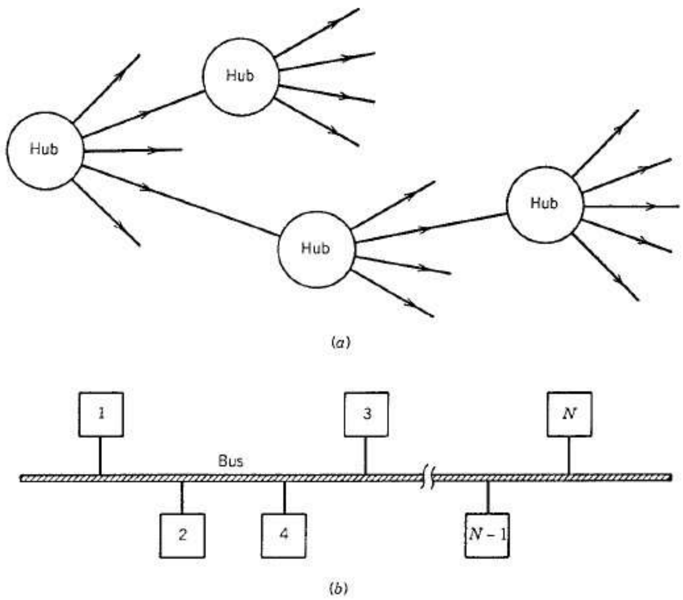


Fig 1.15 the structure of (a) hub topology and (b) bus topology for distribution networks.

For hub topology, channel distribution takes place at central locations, where an automated cross-connect facility switches channels in the electrical domain. Such networks are called metropolitan-area networks (MANs) as hubs are typically located in major cities. The role of fiber is similar to the role of point-to-point links. Several offices can share a single fiber headed for the main hub as the fiber bandwidth is generally much larger than that required by a single hub office.

A concern for the hub topology is related to its reliability—outage of a single fiber cable can affect the service to a large portion of the network. However, additional point-to-point links can be used to guard against such a possibility by connecting important hub locations directly.

For 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

An example is the common-antenna television (CATV) application of bus topology consists of distributing multiple video channels within a city. The use of optical fiber permits distribution of a large number of channels, because of its large bandwidth, as compared to coaxial cables. For high definition television (HDTV), it also requires lightwave transmission because of a large bandwidth (about 100 Mb/s) of each video channel, unless compression techniques are used.

Local-Area Networks

Local-area networks, also known as LANs, refers to networks in which a large number of users within a local area are interconnected in such a way that any user can access the network randomly to transmit data to any other user. Optical-access networks used in a local subscriber loop also fall in this category For such networks, transmission distance are relative short (<10 km). Fiber losses are not a big concern due to the short transmission distance.

The main difference between MANs and LANs is related to the random access offered to multiple users of a LAN. The system architecture plays an important role for LANs, since the establishment of predefined protocol rules is a necessity in such an environment. Common toplogies that are used for such networks include bus, ring, and star configurations.

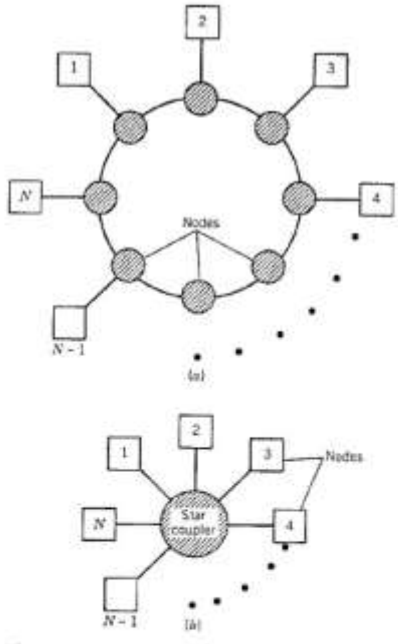


Fig 1.16 the structure of (a) ring topology and (b) star topology for local-area networks.

For bus topology, the structure is similar to the one used in distribution networks. An example is the one provided by Ethernet, whereby a network protocol used to connect multiple computers and used by the Internet. The Ethernet operates at speeds up to 1 Gb/s by using a protocol based on carrier-sense multiple access (CSMA) with collision detection. Although the Ethernet LAN architecture has proven to be quite successful when coaxial cables are used for the bus, a number of difficulties arise when optical fibers are used. There is also a major limitation is related to the losses occurring at each tap, which limits the number of users.

In the case of 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, as known as 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. It can also transmit by appending the data to an empty token. The use of ring topology for fiber-optic LANs has been commercialized with the standardized interface known as the fiber distributed data interface (FDDI) . The FDDI operates at 100 Mb/s by using multimode fibers and 1.3-μmtransmitters based on light-emitting diodes. It is designed to provide backbone services such as the interconnection of lower-speed LANs or mainframe computers.

In the case of the star topology, all nodes are connected through point-to-point links to a central node called a hub, or simply a star. Such LANs are further subclassified 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, before being distributed to drive individual node transmitters. Switching operations can also be performed at the central node since, distribution takes place in the electrical domain. In the passive star configuration, distribution takes place in the optical domain through devices such as directional couplers. The power transmitted to each node depends on the number of users, since the input from one node is distributed to many output nodes. As in the case of bus topology, the number of users supported by passive-star LANs is also limited by the distribution losses.

TYPES OF OPTICAL FIBERS

An optical fiber is a piece of very thin and almost absolutely pure glass. It is thin as human hair. Its outside is made of a cladding of glass which is also another type of glass, with slightly different chemical properties and composition. Hence it has different refractive index compared to inner core material. No single fiber design meets all application requirements mainly due to many economic reasons. However manufacturers have concentrated on three broad categories. This module mainly focuses on the classification of optical fibers and their characteristics.

CLASSIFICATION OF OPTICAL FIBERS

- Based on refractive index profile
- Number of modes transmitted through fiber
- Special optical fibers

Based on refractive index profiles

Optical fibers are classified into two types based on the refractive index profile of core and cladding. They are

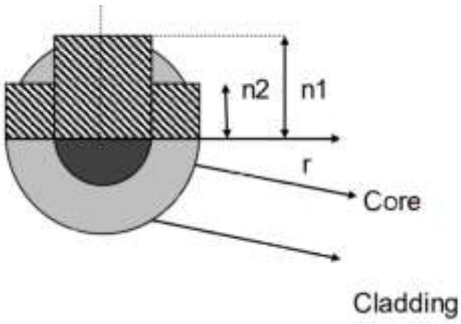
- Step index fiber
- Graded index fiber

In Step index fiber, core has the constant refractive index n_2 as shown in Figure (a). At the core cladding interface there is sudden decrease in the refractive index from n_2 to n_1. It remains constant throughout the cladding part of optical fiber.

The refractive index profile (n) profile with reference to the radial distance ‘r’ from the fiber axis is given as

When r=0 $n(r) = n_1$
$r < a$ $n(r) = n_1$
$r \geq a$ $n(r) = n_2$

where a is core radius of optical fiber.

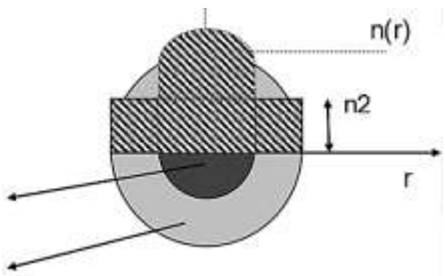


(a) Step index fiber (b) Graded index fiber

Figure 1.17: Optical fiber based on refractive index profiles

Figure 1.17(b) shows another type of optical fiber, graded index fiber, in which the refractive index of core n1 decreases gradually from the centre of core as a function of the radius from the centre of the optical fiber. At the core cladding interface, the refractive index shows decrease from n1 to n2 and it remains constant w.r.t. radial distance r. This type of optical fiber is known as graded index optical fiber. The refractive index (n) profile with reference to the radial distance (r) from the fiber axis is given as:

when r = 0, n(r) = n1……………………………………………(1)



$$r < a \; , n(r) = n_1 \left[1 - \left(2\Delta \left\{\frac{r}{a}\right\}^2\right)\right]^{1/2}$$ …………………..(2)

$$r \geq a \; , n(r) = n_2 = n_1[1 - 2\Delta]^{1/2}$$ ……………………………..(3)

Based on the number of modes propagated through optical fiber

Mode is the one which describes the nature of the electromagnetic wave in waveguide. Optical fiber is considered as cylindrical waveguide. It is the allowed direction whose associated angles satisfy the conditions for total internal reflection. Based on the number of modes that propagates through optical fiber, they are classified as

- Single mode fibers
- Multimode fibers

Single mode or monomode fibers:

In a fiber, if only one mode is transmitted through it then it is said to be a single mode fiber. A typical single mode fiber may have a core radius of 3 μm and a numerical aperture of 0.1 at a wavelength of 0.8 μm as shown in Figure 1.13a. The condition for the single mode operation is given by the V number of the fiber which defined as

$$V = \frac{2\pi n a(\sqrt{2\Delta})}{\lambda} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

For single mode operation, V ≤ 2.405. Here n = refractive index of core; a=radius of the core; λ=wavelength of the light propagating through the fiber; Δ=relative refractive indices difference. Single mode fibre has following characteristics:

Only one path of propagation is available

- V number is less than 2.405
- Core diameter very small
- No dispersion effect
- Higher bandwidth(1000MHz)
- Used for long haul communication
- Fabrication is difficult and costly

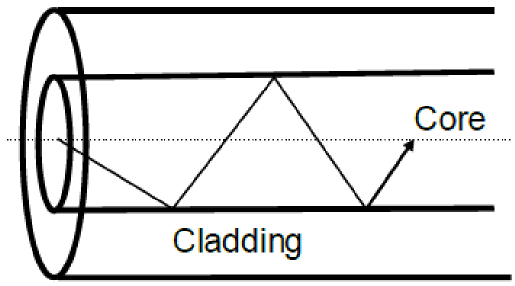


Figure 1.18a :Single mode fiber

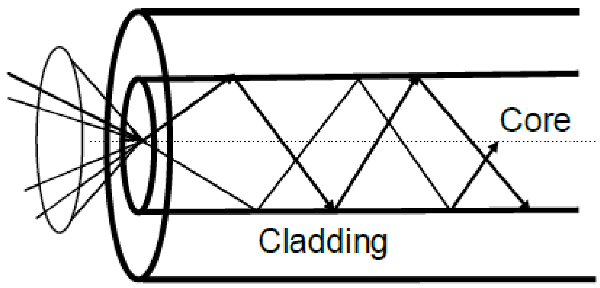


Figure 1.18b: Multimode fibers

Multimode fibers:

If more than one mode is transmitted through optical fiber, then it is said to be multimode fiber as shown in Figure 1.18b. The larger core radii of multimode fibers make it easier to

launch optical power in to the fiber and facilitate the end to end connection of similar powers. Multimode optical fibers have following characteristics:
More than one path is available

- V number is greater than 2.405
- Core diameter is higher
- Higher dispersion
- Lower bandwidth(50MHz)
- Used for short distance communication
- Fabrication is less difficult and not costly

Depending upon the refractive index profile and the number of modes propagated through the optical fiber, they are further classified as
Step index single mode fibers

- Step index multimode fiber
- Graded index single mode fibers
- Graded index multimode fibers

Step Index Single mode optical fibers

The core diameter of this type of fiber is very small i.e. of the order of wavelength of light to be propagated through the fiber. The refractive index profile has step change in the refractive index from core to cladding as shown in Figure

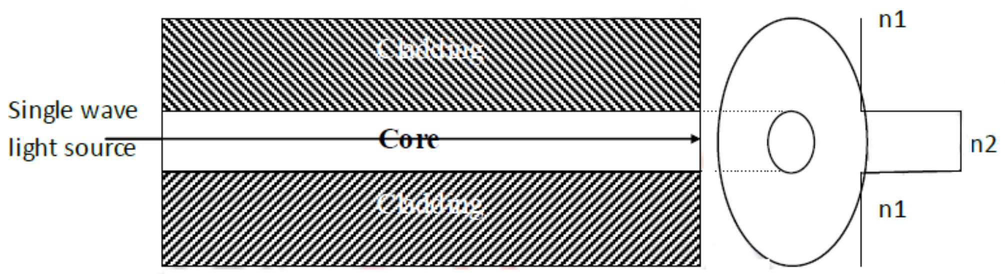


Figure 1.19 :Step index single mode optical fibers

The main characteristics of step index single mode optical fibers are as follows:

1. Very small core diameter

2. Low numerical aperture

3. Low attenuation

4. Very high bandwidth

In order to get single mode, with all other modes cut off, the diameter of the core must satisfy the relation

$$d < \frac{0.776\lambda}{NA}$$

Where λ is wavelength of light propagating through optical fiber
NA is numerical aperture of the optical fiber
Hence if the operating wavelength is 1.3 μm then the core diameters are of the order of 6 to 10μm. The term "***mode field diameter***" (mFd) is another important parameter for single mode fiber. Figure 1.20 shows the light guiding property of the fiber by indicating the boundary where the electric field of the optical wave falls to 1/eth (i.e. 36.8%) of that at the core centre. In single mode fiber significant amount of the power resides outside the fiber core.

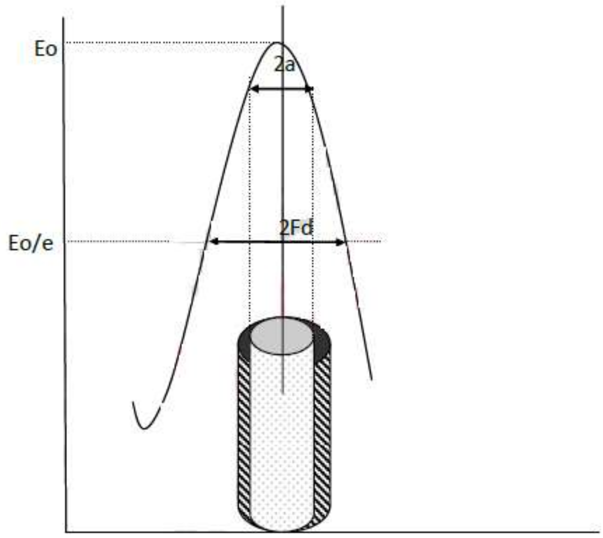


Figure1.20: Optical fiber power distribution across the cone of the step index single mode fiber

The distribution of the optical electric field with the radial position across the core is as shown in Figure 1.15. It is described approximately by a Gaussian expression near the cut off wavelength as follows:

$$E(x) = Eo\ e^{-\left(\frac{x}{fd}\right)^2}$$

$$Where\ fd = \frac{1}{2} \times Mode\ field\ diameter$$

Greater the ratio (Fd/a) the larger the amount of light that propagates in the cladding . In the structure of step index single mode fiber the cladding is kept very thick so that residual field at the cladding outer diameter is very insignificant; any optical field ,which is present at the outer boundary of the cladding is radiated. The theoretical value of 2fd is given by

$$2fd = 2a\left\{0.65 + 0.434\left\{\frac{\lambda}{\lambda_c}\right\}^{3/2} + 0.0149\left\{\frac{\lambda}{\lambda_c}\right\}^{6}\right\}$$

Where λ = operating wavelength
λc = cut off wavelength
2a= core diameter
Thus for a particular cut off wavelength the fd increases with operating wavelength

Disadvantage:
Due to very thin cores creates mechanical difficult in manufacture, handling and splicing of the fibers. It is very expensive.

Step index multimode optical fiber

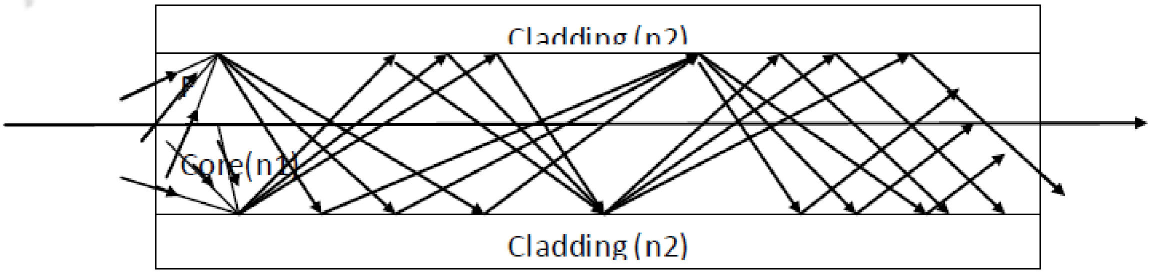


Figure 1.21 :Step index multimode optical fiber propagation (n1>n2)

Practically, light emanating from any point source will have several paths with different angles of incidence at boundary layer. It may also contain different colours with different frequencies. It is called as step index multimode propagation as shown in Figure 1.21. Any other light wave which is meeting the core cladding interface at and above the critical value of θc will also be totally reflected and hence will propagate along the core. However any light wave meeting the core cladding interface at an angle less than θc will pass into and be absorbed by the cladding.

Thus the various light waves travelling along the core will have different propagation paths of different path lengths. Hence they will meet at the other end of the fiber at different time instants. This causes dispersion of signal called as transit time dispersion. This dispersion sets an upper limit on the rate at which the light can be modulated by analog or digital electrical signal. As a result of this distortion the variations of successive pulses may overlap into each other and causes distortion of the information being carried. However this defect can be minimized by making the core diameter of the same order as the wavelength of the light wave to be propagated. The resultant propagation is a single light wave, explained earlier in single mode step index optical fiber. This type of fiber has very high capacity and large bandwidth.

Graded index single mode optical fiber

Graded index optical fiber has a property of gradual variation in refractive index(increasing from the outside of the fiber core to the centre of it). The propagation of light through single mode graded index fiber is similar to that for step index fiber. The light wave travels along the centre of the optical fiber.

Graded index multimode optical fiber

Figure 1.22 shows the refractive index profile and propagation of waves in graded index multimode fiber

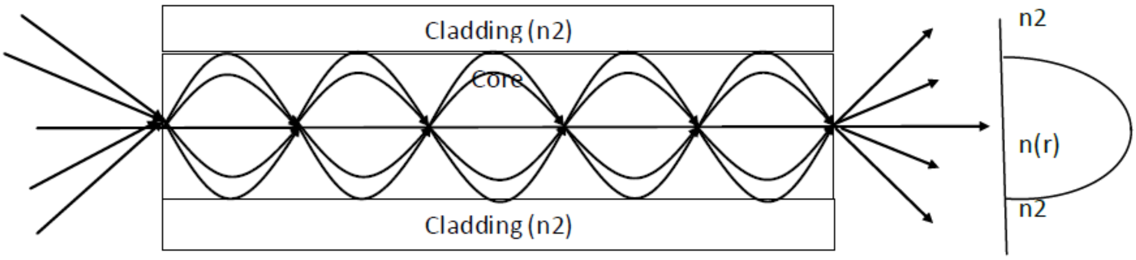


Figure 1.22 :Graded index multimode fiber with refractive index profile

From the figure it is quite clear that light waves or rays with large angle of incidence travel more path lengths than those with smaller angles. But we know that the decrease of refractive index allow a higher velocity of light energy propagation. Thus all waves will reach a given point along the fiber at virtually same time. As a result the transit time dispersion is reduced. This type of light propagation is referred as graded index multimode propagation through optical fiber.

The variation of refractive index of the core of graded index fiber with radius 'r' measured from the centre of core is given by

$$n(r) = n_1 \left[1 - 2\Delta \left(\frac{r}{a}\right) p\right]^2$$

Where n1 is refractive index at the centre of the core

p is index profile

It is noteworthy that as the light velocity decreases with increasing refractive index for modes near the core centre the light velocity is less than that near the core boundary. For approximately parabolic index profile, for various modes the propagation time is nearly equalized. Thus the multimode distortion is reduced. P has typical value of 2.0 for 850nm applications.

In graded index fiber the number of modes is expressed by the formula given by

$$N = \left(\frac{P}{P+2}\right)\left\{\frac{2\pi^2 a^2 (NA)^2}{\lambda^2}\right\}$$

This formula is valid for the number of modes >50

One important thing to mention here is that in all three types of fibers((i.e. step index multimode, step index single mode and graded index multimode) the thickness of cladding material around the fiber core should be at least be several wavelengths. This arrangement will prevent light energy losses due to absorption and scattering.

OTHER TYPES OF OPTICAL FIBERS

1. Plastic fibers

Plastic fibers are manufactured from a polymer perform drawing into a fiber. The losses associated with this type of fiber are about 100s of dB. The operate at low temperature i.e. upto 125 degree celcius whi le glass fibers can be used upto 1000 degree celcius. These are used in sensors, process control and short distance communication

Features

1. High light gathering capacity

2. Large core area

3. Low cost components

4. Uses visible LEDs

5. Easy to connect or couple

Table below shows various plastic fibers with specification commercially available.

Type	Bandwidth	NA	Operating temperature range in degree celcius
SK or SH	50 MHz(50 m length)	0.50	-40 to +75
EK or EH	120MHz(50 m length)	0.47	-40 to 85
DK or DH	50MHz(50 m length)	0.54	-40 to 115
FH	100MHz(20 m length)	0.75	-40 to 125

Plastic fibers are not available for use at long wavelength, because fibers of that type are very difficult to fabricate and also very expensive.

A fiber with glass core and plastic cladding is called as “plastic clad silica” or PCS fiber. They have following characteristics

1. High NA

2. Large core diameter

3. High attenuation

4. Low bandwidth

Advantage of large core is the greater power coupling. The high value of NA permits use of less expensive surface emitting LED's.
Along with high attenuation and low bandwidth plastic fibers have poor mechanical strength and low maximum operating temperature.

SPECIAL OPTICAL FIBERS

No single fiber design meets all application requirements due to economic reasons. Therefore some special types of fibers are manufactured for specialized uses. These are special optical fibers.These are explained in brief here

1. High Purity Silica Fiber(HPSUV)

This type of fiber is suitable for transmission of light in the range of 180 to 800 nm. It is good and cheap. It is coated with aluminum which gives very high mechanical strength and extra power handling capacity as aluminum dissipates heat more quickly. These fibers operate at temperatures upto 400 degree celcius and vacuum.

Characteristics

1. Fiber type: Step index multimode

2. Core material: High purity synthetic silica

3. Cladding material: Doped silica

4. Primary coating: Aluminum or polymer

5. Secondary coating: Polymer

6. NA: 0.24

7. Tensile strength: 7 G Pa

8. Minimum bend radius: 40 times fiber radius

9. Temperature range: -169 to 400 degree celcius

10. Humidity:100%

11. Attenuation values: 1. 248 nm (KrF laser)<1.2dB/m

2. 308 nm (XeCl laser) <0.26dB/m

12. Radiation resistance: Good

13. Maximum intensity of the transmitted power:

1. CW upto 100KW/cm2
2. Pulse upto 500 KW/cm2

2. High Purity Silica (HPSIR)

It is similar to HPSUV fiber with slightly different dopants to give it a longer wavelength capability in the near IR from 500 nm to 2600 nm.

3. Chalcogenide Fiber

This type of fiber is used for transmission of light from 1 to 0.6 μm. They have extremely low losses. There are two types of chalcogenide fibers i.e. A and B. The loss in A type is down to 0.1dB/m. Hence they are particularly suitable for medical applications. The characteristics are

1. Fiber type: Step index multimode
2. Core material: As_2S_3
3. Cladding material: As_xS_{1-x}
4. Primary coating: PTFE
5. Secondary coating: PTFE or PVC
6. NA: 0.3 to 0.5
7. Minimum bend radius: < 10 nm
8. Temperature range: < 200 < T < 100 degree celcius
9. Attenuation values: 1. A type minimum 0.1dB/m

   2. B type minimum 0.6dB/m
10. Radiation resistance: Good
11. Maximum intensity of the transmitted power: 10W(CO laser)
12. Core diameter: 1. CHAL 100: 100μm

    2. CHAL 200:200μm

    3. CHAL 300:300μm

4. Halide fibers:

These fibers are extended to 15 μm region. The most common application is for use with the CO_2 laser in medicine to replace bulk optics delivery systems or in industry. Silver halide fibers are used for transmission of light from 3 to 15 μm. They have low losses and are currently the only known optical fibers for transmission of light from high power, long wavelength lasers like the CO_2 laser. They are very flexible and much more convenient than normal mechanical delivery systems for these long wavelengths.

The fibers comprise a core polycrystalline silver halide surrounded by an opaque tube. Because of high refractive index (2.2) of the material the total internal reflection takes place at the boundary with air. The tube is necessary to prevent UV light from reaching the core which causes premature failure. The normal life time of these fibers is 6 to 12 months depending upon how they are used.

Characteristics

1. Numerical Aperture: < 0.7

2. Outer diameter with protective covering: 0.36 to 1.5 mm

3. Core diameter: 0.1 to 1.2 mm

4. Attenuation at 10.6μm i.e. CO2 laser: 0.5 to 1.5 dB/m

5. Attenuation at 5 to 6μm i.e. CO2 laser:< 2dB

6. Usable wavelength range: 3-15mm

7. Maximum length available: < 15m

8. Yield strength: 150-170MPa

9. Radius of elastic bending: >0.4 cm

10. Operating maximum temperature: > 100 degree celcius

5. Tapered optical fibers

Tapered fibers are useful for getting maximum amount of power from a poor quality laser spot into a fiber. The use of tapered optical fiber is an efficient low cost method of transforming a poor quality laser beam into a uniform output spot.

The concept of conversion of brightness states that the spatial and angular parameters of light anywhere within or at either end of the taper are mutually connected by the formula

$$A_i n_i^2 sin^2\theta_i = A_0 n_0^2 sin^2\theta_0$$

Where n's and θ's represent refracti ve indices and angles respecti vely. Subscripts ' i' and 'o' refer to input and output.

$\frac{A_i}{A_0} = R^2;$ Where R is taper diameter ration and it follows that

$$\frac{(NA)_i}{(NA)_0} = R \ ,$$

It should be noted that if the product of the input NA and the taper diameter ratio R exceeds the NA of the taper's pigtail, the light will escape into the cladding and will be lost. In that case the above relation is no longer true. To avoid light losses the NA of the light beam at the taper's input should be less than the practical value. Figure 8 shows structure of tapered optical fiber

Figure 1.23 :Tapered optical fiber

Characteristics

1. Input to output ratios: upto 5:1

2. Input core diameter:100μm to 4.0 mm

3. Output core diameter: 50 μm to 1.5 mm

4. Taper length: 1-3m

5. Total length: 3-10m

6. Core material: Pure synthetic silica

7. Primary coating: Aluminum or acrylic

8. Optional secondary coating: Epoxy acrylate, flouropolymers

9. Operating temperature: 196-400 degree celcius (Al coated)

10. Humidity:100%

11. Radiation resistance: good

12. Power transmission:

1. CW upto 100KW/cm2

2. Pulsed 145 , 500KW/cm2

13. NA: 0.24

Applications of optical fibers (Wavelength wise)

Table shows use of different types of optical fibers according to operating wavelength

Type	Range of operating wavelength
HPSUV	180nm to 800nm
HPSIR	500 nm to 2.6 µm
Taper	180nm to 2.6 µm
Chalcogenide	1 µm to 6 µm
Silver halide	3.0 µm to 15 µm

Comparison of optical fibers

1. Bandwidth: A good quality step index fiber may have a bandwidth of 50MHz km where as equivalent GRIN fiber can have 200,400 or 600 MHz km bandwidth. Theoretically, the correction gradation in the GRIN fiber will produce nearly an infinite bandwidth

2. Attenuation: GRIN fiber tends to be generally lower attenuation than the step index fiber. There is no fundamental reason why a step index fiber should have higher attenuation than the GRIN fiber. At least theoretically they are made of the exact same kind of glass, with same amount of energy absorption. But as a practical matter, in step index fiber there may be some irregularities at the interface between the core and the cladding which in turn will contribute to mode conversion and some reflection-loss. But in GRIN fiber there is no such interface. Hence the GRIN fiber has no real counterpart for this loss mechanism in the step index fiber. Certain amount of loss from microscopic bubbles and actual attenuation due to dielectric hysteresis etc are present in both the fibers. Attenuation may also be caused by impurity absorption. But the prime culprit is the interface dissipation of the step index fiber

3. Mode Dispersion: There is an inherent advantage in mode dispersion for the graded index fiber compared to the step index fiber. For if a wavefront had originally crossed the fiber axis with smaller inclinations it would have spent more time wading through glass with higher index and would have travelled more slowly. The rays having wide swinging actually travel farther but they spend more of their time travelling at a faster rate.

4. Numerical aperture: It has been observed that for a given fiber diameter the numerical aperture of GRIN fiber is generally smaller than the one on a step index fiber. For a GRIN fiber with an attenuation between 5 and 10dB/km the NA will tend to run between 0.16 and 0.2 whereas a step index fiber of about the same physical size with a loss of the order of 12dB/km will tend to have NA if the order of 0.2 to 0.35.

Table below shows comparison of single mode and multimode fibers

SINGLE MODE FIBER	MULTIMODE FIBER
Only a single mode propagates through fiber	Many modes propagate through fiber
Diameter is much less than multimode fiber < 10 μm	Diameter much larger than single mode fiber
Largest transmission bandwidth	Transmission bandwidth is small compared to single mode fiber
Exhibits low loss	Comparitively more lossy
Superior transmission quality due to absence of modal noise	Lesser transmission quality than single mode fiber

LINEAR EFFECTS IN OPTICAL FIBER

These are

- Attenuation
- Absorption
- Linear Scattering
- Bending Losses

ATTENUATION

Loss of signal Strength while traveling through the optical fiber from the transmitting end to the receiving end is called **attenuation**. As the distance travelled by an optical signal along the fiber increases, the reduction in signal also increases. Therefore, **attenuation** is always expressed in decibel per kilometer (dB/km). Loss of optical signal is shown as reduction in the intensity of optical signal in Fig.

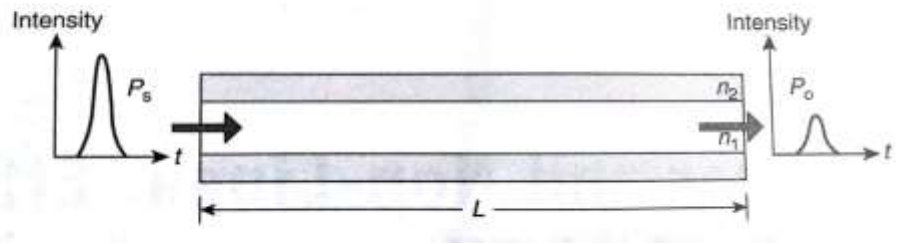


Fig: 1.24 : Attenuation in optical fiber

The two power levels are compared with the unit decibel. If Ps is the input source optical power launched into the optical power and Po is the received output from the fiber,then

$$Number\ of\ decibels(dB) = 10\ log_{10}\frac{Ps}{Po}$$

$$\frac{P_s}{P_o} = 10^{\left[\frac{dB}{10}\right]}$$

In optical communication ,attenuation is usually expressed in decibels per unit length. Therefore

$$\alpha_{dB}L = 10\ log_{10}\frac{Ps}{Po} = 4.343\alpha_p(km^{-1})$$

Where α_{dB} is the signal attenuation per unit length in dB and L is the fiber length.

ABSORPTION

The main cause of absorption is the presence of impurities such as metal particles or moisture in the fiber. Due to these impurities, light of a particular wavelength is absorbed and dissipated as heat.

Absorption is defined as the portion of attenuation resulting from the conversion of optical power into another energy form, such as heat. The absorption in optical fiber is influenced by the following factors:

1. The atomic structure of fiber material.
2. Impurities in fiber material.

Defects in atomic structure, such as missing molecules or oxygen defects, cause absorption. Another cause is the diffusion of hydrogen molecules into the glass.

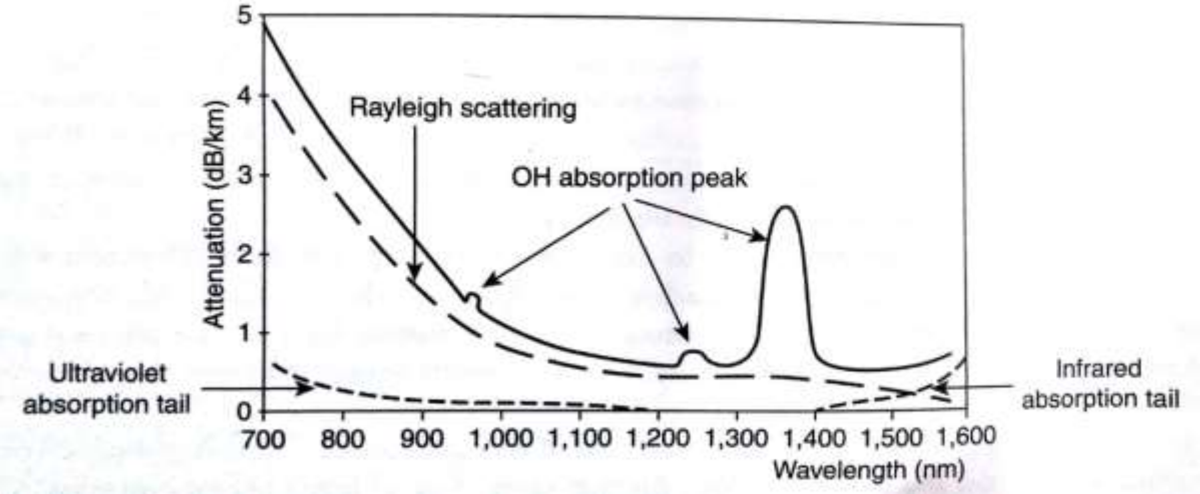


Fig: 1.25 : Fiber Losss

Thus, the main cause of absorption is intrinsic and extrinsic material properties.

Intrinsic Absorption

The silica fiber is the preferred channel for most communication applications because of its low absorption property in the required wavelength range from 700 to 1600 nm. Pure silica has low absorption due to its basic material structure. The attenuation in this wavelength range for pure silica is shown in Fig. 1.25; the low attenuation range is between the ultraviolet and infrared regions. Intrinsic absorption in this region is due to the stimulation of electron transitions within the glass by higher energy excitation. The tail of the ultraviolet absorption band is shown in Fig. 1.25. It may extend into the short wavelength region and also into the infrared and far infrared region. Intrinsic absorption is mainly caused by the interaction of photons with the molecular vibrations within the glass. The vibrations of Si-O, 60-0, 8-0, and P-O give rise to absorption.

Extrinsic absorption

Extrinsic absorption is caused by metallic impurities such as iron, nickel, and chromium introduced into the fiber material during fabrication. Another major cause is absorption due to water dissolved in glass. Water in silica glass forms silicon-hydroxyl(Si-OH) bonds, which are bonded into the glass structure and have stretching vibrations between 2700 and 4200 nm. However, the harmonics or overtones of the fundamental absorption occur at 1 38, 1.25, and 0.95 μm. Figure 1.25 shows the presence of the three OH harmonics. The level of the OH harmonic absorption is also indicated.

LINEAR SCATTERING

The scattering phenomenon transfers optical power of one mode to another mode. During this process, the signal may get attenuated because the transfer of power may be to a leaky mode, which does not continue to propagate through fiber. There are two categories of linear scattering:

1. Rayleigh scattering.
2. Mie scattering.

RAYLEIGH SCATTERING

Rayleigh Scattering occurs due to material inhomogeneties. The density and compositional variations cause refractive index fluctuations. This effect can be reduced by improving the fabrication process. Attenuation caused by Rayleigh Scattering is proportional to the fourth power of the wavelength ($\frac{1}{\lambda^4}$)

Mathematically

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

where γ_R is the Rayleigh sanding coefficient, λ is the optical wavelength, *n* is the refractive index of the medium, *P* is the average photo elastic coefficient, β_c is the isothermal compressibility at a fictive temperature T_F , and K is Bolmnann's constant. Now

Transmissivity or transmission factor of the Fiber = $e^{-\gamma_R L}$

where L is the length of fiber. From the equation of γ_R we can say that Rayleigh scattering can be strongly reduced by operating at the longest possible wavelength.

$$Attenuation = 10\ log\left\{\frac{1}{\textbf{Transmissivity or transmission factor of the Fiber}}\right\}$$

MIE SCATTERING

Mie scattering occurs when the size of the inhomogeneties is comparable to the guided wavelength, for example, non-perfect cylindrical structure, core-cladding refractive index difference, irregularities in core-cladding interface, change in fiber diameter with length, presence of air bubbles, etc.

The scattering created by such inhomogeneties is mainly in the forward direction. Inhomogeneties can be reduced by the following ways:

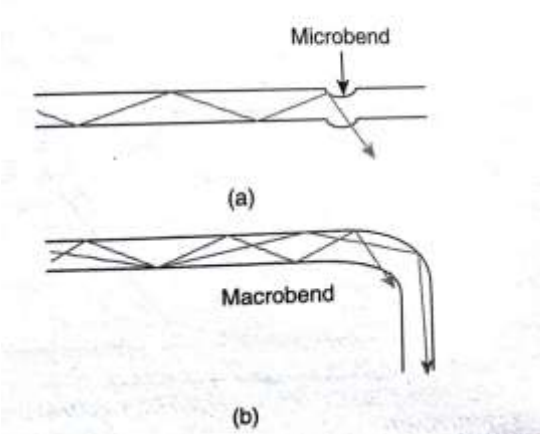
1. Removing imperfections such as non-uniform fiber diameter, presence of bubbles, etc.
2. Increasing the relative refractive index difference to make the fiber more guiding
3. Carefully controlled extrusion and coating of the fiber.

BENDING LOSSES

In an optical fiber, radiation losses take place at the bends, because the light traveling inside the fiber is slower when compared to the evanescent field outside the fiber. (The light wave propagating through the fiber decays exponentially away from the core-cladding boundary. This part of light wave in cladding is called evanescent field. As the evanescent wave is the integral part of a guided wave, any modification of the evanescent field modifies the guided wave.) This velocity difference inhibits the guiding of light.

Depending upon the radius of the bend, there are two types of bends:

l. Microbends. 2. Macrobends.



MICRO BENDS/ CABLING LOSS/ PACKAGING LOSS

If the radius of curvature is a few micrometers, the bend is called a microbend. Microbends an occur due to any of the following reasons:

1. Non-Uniformities in the manufacturing of fiber
2. Non-uniform mechanical tensile forces by which the fiber is pressed against a rough surface.
3. Non-uniform lateral pressure created during cabling of fiber.

Micro-bending losses can be minimized by extruding a compressible jacket over fiber.

In multimode fibers micro bending losses is expressed mathematically as

$$Loss_{M_{microbend}} = Nh^2 \left(\frac{a^4}{b^6 \Delta^3}\right) \left[\frac{E}{E_F}\right]^{\frac{3}{2}}$$

where N is the number of bumps, h is the height of the bump per unit length, b is the fiber diameter, a is the core radius, Δ is the relative refractive index difference, E is the elastic modulus of the surrounding medium, and E_F is the elastic modulus of the fiber.

In single-mode fiber, the microbending loss is expressed mathematically as

$$Loss_{S_{microbend}} = 0.05\alpha_m \frac{K^4 (Fd)^6 (NA)^4}{a^2}$$

Where α_m is the attenuation constant, K is the wave vector $=\frac{2\pi}{\lambda}$, *a* is the care radius, and *Fd* is the half of mode field diameter in single-mode fiber.

MACROBEND LOSS/LARGE CURVATURE RADIATION LOSS

If the radius is large compared to the fiber diameter, the bend is called a macrobend. Bending losses can be reduced by using

1. The shortest possible operating wavelength.

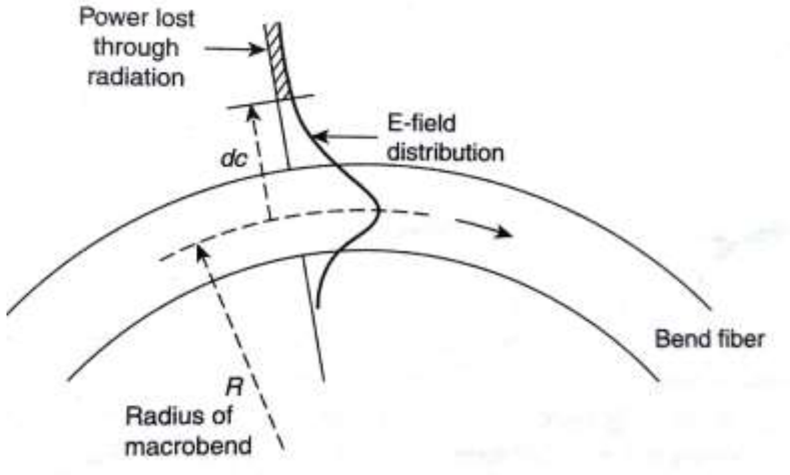
2. A fiber with a large relative refractive index difference.

These losses are also called "large-curvature radiation losses," because these are present in fibers whose radius of curvature is larger than the fiber diameter. The modal electric field distribution has a small portion extending into the cladding, which is called the evanescent field. As we go away from the core, the evanescent held decays exponentially. At the macrobend, the evanescent field, which is at the far end from the center of core, must move faster to keep up with the speed of the held in the core. If the fiber bend radius is gradually reduced, at some value of radius the loss becomes maximum, and this radius is called the critical radius. Here, a very high mode phase velocity (nearly equal to speed of light) is required, which is impossible. So, some modes are converted to higher order modes, which are then radiated outside

The macrobend losses occur when optical fibers are packed for transportation during the installation process. Mathematically, the macrobend loss is expressed as

$$Loss_{macrobend} = 10 log \left[\frac{(\alpha + 2)}{(2\alpha)\left[\frac{a}{R\Delta}\right]}\right]$$

Where ***α*** is the profile parameter, ***a*** is the core radius, ***R*** is the bend radius,and Δ is the index difference**.**



Radiation loss at macrobending

NON-LINEAR EFFECTS IN FIBER

The refractive index of a material is a function of the Frequency as well as intensity of light traveling through it. To overcome the losses in optical power, the input optical power can be increased. However, after a certain threshold power level, that is, at high intensity, if there are a number of signal wavelengths present, then the non-linear effects in fiber are significant. Non-linear effect can cause reduction in power or gain in power at different wavelengths, crosstalk between adjacent channels, or wavelength conversion. Thus the optical system performance may degrade. In some applications, non-linear effects can be useful also. Non-linear effects can be divided into two cases based on their origins:

1. Stimulated scattering.
2. Optical Kerr effects.

Optical Kerr effect is the result of intensity dependence of the refractive index of an optical fiber, leading to a phase constant that is a function of the optical intensity, whereas Stimulated scattering is a result of scattering leading to an intensity-dependent attenuation constant. There are two stimulated scattering phenomena in an optical fiber: **Raman scattering and Brillouin scattering**. The intensity dependence of the refractive index results in seif-phase modulation (SPM), cross-phase modulation (XPM or CPM), and four-wave mixing (FWM). Another difference between stimulated scatterings and the effects of a non-linear refractive index is that the former is associated with threshold powers at which their effects become significant.

STIMULATED RAMAN SCATTERING

The interaction between the incident optical signal (photon) and molecular vibrations gives rise to stimulated Raman scattering (SRS). Due to the interaction, some part of the energy of the incident photon is absorbed by the molecule. This results in the scattering of the photon. The frequency as well as energy of the incident photon reduces in this process, and this modified photon is called the ***Stokes photon***. The reduction in frequency is equal to the molecular vibration frequency, which is called the ***Stokes frequency*** and the incident optical signal is called a ***pump wave***. In general, the criterion used to determine the level of scattering effects is the threshold power $P_{RamamTh}$ defined as the input power level that can induce the scattering effect so that half of the power (3-dB power reduction) is lost at the output of an optical fiber of length L. The Raman threshold power $P_{RamamTh}$ for a single-channel optical system is given as

$$PRamamTh = \frac{32\alpha A_{eff}}{g_R}$$

Where α is the attenuation coefficient A_{eff} is the effective core area of an optical fiber, and g_R is the Raman Gain Coefficient.

Reduction in SRS Penalty

Different schemes used for reduction of power penalty in SRS process are as follows:

1. Dispersion phenomenon in a channel reduces the SRS penalty. The signals in different channels travel at different velocities and hence reduce the chances of overlap between pulses propagating at different wavelengths..
2. By reducing channel spacing, SRS can be reduced.
3. By keeping the power level of each channel below the threshold level, SRS can be reduced. To achieve this, distance between amplifiers has to be reduced.

STIMULATED BRILLOUIN SCATTERING

The interaction between a Strong optical signal and an acoustic wave gives rise to the non-linear effect called stimulated Brillouin scattering. It causes refractive index variations, that in turn cause the scattering of the optical signal in the backward direction .Due to back-scattering there is a loss of signal power. The frequency of scattered light also get down-shifted. The shift in frequency is equal to frequency of an acoustic wave. The Brillouin threshold power is given as

$$PBrillouinTh = \frac{42\ \alpha\ A_{eff}}{g_B}\left\{1 + \frac{v_P}{v_B}\right\}$$

where g_B is the Brillouin gain coefficient, v_P is the signal line width, and v_B is the Brillouin gain bandwidth.

Reduction in Power Penalty

When any non-linear effect contributes to signal impairment, an additional amount of power is needed at the receiver to maintain the same BER as in the absence of non-linear effects. The different schemes used to reduce the power penalty due to SBS are as follows:

1. Power level per WDM channel should be kept much below the SBS threshold. So the spacing between amplifier stages should be reduced in long-haul systems..
2. The line width can be increased by direct modulation of the source laser. But this may result in significant dispersion, which can be reduced by suitable dispersion management.

COMPARISON OF RAMAN AND BRILLOUIN PROCESS

In spite of many similarities between SBS and SRS, the SBS differs from the SRS in several ways.

1. Brillouin shift originates from the photon-acoustic photon interaction while Raman shift is due to photon-optical photon interaction.
2. SBS occurs only in the backward direction whereas SRS can occur in both forward and backward directions.
3. Brillouin scattering occurs due to Bragg-type scattering from propagating acoustic waves, and a large number of molecules are involved, while Raman scattering is the result of individual molecular motion.
4. The SBS Stokes shift is smaller (0.09 nm shift in 1550 nm) as compared to SRS Stokes shift (100 nm shift in 1550 nm).
5. The Brillouin gain bandwidth is extremely narrow in comparison to Raman gain bandwidth.
6. The threshold power level for SBS is quite low compared to that of SRS.
7. SBS does not produce crosstalk between adjacent channels, while SRS produces crosstalk.

KERR EFFECTS

Electro-optic effects refer to changes in the refractive index of a material induced by the application of an external electric field. This field modulates the optical properties of the device. Electro-optic effects are classified as first and second-order effects. Let the refractive index n be a function of the applied electric field n = n(E). Expanding this by a Taylor series in E, we get

$$\boldsymbol{n' = n + a_1E + a_2E^2 + \cdots \ldots}$$

The coefficient $\boldsymbol{a_1}$ is called the linear electro-optic effect, the coefficient $\boldsymbol{a_2}$ is called the second order electro-optic effect, and the higher order terms have been found to be negligible for the highest practical electric fields and are ignored.

The change in n due to the linear term is called Pockels effect:

$\Delta\boldsymbol{n = a_1E}$

The change in n due to the second-order term is called Kerr effect:

$$\Delta n = a_2 E^2 = (\lambda K)E^2$$

Here K is the Kerr coefficient measured in m/V^2. It is noteworthy that K depends on the wavelength. A typical value for the Kerr coefficient of glass is $3 \times 10^{-15}\ m/V^2$.

All materials exhibit the Kerr effect. However, only **non-centrosymmetric** materials exhibit the Pockels effect. GaAs is an example of a material that exhibits Kerr effect.

The ***Kerr effect*** or the ***quadratic electro-optic effect*** (QEO effect) is a change in the refractive index of a material in response to an electric field. It is distinct from the *Pockels effect* in that the induced index change is directly proportional to the square of the electric field instead of the magnitude of the field.

In Optical Kerr effect ,the electric field is due to the light itself. This causes a variation in the index of refraction which is proportional to the local irradiance of the light. This refractive index variation is responsible for the non-linear optical effects of self-focusing and self-phase modulation, and is the basis for Kerr lens mode locking. This effect only becomes significant with very intense beams such as those from lasers.

FOUR-WAVE MIXING

Consider three optical frequencies, f1,f2 and f3 closely spaced (in terms of wavelength) then from the interaction of the three, a fourth optical wave frequency f_{fwm} is generated, such that $f_{fwm} = f_1 + f_2 - f_3$. This is known as four-wave mixing (FWM) or four-photon mixing.

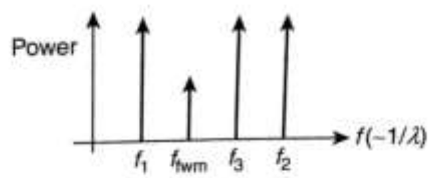


Fig: 1.26 Four-wave mixing

The FWM component E_{FWM}, at the output of fiber segment L, generated by 3 componentsE_1,E_2,E_3 with angular frequency ω, refractive index n, non-linear refractive index χ and loss α is described by

$$E_{FWM} = j\left[\frac{2\pi\omega}{nc}\right] d\chi E_1 E_2 E_3 e^{-\alpha(\frac{L}{2})} F(\alpha, L, \nabla\beta)$$

where F(α, L, ,$\nabla\beta$) is a function of fiber loss, fiber length, and propagation variation (phase mismatch) related to channel spacing and dispersion.

The output power of the f_{fwm} and the efficiency of four-wave mixing depend on the following factors:

1. Refractive index.
2. Fiber length.
3. Chromatic dispersion of the fiber.
4. Channel Spacing
5. Power densities of the contributing frequencies f1,f2 & f3
6. Higher order polarization properties of the material.

Four-wave mixing is independent of bit rate

When N signals are involved in the FWM process,the number of FWM generated signal is given by

$$M = \frac{N^2(N-1)}{2}$$

FWM efficiency depends on the following parameters

1. Material dispersion
2. Channel separation
3. Fiber length
4. Optical power level of each contributing channel.

REDUCTION IN FWM

Four-wave mixing Is a phenomenon that cannot be entirely eliminated. However, it can be greatly minimized so that its effect is not destructive. Different methods to reduce FWM are as follows:

1. Uneven spacing between channels.
2. Increasing channel spacing.
3. Power to be launched into the fiber is reduced.
4. Near-zero net chromatic dispersion is maintained by using segments of fibres with opposing non-zero dispersion characteristics after long spans of standard fiber cable.

SELF-PHASE MODULATION

In self-phase modulation, the optical pulse exhibits a phase shift induced by refractive index and the refractive index varies with intensity of optical signal. The most intense regions of the pulse are slowed down the most, so they exhibit the greatest phase shift.

A phase shift changes the distances between the peaks of an oscillating function and the oscillation frequency along the horizontal axis.

A phase shift is equivalent to stretching out or squishing part of an oscillating Function along its horizontal axis. Figure 1.27(a) shows a sine wave having constant frequency throughout the length. Figure 1.27(b) shows the same sine wave after undergoing a phase shift such that the right-hand side of the wave has a lower frequency than the left-hand side. As a result, the wave is chirped. There is an ordered variation in frequency along the horizontal axis.

The same concepts of phase shift and chirp may be applied to an optical pulse. Figure 1.28(a) shows an unchirped Gaussian pulse and Fig. 1.28(b) shows the same pulse after being chirped by a phase shift. Notice also that the chirped pulse has the same envelope as the unchirped pulse. This is because self-phase modulation only broadens the pulse in the frequency domain. not the time domain. As in Fig. 1.28, self-phase modulation leads to chirping with higher frequencies on the trailing (left-hand) side of the pulse and lower frequencies on the leading (right-hand) side. Self-phase modulation may cause errors at the receiving end of a fiber-optic communication system. Particularly in wavelength-division multiplexed systems. the frequencies of individual signals need to stay within strict upper and lower bounds to avoid encroaching on the other signals.

For a propagation distance of L,the phase of signal s given by

$$\emptyset(\boldsymbol{L},\boldsymbol{\tau}) = \frac{\boldsymbol{2\pi n_0 L}}{\boldsymbol{\lambda}} + \frac{\boldsymbol{2\pi n_2 L_{eff}}}{\boldsymbol{\lambda}}$$

Where L_{eff} is the effective transmission distance taking into account the fiber attenuation.

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

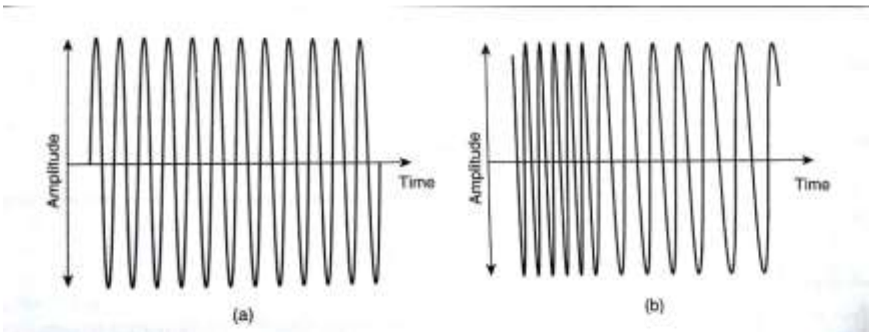


Fig 1.27: (a) Un chriped sine wave (b) A chriped sine wave

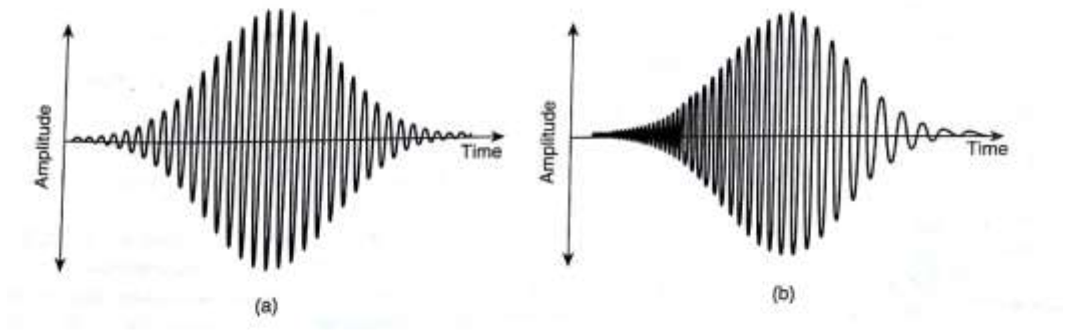


Fig 1.28: Un chriped Gaussian pulse (b) A chriped gaussian pulse

CROSS-PHASE MODULATION (XPM OR CPM)

Cross phase modulation (XPM) is due to the non-linear effect of the refractive index on the optical intensity. The total non-linear phase shift on a given channel is due to the combined intensities of all transmitted Channels which can result in cross talk among WDM channels. When N channels are transmitted in a. single optical fiber the non-linear phase shift on the jth channel is given by

$$\emptyset(L,\tau) = \frac{2\pi n_0 L}{\lambda} + \frac{2\pi n_2 L_{eff}}{\lambda}\left\{I_j(\tau) + 2\sum_{m\neq j}^{N} I_m(\tau)\right\} \quad \text{.........(1)}$$

Where $I_m(\tau)$ is the optical intensity of the m^{th} channel. The first term in the parentheses on the right-hand side of Eq. (1) corresponds to SPM discussed in the previous section, whereas the second term is responsible for CPM. The factor of 2 in Eq. (1) indicates that the effect of CPM from a neighboring channel is two times stronger than that caused by SPM itself.

In continuous-wave signals, CPM would dominate over SPM according to Eq. (1). For pulses at different wavelengths, the effect of CPM depends on the relative temporal locations of those pulses. CPM is strongest when pulses completely overlap one another. Additionally, the probability that all channels transmit bit 1 has to be taken into consideration, similar to the case of SRS. The low probability of all channels simultaneously transmitting bit 1 reduces the effect of CPM on average. Under the presence of dispersion, pulses at different wavelengths travel at different group velocities, which cause pulses to walk off from one another, reduce the effect of CPM. If the dispersion discrepancy among channels is more, the pulses walk off from one another more rapidly. In Other words, the effect of CPM is inversely proportional to dispersion discrepancies among channels in WDM systems. Thus, in order to minimize the impairment caused by CPM, the channel separation and /or local dispersion have to be properly chosen in WDM systems.

DISPERSION

In digital communication, information is transmitted in the form of coded pulses. which become unrecognizable after traveling a long distance. Because of pulse broadening. adjacent pulses get overlapped and hence limit the maximum number of pulses sent per second. This phenomenon of pulse broadening is referred as dispersion,and media that possess this property is called dispersive media .An example of disersion seen in nature is a rainbow, in which the white light is split into different color components. Altermtively, using the prism arrangement, dispersion causes separation of white color into different wavelength components.

There are two different types of dispersion in optical fibers:

1. Intramodal dispersion.
2. Intermodal dispersion.

Intramodal chromatic dispersion occurs in all type of fibers. Intermodal or modal dispersion occurs only in multimode fibers. Each type of dispersion mechanism leads to pulse spreading. The spreading of the optical pulse limits the information-carrying capacity of the fiber.

Intramodal Dispersion or Chromatic Dispersion

Intramodal or chromatic dispersion depends primarily on fiber materials. There are two types of intramodal dispersipn:

1. Material dispersion.
2. Waveguide dispersion.

Light is a type of electromagnetic wave sent through an optical fiber. It is a combination of electric and magnetic fields orthogonal to each other.This wave travels through free space at a constant speed of 3×10^8 mls.When the same electromagnetic wave travels through a medium of refmctive index n. the speed is reduced to

$$c' = \frac{3 \times 10^8}{n}\ m/s$$

The above equation indicates that if the refractive index is higher. that is, if the material is denser, the speed of light in the material is lower than the speed of light in vacuum.

The refractive index of a material is a frequency-dependent parameter, therefore the speed of light in a particular material is a frequency-dependent phenomenon, and is called chromatic dispersion.

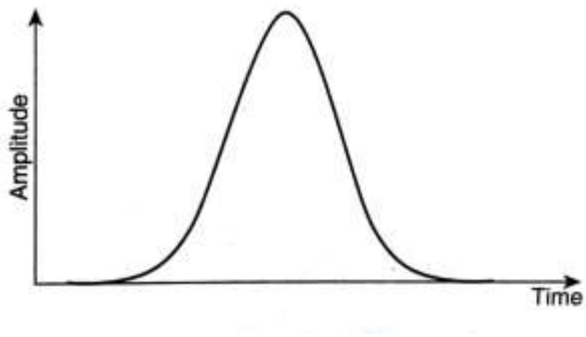


Fig 1.29: A Gaussian Pulse

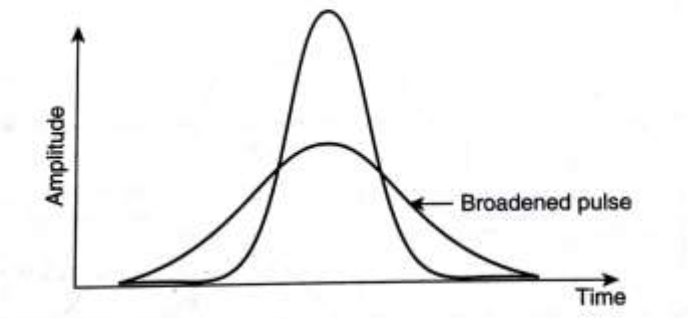


Fig 1.30: Pulse Broadens due to Chromatic dispersion

The optical pulse used in telecommunication applications has a special shape, and is called a Gaussian pulse shown in Fig. 1.29. It contains a single bit of information and consists of thousands of photons. This pulse is very intense because the photons are more concentrated in the center of pulse.

Optical pulses generated by an ideal monochromatic source should contain photons of a single frequency, and all photons will then travel at same speed. But practically such a source is am available. In practical systems an LED or laser source is used, Which is not truly monochromatic. Thus an optical pulse contains photons with different frequencies. So the traveling speed of these photons will be slightly different and this will cause the pulse broadening, as shown in Fig. 1.30. The broadened pulse has reduced peak intensity as compared to transmitted pulse; hence, if the pulses are overlapped, it becomes very difficult to detect. Thus, chromatic dispersion is the main limiting factor for high-data-rate transmission.

This phenomenon can be useful if it is combined with self-phase modulation to obtain optical solutions.

MATERIAL DISPERSION

Material dispersion is caused by refractive-index variation as a function of the optical wavelength. The various spectral components of a given mode will propagate with different speeds depending on the wavelength. Therefore, if the spectral width $\Delta\boldsymbol{\lambda}$ of the source is larger (e.g., when an LED is used), the pulse broadening due to this effect may be significant. Thus, material dispersion depends on the spectral width of the source. All the wavelengths ($\lambda \pm \Delta\boldsymbol{\lambda}$) in the spectral width of the optical source can propagate through the optical fiber with different speeds, causing more dispersion. Material dispersion is an intramodal effect and of particular importance for single-mode and LED systems.

$$D_{Material} = \frac{\lambda}{c}\left|\frac{d^2 n}{d\lambda^2}\right|$$

$D_{Material}$ is zero at λ=1.276 μm for pure silica and hence this wave length is referred as the Zero dispersion wavelength.(λ_{ZD})

WAVEGUIDE DISPERSION

Waveguide dispersion is an intramodal effect. It occurs because a single-mode fiber confines only about 80% of the optical power to the core of the fiber. It occurs within one mode for a single-mode fiber, while in a multimode fiber it occurs in each mode. Every mode in a multimode system will have its own waveguide dispersion. In terms of the modal propagation constant $\boldsymbol{\beta}$ varies as $\boldsymbol{a/\lambda}$. The optical fiber radial dimension (radius a) relative to the light wavelength $\boldsymbol{\lambda}$. is now the important parameter.

$$\tau_{waveguide} = \frac{L}{c}\left[n_2 + n_2\Delta\frac{d(Vb)}{dV}\right]$$

Where $\Delta = \frac{n_1 - n_2}{n_1}$

$$b = \frac{\frac{\beta^2}{k^2} - {n_2}^2}{{n_1}^2 - {n_2}^2}$$; is the normalized propagation constant

$V = ka\sqrt{{n_1}^2 - {n_2}^2}$; Normalized frequency

INTERMODAL DISPERSION

Intermodal or modal dispersion occurs only in multimode fiber. The input light pulse is made up of a number of modes. All these different modes travel through the optical liber with different speeds and in different directions. So the distance travelled by each mode is also different. Thus, the time taken by each mode to cover the same distance is different, as shown in Fig. 1.31. This causes pulse broadening. The pulse broadening effect increases with increase in distance travelled by a light pulse through optical fiber. Modal dispersion is the main source of dispersion in multimode fibers. As single-mode fibers propagate only the fundamental mode, modal dispersion does not exist in single-mode fibers. Therefore, single-mode fibers exhibit the lowest amount of to total dispersion. Single mode fibers also exhibit the highest possible bandwidth, and are therefore preferred for long-haul communication.

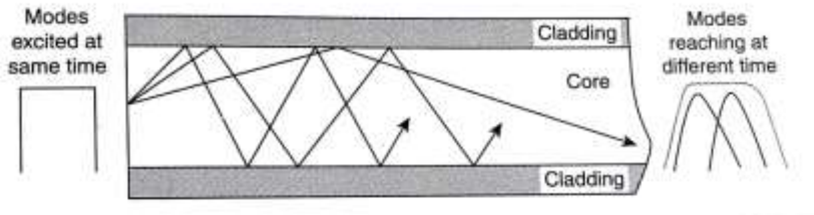
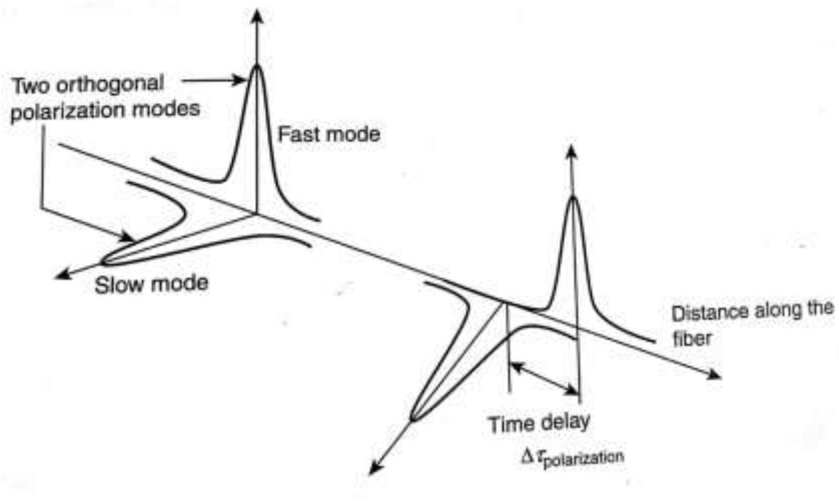


Fig 1.31: Intermodal dispersion

POLARIZATION-MODE DISPERSION

Another source of pulse broadening is the fiber birefringence in the polarization states of an optical signal. Birefringence can result from intrinsic factors such as geometric irregularities of the fiber core or internal stress on it .Other causes of birefringence are bending, twisting or pinching of the fiber



polarization dispersion

Polarization State is a fundamental property of an optical signal. Polarization refers to the electric field orientation of the light signal. If the polarization state varies with distance travelled by light through the fiber, as shown in Fig. 1.32, and the fiber is birefringent, it causes each polarization mode to travel at a slightly different velocity. The resulting difference in propagation times $\Delta\tau_{Polarization}$ between the two orthogonal polarizing modes will result in pulse broadening. This is the polarization mode dispersion (PMD). The arrival time difference between two orthogonal polarizations is given by $\Delta\tau_{Polarization} = \left[\frac{L}{v_{gx}} - \frac{L}{v_{gy}}\right]$

MODULE II
FABRICATION OF FIBRES& OPTICAL SOURCES

2.1 FIBRE MATERIALS

For the fabrication of Optical fiber;

1. Two materials with slightly different refractive index for making of core and cladding are required
2. These materials should be transparent to light in the operating wavelength range of around 800-1,600 nm.
3. The materials should have low attenuation.
4. These materials should have low Intrinsic and scattering losses.
5. The materials must allow the making of long, thin, and flexible fibers.
6. The materials should be cheap and abundant.

Most of these requirements are met by glasses and plastic polymers.

Optical fibers require a high-index core and a low-index cladding, but the refractive index of pure silica is uniform. 50 fiber cannot be fabricated from pure silica. To change the refractive index of silica, dopant should be added. Thus in silica fibers, both core and cladding are made of silica, differentiated by different doping levels. Most dopants, when added, increase the refractive index of silica. So, doped silica can be used as core material. The most common core dopant material is germanium, with pure silica forming the cladding. A few materials like fluorine reduce the refractive index of silica, so they can form the cladding on the pure silica core.

Another material used for optical fiber fabrication is plastic. It is lightweight, inexpensive, flexible, has large NA. and is easy no handle, but has much higher attenuation. The best plastic fiber has a loss of approximately 50 dB/km At shorter wavelengths, the loss is less as compared to the near-infrared region Therefore, these fibers have limited applications. Different dopant materials are added in the fabrication of low-loss, long wavelength optical fibers For example

1. Heavy-metal fluorides (e.g., zirconium and beryllium fluoride)
2. Chalcogenide glasses (e.g., arsenic/sulfur).
3. Crystalline materials (e.g., silver bromide and silver chloride).

2.1.1.GLASS FIBERS

Optical fibers are made up of oxide glasses. The most common of which is silica ($Si0_2$) Glass composed of pure silica is referred to as silica glass, fused silica, or vitreous silica. The glass is made by fusing mixtures of metal oxides, sulfides, or selenides.

Some of its desirable properties are as follows:

1. A resistance to deformation at high temperatures.
2. A high resistance to breakage from thermal shock because of its low thermal expansion
3. Good chemical durability.
4. A high transparency in both the visible and infrared regions of 1nterest to many fiber-optic systems.

   In order to produce two similar materials having slightly different indices of refraction for the core and the cladding, fluorine or various oxides are commonly added to the silica (see Table 2.1).

Core	Cladding
SiO_2	B_2O_3-SiO_2
GeO_2-SiO_2	SiO_2
P_2O_5-SiO_2	SiO_2

Table 2.1: Various dopants used to make core & cladding of various fibers

These dopants can be classified into two basic groups: dopants Which increase the refractive index and dopants Which decrease the refractive index. For example, B_2O_3 and fluorine dopants decrease a materials refractive index, whereas GeO_2 and P_2O_5 will increase a material's refractive index

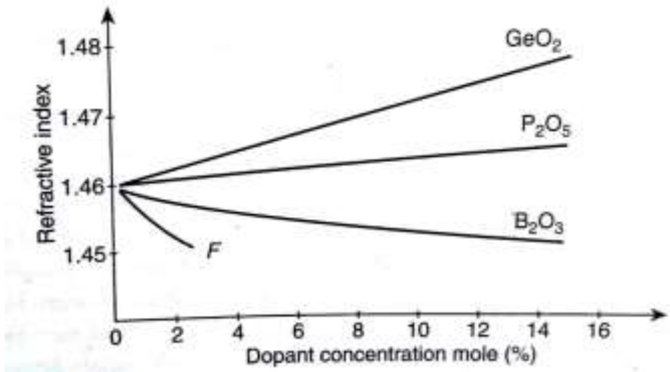


Figure 2.1: Refractive index as a function of dopant materials and their concentration.

2.1.2 HALIDE GLASS FIBERS

The absorption of silica rises rapidly at longer wavelengths. The materials that are transparent in this range are zirconium fluoride (ZrF4) and barium fluoride (BaF_2) with some other components added to form the glass compound. It has been found that fluoride glasses have extremely low transmission losses at wavelengths in the range of 0.2-8 pm. Fluoride glasses belong to a general family of halide glasses in which the anions are from elements in Group VII of the periodic table, namely fluorine, chlorine, bromine, and iodine. These fibers are used in erbium doped fiber amplifiers because of their desirable optical characteristics.

2.1.3 CHALCOGENIDE GLASS FIBERS

Chalcogenide glass has high optical non-linearity, and so it is used in applications such as all-optical switches and fiber lasers. Chalcogenide glass fibers contain arsenic, germanium, phosphorus, sulfur, selenium, or tellurium. Theoretically, the minimum attenuation for these materials has been estimated at l dB/m.

2.1.4 ACTIVE GLASS FIBERS

When the rare-earth elements are incorporated into a normally passive glass, it results in the material having new optical and magnetic properties. These new properties allow the material to perform amplification, attenuation, and phase retardation on the light passing through it. Two commonly used materials for fiber lasers are erbium and neodymium.

2.1.5 PLASTIC OPTICAL FIBERS

Plastic fibers are generally used for short haul (up to 100 m) applications because they give rise to high attenuation of the optical signal. However, their mechanical strength is high. Plastic fibers are lighter and lower in cost than glass. Their operating temperature can go up to 125°C. For example, plastics can be used in medical applications and in some sensors where only shorter fiber lengths are needed. In addition, the mechanical flexibility of plastic allows these fibers to have large cores. These factors permit its use in inexpensive, economically attractive systems. The following are examples of some of the compounds used in plastic fibers:

1. A polysterene core/methyl methacrylate cladding.
2. A polymethyl methacrylate core/copolymer cladding.

2.2 FABRICATION OF OPTICAL FIBERS

The methods of preparing the extremely pure optical glasses generally fall into two major categories which are:

(a) Conventional glass refining techniques in which the glass is processed in the molten state (melting methods) producing a multicomponent glass structure;

(b) Vapour-phase deposition methods producing silica-rich glasses which have melting temperatures that are too high to allow the conventional melt process.

2.2.1 LIQUID-PHASE (MELTING) TECHNIQUES

The first stage in this process is the preparation of ultrapure material powders which are usually oxides or carbonates of the required constituents. These include oxides such as SiO_2, $Be0_2$, B_20_2 and A_20_3, and carbonates such as Na_2CO, K_2CO_3, $CaCO_3$, and $BaCO_3$, which will decompose into oxides during the glass melting. Very high initial purity is essential and purification accounts for a large proportion of the material cost.. The purification may therefore involve combined techniques of fine filtration and coprecipitation. followed by solvent extraction before recrystallization and final drying in a vacuum to remove any residual OH ions .

The next stage is to melt these high purity, powdered. low-melting point glass materials to form a homogeneous, bubble-free multicomponent glass. A refractive Index variation may be achieved by either a change in the composition of the various constituents or by ion exchange when the materials are in the molten phase. The melting of these multicomponent glass systems occurs at relatively low temperatures between 900 and 1300 °C. and may take place in a silica crucible. However, contamination can arise during melting from several sources including the furnace environment and the crucible.

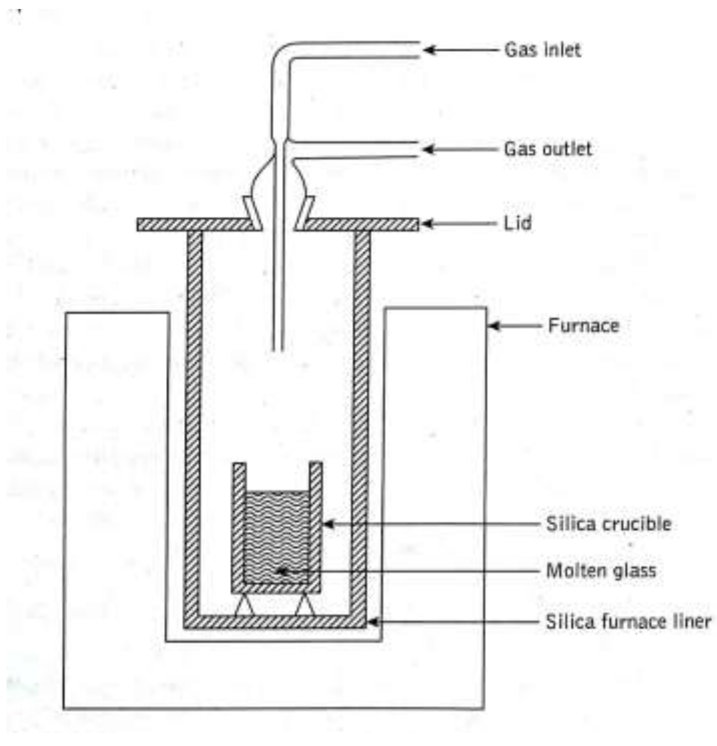


Fig 2.2 Glass making Furnace for production of High purity silica glasses

Silica crucibles can give dissolution into the melt which may introduce inhomogeneities into the glass, especially at high melting temperatures. A technique for avoiding this involves melting the glass directly into a radio-frequency (RF approximately 5 MHz) induction furnace while cooling the silica by gas or water now, as shown in Figure 2.3 .The materials are preheated to around 1000°C where they exhibit sufficient ionic conductivity to enable coupling between the melt and the RF held. The melt is also protected from any impurities in the crucible by a thin layer of solidified pure glass which forms due to the temperature difference between the melt and the cooled silica crucible.

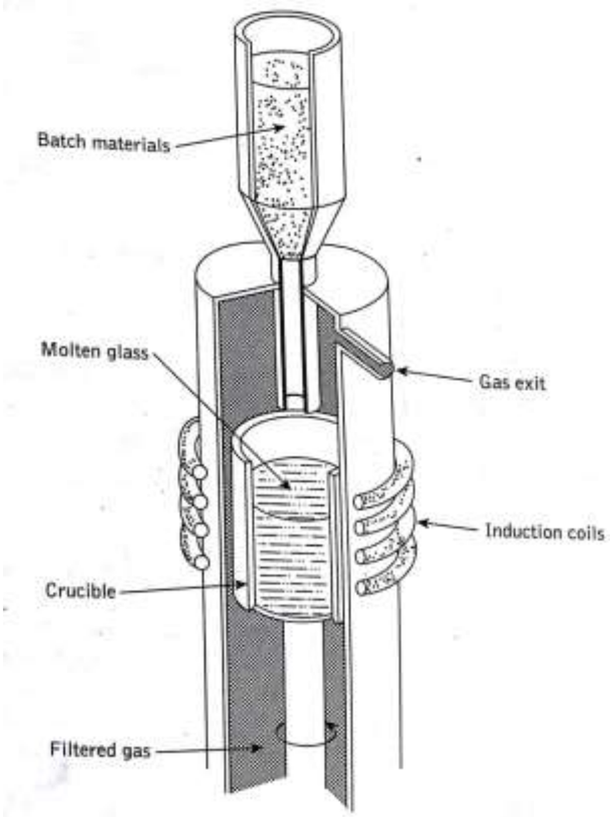


Fig 2.3 : High purity melting using RF induction furnace.

In both techniques the glass is homogenized and dried by bubbling pure gases through the melt, while protecting against any airborne dust particles either originating in the melt furnace or present as atmospheric contamination. After the melt has been suitably processed, it is cooled and formed into long rods (cane) of multicomponent glass.

FIBER DRAWING

An original technique for producing fine optical fiber waveguides was to make a preform using, the rod in tube process. A rod of core glass was inserted into a tube of cladding glass and the preform was drawn in a vertical muffle furnace. This technique was useful for the production of step index fibers with large core and cladding diameters where the achievement of low attenuation was not critical as there was a danger of including bubbles and particulate matter at the core-cladding interface.

Indeed, these minute perturbations and impurities can result in very high losses of between 500 and 1000 dB km‘l after the fiber is drawn .

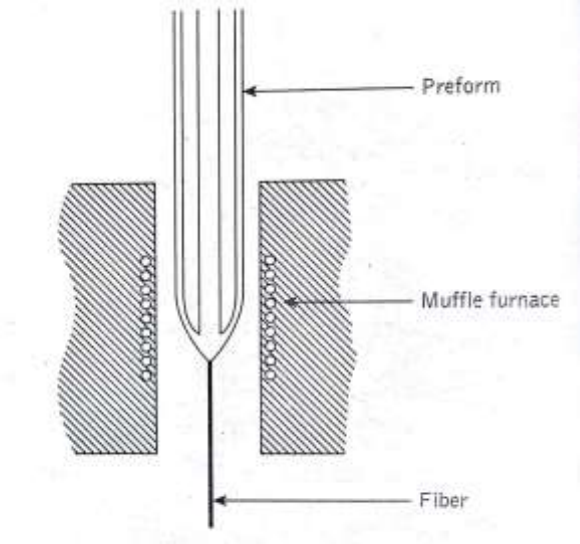


Fig: Optical fiber from a preform

Subsequent development in the drawing of optical fibers (especially graded index) produced by liquid-phase techniques has concentrated on the double-crucible method. In this method the core and cladding glass in the form of separate rods is fed into two concentric platinum crucibles, as illustrated in Figure.

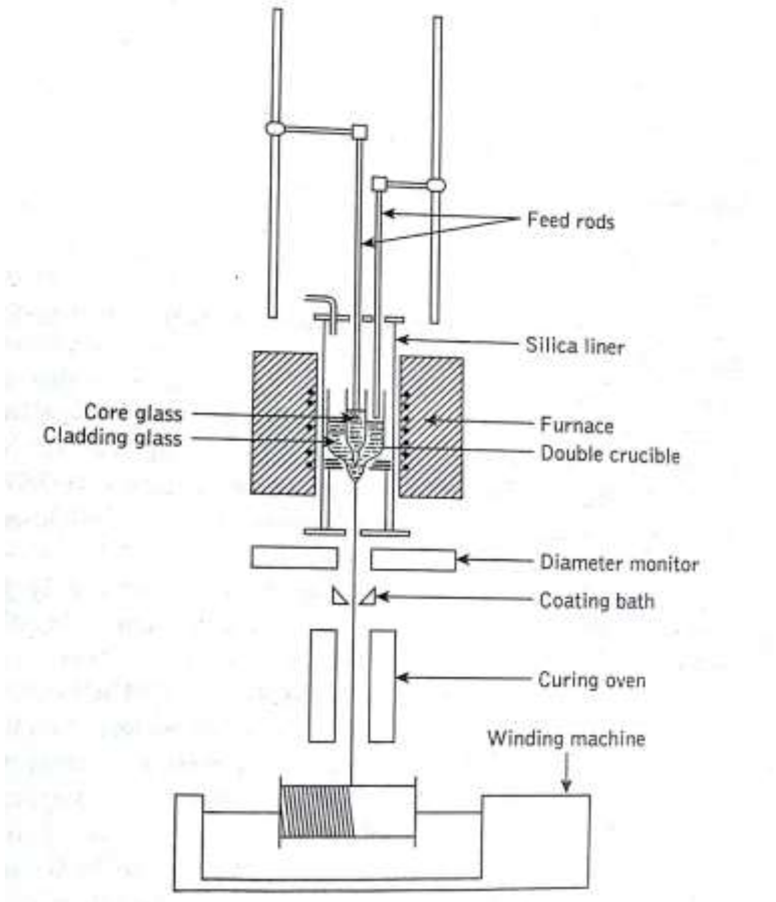


Fig: The double crucible method for fiber drawing

The assembly is usually located in a muffle furnace capable of heating the crucible contents to a temperature of between 800 and 1200°C. The crucibles have nozzles in their bases from which the clad fiber is drawn directly from the melt, as shown in Figure. Index grading may be achieved through the diffusion of mobile ions across the core-cladding interface within the molten glass. It is possible to achieve a reasonable refractive index profile via this diffusion process, although due to lack of precise control it is not possible to obtain the optimum near-parabolic profile which yields the minimum pulse dispersion .Hence graded index fibers produced by this technique are subsequently less dispersive than step index fibers, but do not have the bandwidth-length products of optimum profile fibers.

2.2.2 VAPOR-PHASE DEPOSITION TECHNIQUES

Vapour-phase deposition techniques are used to produce silica-rich glasses of the highest transparency and with the optimal optical properties. The starting materials are volatile compounds such as $SiCl_4$, $GeCl_4$, SiF_4. BCl_3, 0_2, BBr_3, and $POCl_3$, which may be distilled to reduce the concentration of most transition metal impurities to below one part in 10^9. giving negligible absorption losses from these elements. Refractive index modification achieved through the formation of dopants from the nonsilica starting materials. These vapour phase dopants include TiO_2, GeO_2,P_2O_5,Al_2O_3,B_2O_3,and F.

Gaseous mixtures of the silica-containing compound, the doping material and oxygen are combined in a vapour phase oxidation reaction where the deposition of oxides occurs. The deposition is usually onto a substrate or within a hollow tube and is built up as a stack of successive layers Hence the dopant concentration may be varied gradually to produce a graded Index profile or maintained to give a step index profile. In the case of the substrate that directly results in a solid rod or preform whereas the hollow tube must be collapsed to give a solid preform from which the fiber may be drawn.

- **OUTSIDE VAPOR-PHASE OXIDATION PROCESS**

This process which uses flame hydrolysis stems. The best known technique of this type is often referred to as the outside vapour-phase oxidation (OVPO) or the outside vapour-phase deposition (OVD) process. In this process the required glass composition is deposited laterally from a 'soot' generated by hydrolyzing the halide vapors in an oxygen-hydrogen flame. Oxygen is passed through the appropriate silicon compound (i.e. $SiCl_4$) which is vaporized, removing any impurities. Dopants such as $GeCl_4$ or $TiCl_4$ are added and the mixture is blown through oxygen-hydrogen flame .

$$SiCl_4+2H_2O \rightarrow SiO_2+ 4HCl$$

$$SiCl_4 + O_2 \rightarrow SiO_2+2Cl_2$$

$$GeCl_4+O_2 \rightarrow GeO_2+2Cl_2$$

$$TiCl_4+ O_2 \rightarrow TiO_2+2Cl_2$$

The silica is generated as a fine soot which is deposited on a cool rotating mandrel. The flame of the burner is reversed back and forth over the length of the mandrel until a sufficient number of layers of silica (approximately 200) are deposited on it. When this process is completed the mandrel is removed and the porous mass of silica soot is sintered (to form a glass body).

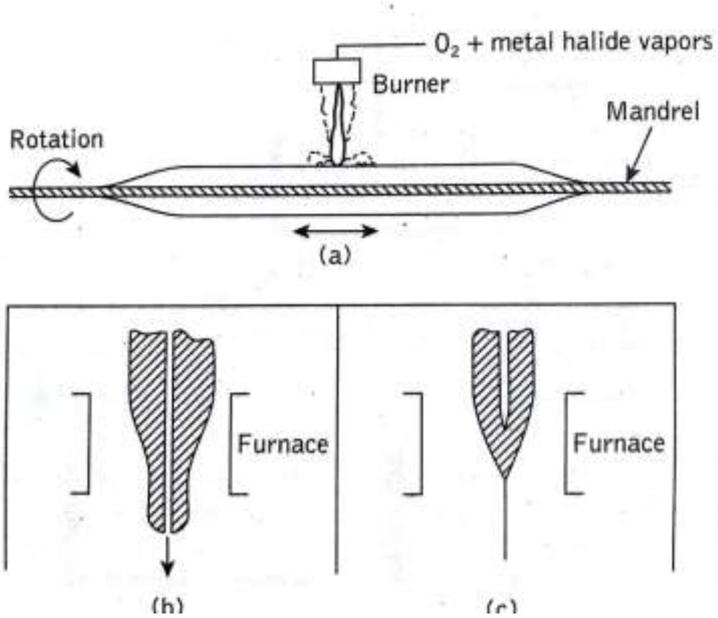


Fig: (a).Soot deposition (b) Preform sintering (C) Fiber drawing

VAPOUR AXIAL DEPOSITION

VAD uses an end-on deposition onto a rotating fused silica target. The vaporized constituents are injected from burners and react to form silica soot by flame hydrolysis. This is deposited on the end of the starting target in the axial direction forming a solid porous glass preform in the shape of a boule. The preform which is growing in the axial direction is pulled upwards at a rate which corresponds to the growth rate. It is initially dehydrated by heating with $SOCl_2$ using the reaction:

$H_2O + SOCl_2 \rightarrow 2HCl + SO_2$

and is then sintered into a solid preform in a graphite resistance furnace at an elevated temperature of around 1500 °C. Therefore, in principle this process may be adapted to draw fiber continuously, although at present it tends to be operated as a batch process partly because the resultant preforms can yield more than 100 km of fiber .

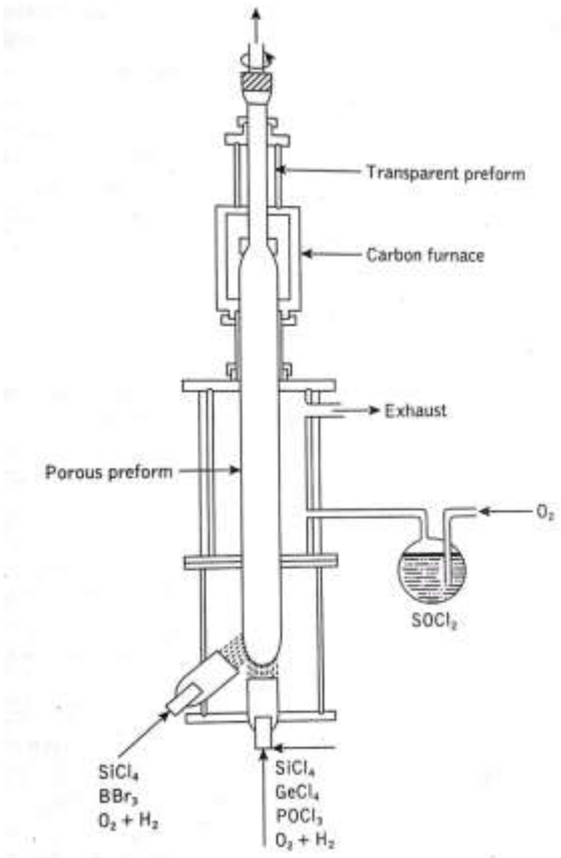


Fig: VAD Process

MODIFIED CHEMICAL VAPOR DEPOSITION

The MCVD process is also an inside vapor-phase oxidation (IVPO) technique taking place inside a silica tube, as shown in Figure. However, the vapor-phase reactants (halide and oxygen) pass through a hot zone so that a substantial part of the reaction is homogeneous (i.e. involves only one phase; in this case the vapor phase). Glass particles formed during this reaction travel with the gas flow and are deposited on the walls of the silica tube. The tube may form the cladding material but usually it is merely a supporting structure which is heated on the outside by an oxygen-hydrogen flame to temperatures between 1400 and 1600 °C. Thus a hot zone is created which encourages high-temperature oxidation reactions. These reactions reduce the OH impurity concentration to levels below those found in fibers prepared by hydride oxidation or flame hydrolysis.

The hot zone is moved back and forth along the tube allowing the particles to be deposited on a layer-by-layer basis giving a sintered transparent silica film on the walls of the tube. The film may be up to 10 pm in thickness and uniformity is maintained by rotating the tube. A graded refractive index profile can be created by changing the composition of the layers as the glass is deposited. Usually, when sufficient thickness has been formed by successive traverses of the burner for the cladding, vaporized chlorides of germanium ($GeCl_4$) or phosphorus ($POCl_3$) are added to the gas flow. The core glass is then formed by the deposition of successive layers of germanosilicate or phosphosilicate glass. The cladding layer is important as it acts as a barrier which suppresses OH absorption losses due to the diffusion of OH ions from the silica tube into the core glass as it is deposited. After the deposition is completed the temperature is increased to between 1700 and 1900 °Cr The tube is then collapsed to give a solid preform which may then be drawn into fiber at temperatures of 2000 to 2200 °C.

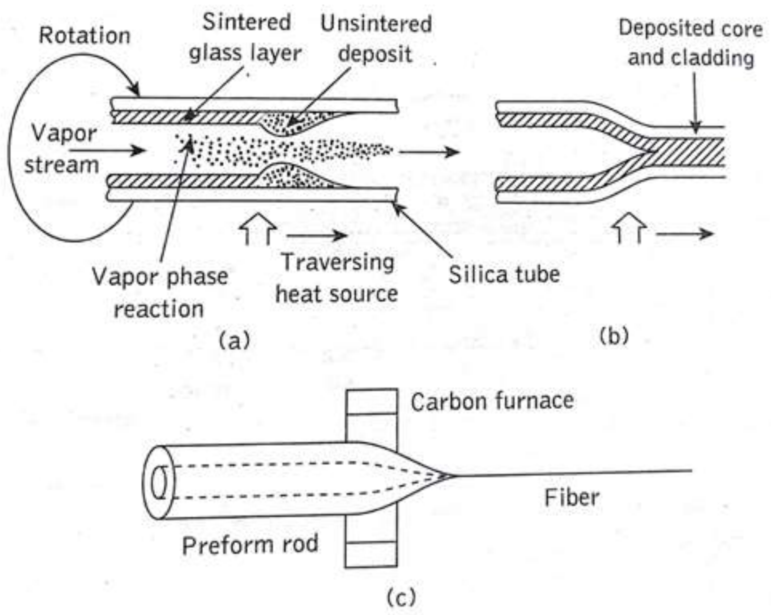


Fig: (a) deposition (b) collapse to produce preform (c) fiber drawing.

This technique is the most widely used at present as it allows the fabrication of fiber with the lowest losses. Apart from the reduced OH impurity contamination the MCVD process has the advantage that deposition occurs within an enclosed reactor which ensures a very clean environment. Hence, gaseous and particulate impurities may be avoided durin g both the layer deposition and the preform collapse phases. The process also allows the use of a variety of materials and glass compositions.

PLASMA-ACTIVATED CHEMICAL VAPOR DEPOSITION (PCVD)

This method, involves plasma-induced chemical vapor deposition inside a silica tube, as shown in Figure. The essential difference between this technique and the MCVD process is the stimulation of oxide formation by means of a non-isothermal plasma maintained at low pressure in a microwave cavity (2.45 GHz) which surrounds the tube. Volatile reactants are introduced into the tube where they react heterogeneously within the microwave cavity, and no particulate matter is formed in the vapor phase.

The reaction zone is moved backwards and forwards along the tube by control of the microwave cavity and a circularly symmetric layer growth is formed. Rotation of the tube is unnecessary and the deposition is virtually 100% efficient. Film deposition can occur'at temperatures as low as 500 °C but a high chlorine content may cause expansivity and cracking of the film. Hence the tube is heated to around 1000 °C during deposition using a stationary furnace.

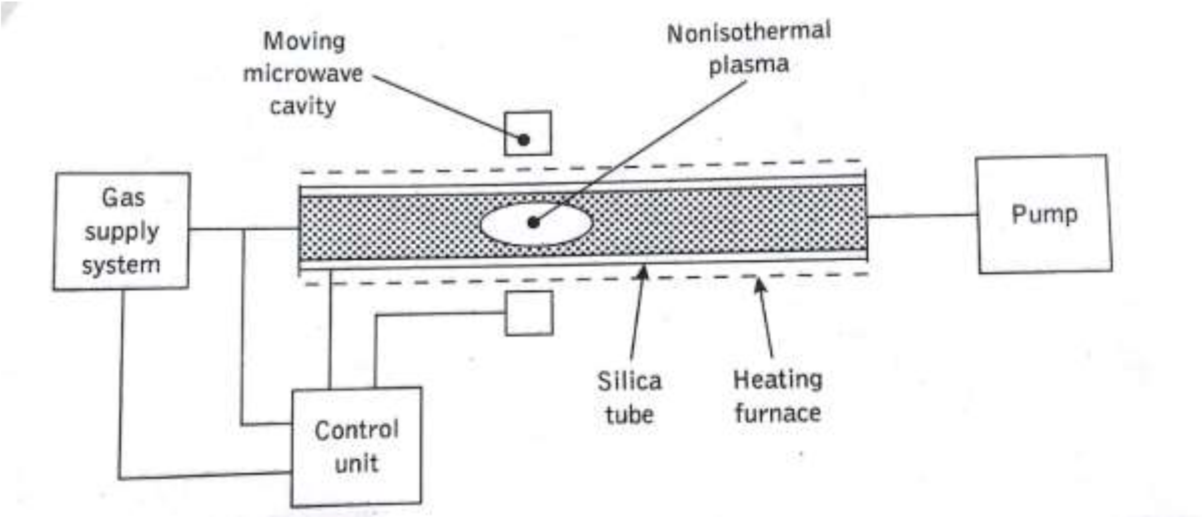
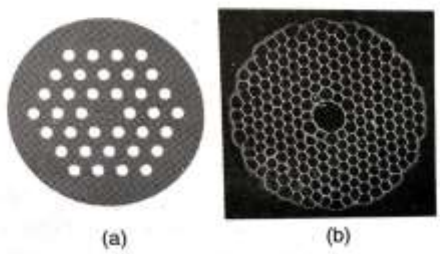


Fig: The apparatus used in PCVD Process

The high deposition efficiency allows the composition of the layers to be accurately varied by control of the vapor-phase reactants. Also, when the plasma zone is moved rapidly backwards and forwards along the tube, very thin layer deposition may be achieved, giving the formation of up to 2000 individual layers. This enables very good graded index profiles to be realized .which are a close approximation to the optimum near-parabolic profile. Finally, the PCVD method also lends itself to large-scale production of Optical fibers with preform sizes that would allow the preparation of over 200 km of fiber.

2.3 PHOTONIC CRYSTAL FIBRE

A photonic crystal fiber (PCF) is made up of a periodic structure of capillaries filled with air and arranged in a hexagonal lattice as shown in Fig.



Photonic crystal fibers: (a) Solid core structure and (b) hollow core structure.

It has been shown that light can propagate in crystal Structure defects. By removing one or more capillaries, the defect is created. PCF combines the properties of optical fibers and photonic crystals. The traditional fiber is proved as the best choice for many telecom and non-telecom applications. However, there are many constraints in the design of their structures (e.g., limited core diameter for single-mode fiber, limited choice for fiber material, mode cut-off wavelength, etc.). But, in the case of PCF we have high flexibility in the design. We can vary the parameters, such as type of lattice, lattice pitch, refractive index of glass, number of air holes, their shape and diameter, etc. By varying these parameters we can design a single-mode fiber, which can be operated in all wavelength ranges, where there is no cutoff wavelength.

By varying the structure, the desired dispersion characteristics can be obtained. It is possible to design a PCP with zero, low, or anomalous dispersion in the visible wavelength range. There are two guiding mechanisms in a PCF:

1. Index guiding (such as in a traditional optical fiber).

2. Photonic bandgap mechanism.

2.3.1 INDEX-GUIDED PCF

Although the principles of guidance and the characteristics of index-guided PCFs are similar to those of conventional fiber, there is greater index contrast since the cladding contains air holes with a refractive index of 1 in comparison with the normal silica cladding index of 1.457 which is close to the germanium-doped core index of 1.462. A fundamental physical difference, however, between index-guided PCFs and conventional fibers arises from the manner in which the guided mode interacts with the cladding region. Whereas in a conventional fiber this interaction is largely first order and independent of wavelength, the large index contrast combined with the small structure dimensions cause the effective cladding index to be a strong function of Wavelength. For short wavelengths the effective cladding index is only slightly lower than the core index and hence they remain tightly confined to the core. At longer wavelengths, however, the mode samples more of the cladding and the effective index contrast is larger. This wavelength dependence results in a large number of unusual optical properties which can be tailored. For example, the high index contrast enables the PCF core to be reduced from around 8 um in conventional fiber to less than 1 pm, which increases the intensity of the light in the core and enhances the nonlinear effects.

Fig: Two index guided photonic crystal fibers .The dark areas are air holes and white areas are silica.

Two common index-guided PCF designs are shown diagrammatically in Figure. In both cases a solid-core region is surrounded by a cladding region containing air holes. The cladding region in Figure (a) comprises a hexagonal array of air holes while in Figure (b) the cladding air holes are not uniform in size and do not extend too far from the core. It should be noted that the hole diameter ***d*** and hole to hole spacing or pitch **Λ** are critical design parameters used to specify the structure of the PCF. For example, in a silica PCF with the structure depicted in Figure (a) when the air fill fraction is low (i.e. d/ **Λ** < 0.4), then the fiber can be single-moded at all wavelengths This property, which cannot be attained in conventional fibers, is particularly significant for broadband applications such as wavelength division multiplexed transmission .

As PCFs have a wider range of optical properties in comparison with standard optical fibers, they provide for the possibility of new and technologically important fiber devices. When the holey region covers more than 20% of the fiber cross-section, for instance, index-guided PCFs display an interesting range of dispersive properties which could find application as dispersion-compensating or dispersion-controlling fiber components .In such fibers it is possible to produce very high optical nonlinearity per unit length in which modest light intensities can induce substantial nonlinear effects. For example, while several kilometers of conventional fiber are normally required to achieve 2R data regeneration .;it was obtained with just 3.3 m of large air-filling fraction PCF .In addition, filling the cladding holes with polymers or liquid crystals allows external fields to be used to dynamically vary the fiber properties. The temperature sensitivity of a polymer within the cladding holes may be employed to tune a Bragg grating written into the core [Ref. 83]. By contrast, index-guided PCFs with small holes and large hole spacings provide very large mode area (and hence low optical nonlinearities) and have potential applications in high-power delivery (e.g. laser welding and machining) as well as high-power fiber lasers and amplifiers . Furthermore, the large index contrast between silica and air enables production of such PCFs with large multi-moded cores which also have very high numerical aperture values (greater than 0.7). Hence these fibers are useful for the collection and transmission of high optical powers in situations where signal distortion is not an issue. Finally, it is apparent that PCFs can be readily spliced to conventional fibers, thus enabling their integration with existing components and subsystems.

2.3.2 PHOTONIC BANDGAP FIBERS

Photonic bandgap (PBG) fibers are a class of micro structured fiber in which a periodic arrangement of air holes is required to ensure guidance. This periodic arrangement of cladding air holes provides for the formation of a photonic bandgap in the transverse plane of the fiber. As a PBG fiber exhibits a two-dimensional bandgap, then wavelengths within this bandgap cannot propagate perpendicular to the fiber axis (ie. in the cladding) and they can therefore be confined to propagate within a region in which the refractive index is lower than the surrounding material. Hence utilizing the photonic bandgap effect light can ,for example. be guided within slow-index, air-filled core region creating fiber properties quite different from those obtained without the bandgap. Although. as with index-guided PCFs. PBG fibers can also guide light in regions with higher refractive index, it is the lower index region guidance feature which is of particular interest. In addition. a further distinctive feature is that while index-guiding fibers usually have a guided mode at all wavelengths;PBG fiber only guide in certain wavelength bands, and furthermore it is possible to have wavelengths at which higher order modes are guided while the fundamental mode is not.

Two important PBG fiber structures are displayed in Figure. The honeycomb fiber design shown in Figure (a). A triangular array of air holes of sufficient size as displayed in Figure (b). however. provides for the possibility. unique to PBG fibers, of guiding electromagnetic modes in air. In this case a large hollow cone has been defined by removing the silica around seven air holes in the center of the structure. These fibers. which are termed air-guiding or hollow-core PBG fibers, enable more than 98% of the guided mode held energy to propagate in the air regions . The fabrication of hollow-core fiber with low propagation losses, however, has proved to be quite difficult. with losses of the order of 13 dB km^{-1} .

2.4 FIBRE CABLES

{Assignment}

2.4 OPTICAL SOURCES

2.4.1 LIGHT EMITTING DIODES(LED)

A light-emitting diode (LED) is essentially a pn junction diode. When carriers are injected across a forward-biased junction, it emits incoherent light. Most of the commercial LEDs are realized using a highly doped n and a p junction. To understand the principle, let us consider an unbiased pn+ junction (Fig. (a) shows the pn+ energy band diagram). The depletion region extends mainly into the p-side. There is a potential barrier from E_C on the n-side to Ec on the p-side, called the ***built-in voltage***, V_0. This potential barrier prevents the excess free electrons on the n+ side from diffusing into the p-side.

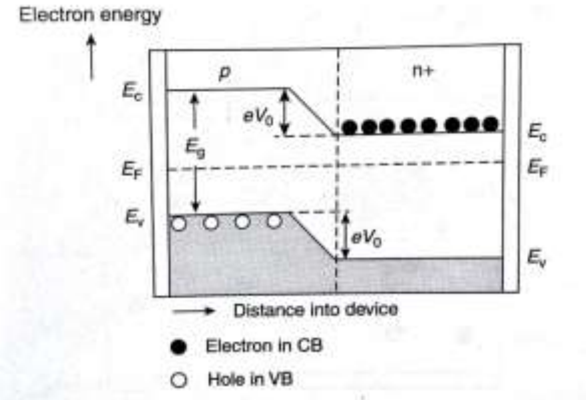
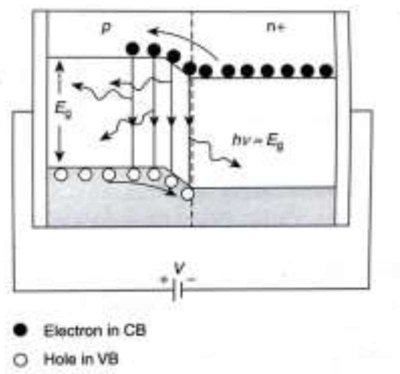


Fig: (a) pn+ energy band diagram Unbiased



Fig(b): pn+ under biased condition

When a voltage V is applied across the junction as shown in Fig. (b), the built-in potential is reduced from Vo to (V_0- V). This allows the electrons from the n+ side to get injected into the p-side. Since electrons are the minority carriers in the p-side, this process is called ***minority carrier injection***. However, the hole injection from the p-side to n+ side is very less and so the current is primarily due to the flow of electrons into the p-side.

The recombination of the holes and minority carriers injected in the p-side results in spontaneous emission of a light photon of energy ***Eg = hv*** as shown in Fig. (c). This spontaneous emission process is called as ***injection electroluminescence***, because the optical emission takes place due to injection of electrons.

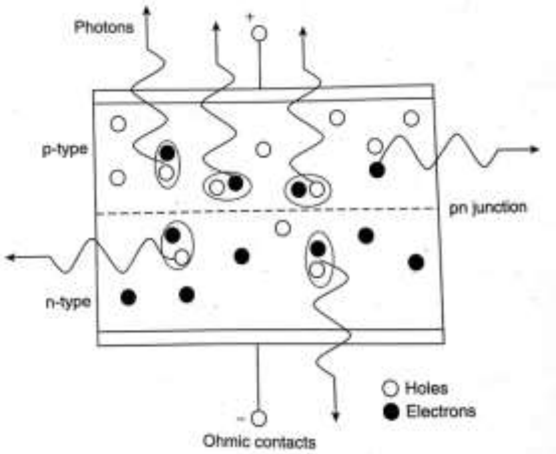


Fig (C) : Carrier recombination results in spontaneous emission

The reabsorption of emitted photons is avoided by properly designing the LED structure. The wavelength of the light emitted, and hence the color, depends on the band gap energy of the materials forming the pn junction.

The emitted photon energy is approximately equal to the bandgap energy of the semiconductor. The following equation relates the wavelength and the bandgap energy:

$$h\upsilon = E_g$$

$$h\frac{c}{\lambda} = E_g$$

$$\lambda = h\frac{c}{E_g}$$

where h is Planck's constant, c is the speed of the light, and Eg is the bandgap energy. Substituting the values of h and c gives

$$\lambda = \frac{1.24}{E_g}$$

Where λ is written in µm and Eg in eV .Thus, a semiconductor with a 2 eV bandgap emits light at about 620 nm in the red. A 3 eV bandgap material would emit at 414 nm in the violet.

DIRECT AND INDIRECT RECOMBINATION

The recombination can be classified into the following two kinds:

1. Direct recombination.

2. Indirect recombination.

Direct Recombination

In direct bandgap materials, the minimum energy of the conduction band lies directly above the maximum energy of the valence band in momentum space energy. Figure shows the electron energy (E)-momentum (k) plot of a direct bandgap material. In this material, free electrons at the bottom of the conduction band can recombine directly with free holes at the top of the valence band, as the momentum of the two particles is the same. This direct transition of electron from the conduction band to the valence band provides an efficient mechanism for photon emission and the average time the minority carrier remains in a free state before recombination, that is, the minority carrier lifetime is short (10^{-8} to 10^{-10} s). This is known as ***direct recombination***. Direct recombination occurs spontaneously

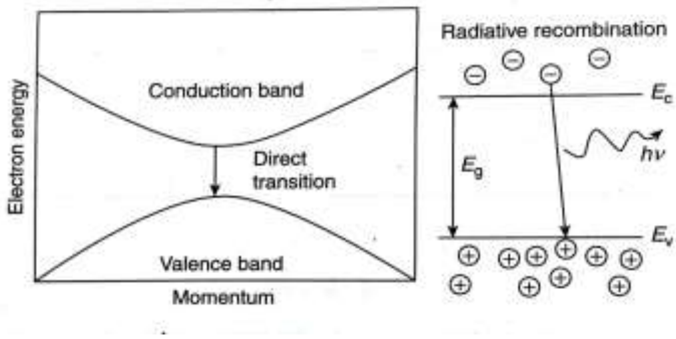


Fig: Direct Bang gap & Direct recombination

Indirect Recombination

In the indirect bandgap materials, the minimum energy in the conduction band is shifted by a k-vector relative to the valence band. The k-vector difference represents a difference in momentum. Due to this difference in momentum, the probability of direct electron-hole recombination is less and relatively slow (10^{-2} to 10^{-4}).

For electron-hole recombination to take place, it is essential that the electron loses momentum such that it has a momentum value corresponding to the maximum energy of the valence band. In these materials, additional dopants (impurities) are added which form very shallow donor states. These donor states capture the free electrons locally, providing the necessary momentum shift for recombination. These donor states serve as the recombination centers. This is called ***indirect (non-radiative) recombination***.

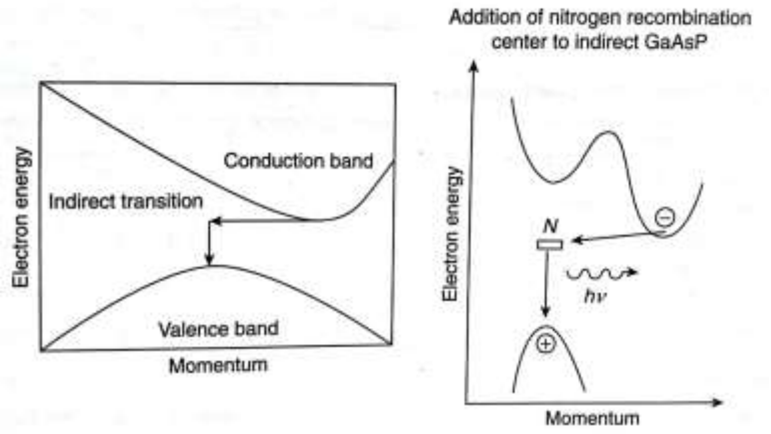


Fig:indirect Bang gap & non-radiative recombination

QUANTUM EFFICIENCY OF LED

The internal quantum efficiency of LED is the ratio of photons generated to injected electrons. The internal quantum efficiency of simple homojunction LED is only about 50% due to absence of stimulated emission. It totally relies on spontaneous emission, Which allows non-radiative recombination within the structure due to crystalline imperfections and impurities. This reduces the efhciency greatly. With double heterojunction structure, internal efficiencies of about 60%-80% can be obtained.

The internal Quantum efficiency (η_{int}) of LED is the ratio of the radiative recombination rate to the total recombination rate.

$$\eta_{int} = \frac{r_r}{r_t} = \frac{r_r}{r_r + r_{nr}}$$

$$\eta_{int} = \frac{R_r}{R_t}$$

For exponential decay of excess carriers, the radiative recombination lifetime is

$$\tau_r = \frac{\Delta_n}{r_r}$$

The non-radiative recombination lifetime is

$$\tau_{nr} = \frac{\Delta_n}{r_{nr}}$$

The total recombination lifetime is

$$\tau = \frac{\Delta_n}{r_t}$$

Therefore

$$\frac{1}{\tau} = \frac{1}{\tau_r} + \frac{1}{\tau_{nr}}$$

And Internal Quantum efficiency is

$$\eta_{int} = \frac{1}{1 + \frac{r_{nr}}{r_r}} = \frac{1}{1 + \frac{\tau_r}{\tau_{nr}}}$$

$$\eta_{int} = \frac{\tau}{\tau_r}$$

THE EXTERNAL QUANTUM EFFICIENCY

The external quantum efficiency of LED is defined as the ratio of photons emitted from the LED to the number of internally generated photons. To find the external quantum efficiency, we need to consider the radiation geometry for an LED and reflection effects at the surface of LED. Most of the light generated within the device is trapped by total internal reflection as indicated in figure, when it is radiated at an angle greater than critical angle for crystal-air interface. Only light falling within a cone defined by the critical angle will be emitted from an optical source.

The cone defined by critical angle is

$$\Phi_c = \frac{\pi}{2} - \theta_c$$

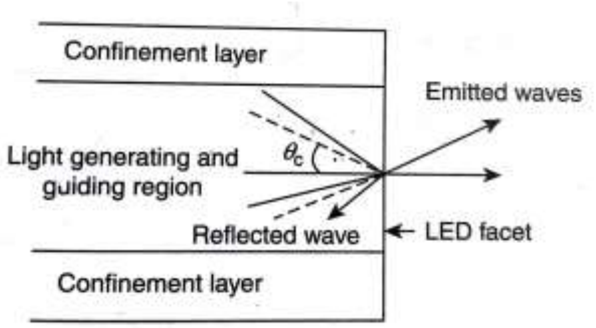


Fig: Light emitted by LED

$$\eta_{ext} \approx \frac{1}{n(n+1)^2}$$

DOUBLE HETEROJUNETION LED

The LED realized using two differently doped semiconductors that are of the same material is called a homo-junction. When the LEDs are realized using different bandgap materials, they are called a hetero-structure device. A hetero-structure LED is brighter than a homo-junction LED.

Heterojunctions are classified as an isotype (n-n or p-p) or an anisotype (p-n). This sandwich structure confines the carriers and the optical field in the central active layer. It effectively reduces the carrier diffusion length and hence the arm of region where radiative recombination may take place. A heterojunction is formed between two semiconductors which have different band gaps but same lattice parameters so that they can be grown together as a single crystal. For example, a heterojunction may be formed between GaAs and its ternary alloy $Ga_{1-x}Al_xAs$. The narrow bandgap material such as n or p type GaAs is sandwiched between layers of wider bandgap materials such as p or n-type GaAlAs to form a double heterostructure (DH).

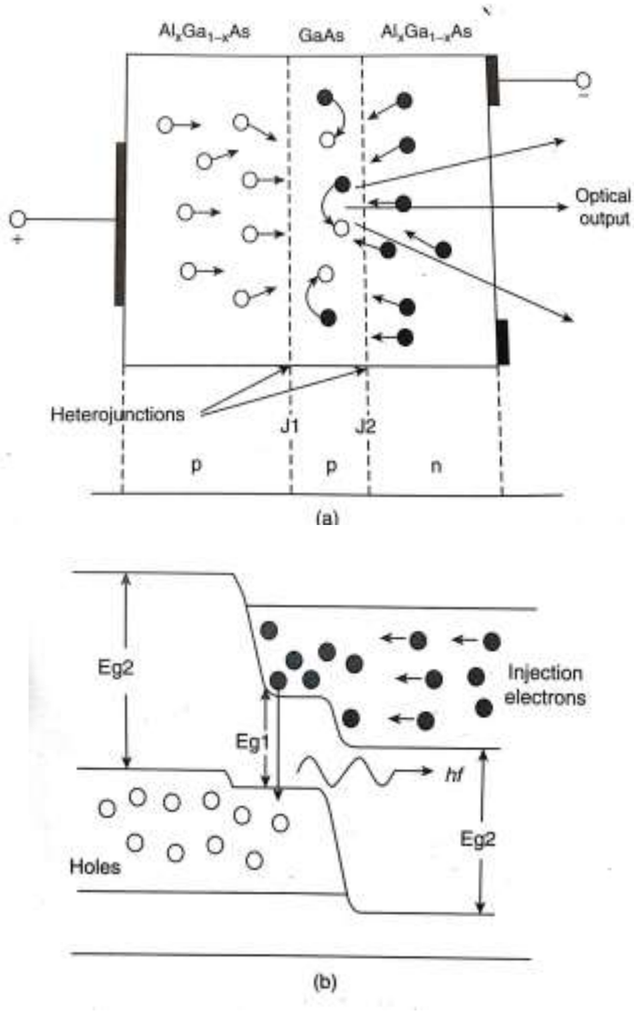


Fig: (a) DH layer structure (b) Energy band diagram

When the DH-LED is forward-biased, the holes from p-GaAlAs are injected into n-GaAs, but are prevented from going into n-GaAlAs by a potential barrier at J2. Similarly, the electrons from n-GaAlAs are injected into n-GaAs but prevented from going further by potential barrier at junction J1. Thus, a large number of carriers are confined in the central layer of n-GaAs, where they recombine to produce optical radiation of wavelength corresponding to the bandgap of n-GaAs. As most of the activity takes place in the central layer, it is called an active layer. This structure gives more radiative recombinations, hence a brighter LED. The radiations generated by band to band transitions in the active layer cannot excite the carriers in the adjoining layers because E_{g1} is less than E_{g2} . Thus, the confining layers of wider bandgap material are transparent to this radiation. The radiation may be collected through the surface or edge.

The limitation of GaAs/ $Ga_{1-x}Al_xAs$ based LED is that the range of wavelengths (800-900 nm) emitted is outside the wavelength limits of lowest attenuation and zero total dispersion of optical fibers. Therefore, such emitters cannot be used in long-haul communication systems.

LED STRUCTURE

The major types of LED structures are as follows:

1. Planar LED.
2. Dome LED.
3. Surface-emitting LED.
4. Edge-emitting LED.
5. Super luminescent LED.
6. Polymer LED.

Planar LED

The geometry and internal structure of LED play an important role in emitting light from its surface. Simple planar LEDs emit light in all directions., as shown in Fig. (a) and most of the emissions come from their surfaces. The light is emitted in a broad cone, with intensity falling off roughly with the cosine of the angle from the normal to the semiconductor junction, that is, Lambertian distribution.

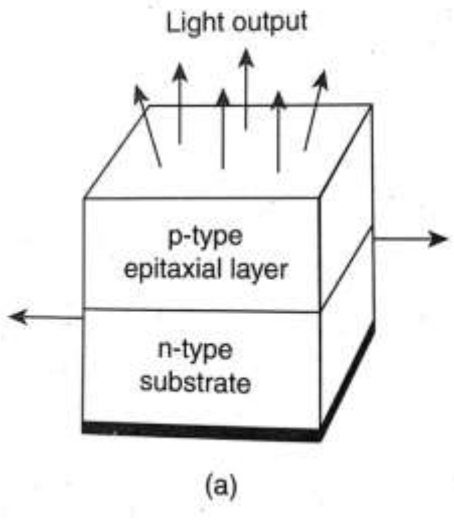


Fig: Planar LED Structure

The LED structures are organized such that most of the recombinations take place on the surface in the following two ways

1. The doping concentration of the substrate is increased, so that additional free minority charge carrier electrons move to the top, recombine, and emit light at the surface.
2. The diffusion length L is increased.

$$\text{Now } L = \sqrt{D\tau}$$

where D is the diffusion coefficient and τ is the carrier lifetime.

The LED structure should be such that the photons generated from the device are emitted without being reabsorbed. This is achieved by making p-layer on the top thin enough to create a depletion layer

Dome LED

Another widely used structure is dome LED ,where 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. Let us calculate the critical angle for GaAs-air interface

For GaAs, the refractive index n_1 = 3.6 and for air, the refractive index n_2=1

$$\theta_c = sin^{-1}\left(\frac{n_2}{n_1}\right) = sin^{-1}\left(\frac{1}{3.6}\right) = 16.12^0$$

The optical rays making angle of incidence greater than 16° will suffer total internal reflection. To reduce the problem, dome or hemisphere structure is preferred so that the light rays will strike the surface at an angle < θ_c and the surface does not experience the total internal reflection. However, it is practically expensive to make pn junction of the dome shape. Therefore, it is encapsulated into dome-shaped plastic medium having higher refractive index than that of air.

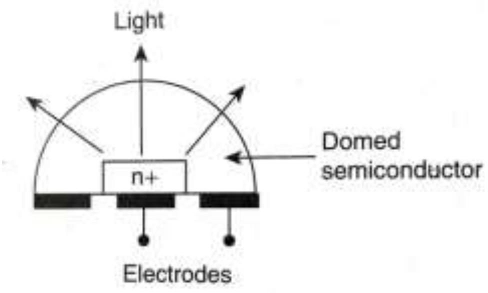


Fig: Dome structure

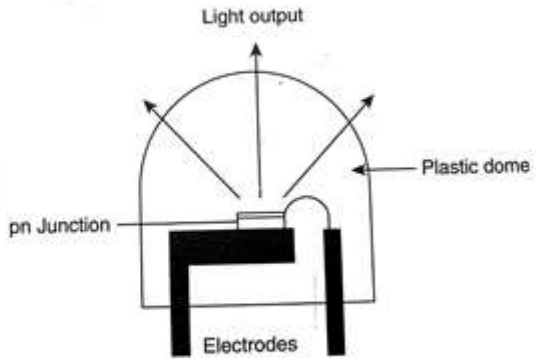


Fig: LED encapsulated Dome shaped plastic medium

Surface-Emitting LED

In the case ofsurface-emitting light diodes (SELED), the light beam is emitted from the top of the diode as shown in Fig. and not from the side. The beam's emission cone is typically 120° and the guiding has a circular symmetry. The large beam emission angle is caused by a difference in refractive index between the semiconductor (high index) and the fiber or the glass material used for coupling with the Fiber (low index). The total output power is between 500 μW and 1 mW

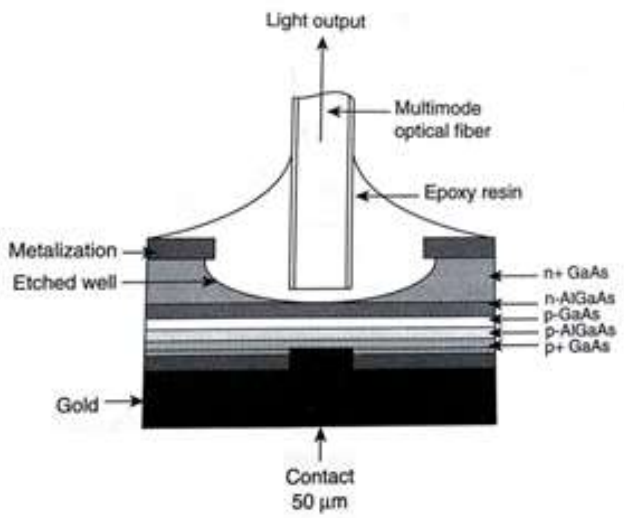


Fig: AlGaAs DH surface Emitting LED

The bottom p+ GaAs and top n+ GaAs layers are included for the realization of low-resistance Ohmic contacts. A deep well is etched to reach the top n-AlGaAs layer to avoid the reabsorption of the emitted radiation in the top n-GaAs layer. This well also gives support to the fiber, which is butt-coupled to the device and held in place with an epoxy resin of appropriate refractive index to enhance the external power eihciency of the device. Photons are generated in the thin p-GaAs region and emitted from the top surface. The heterostructure and reflection from the back crystal face ensures surface emission. Thus, the forward radiance of these devices is very high. The top n-GaAs contact layer ensures low contact resistance and thermal resistance and allows high current densities and high radiation intensity. The Fiber is properly aligned to optimize coupling of the emitted radiation. The power coupled (PC) into a multimode Step index fiber can be calculated from

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

where r is the Fresnel reflection coeHicient at the fiber surface, A is the Fiber cross-section, and R_D is the radiance of source.

Edge-Emitting LED

An edge-emitting LED (EELED) is a high-radiance structure. The light is produced in a very thin active layer and it is emitted from the side of a structure. Due to carrier confinement layers, the beam divergence is narrowed to 30° in a plane perpendicular to the junction, while in the plane of junction due to absence of confinement, a Lambertian pattern output gives 120° divergence. Thus, an elliptical pattern is obtained. At low injection current, the efficiency of EELED is less, hence preferably it is operated at high intensity current. This type of LED gim the output between 500 µW and 1 mW. ,

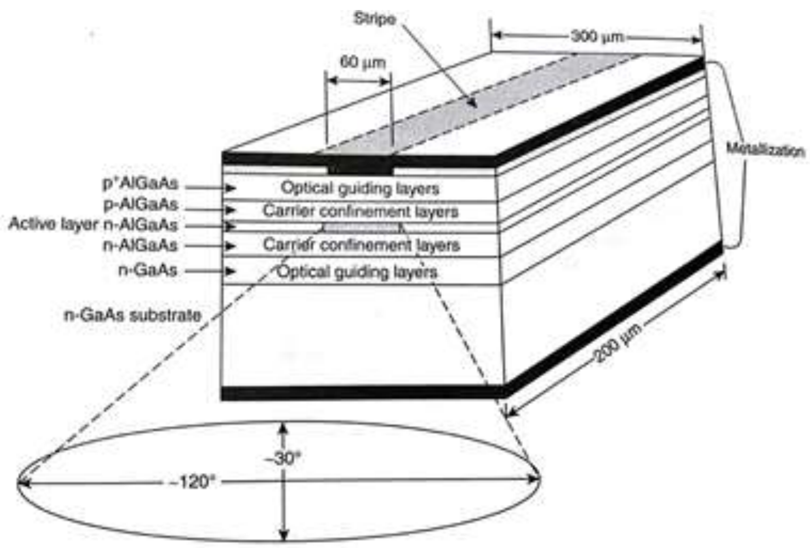


Fig: EELED structure

The device consists of an active junction region, which is the source of the incoherent light. A very large population of carriers for recombination is created in this region by forward-bias injection, and two InGaAsP layers on bath sides serve as carrier confinement layers, on the outer sides of which are doped InP layers. These serve at the cladding layers and the region in between forms an optical waveguide. The photons are generated in the very thin active region and spread into the guiding layers, without reabsorption, because of their larger bandgaps. The stripe geometry is made by selective metallization on the top surface through a window opened in a SiO_2 layer which allows higher carrier injection densities for the same drive current. To match the typical fiber core diameter (50-100 µm), the contact stripes for the edge emitter are made 50~70 µm wide. The emission pattern of the aigt emitter is more directional than that of the surface emitter.

Super Luminescent LED

Super luminescent LEDs (SLEDs) are different from EELEDs and surface-emitting LEDs in several ways. in: SLED, there is Stimulated emission with amplification but insufficient feedback for laser omnations to coal. It has the following advantages over EELEDs and SELEDs:

1. The spectral width is narrower.
2. Light coming from an SLED is more coherent and its degree of polarization is higher
3. The output beam is more directional, like a laser, which allows for better coupling in the fibers.
4. A U-shaped cut in the active layer shown in Fig. increases the density of the carriers, which improves the power efficiency, reaching 18 or 20 mW

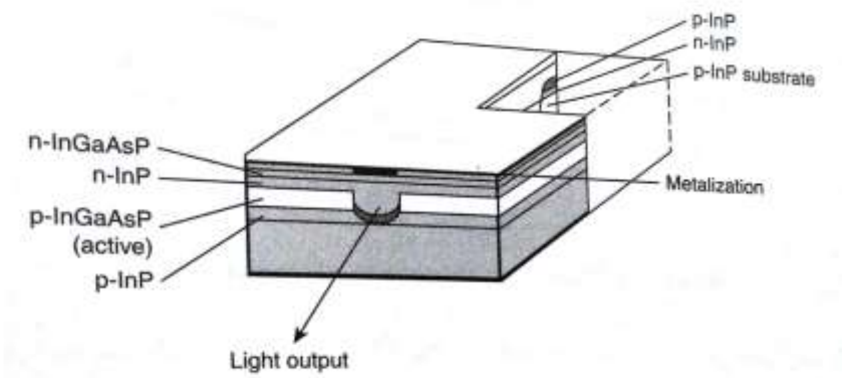


Fig: InGaAsP Super luminescent LED

GaAsP/InP SLED emits at 1300 nm. It comprises a buried active layer within U-shaped groove on the p-type InP substrate. One end of the structure is made optically lossy to prevent reflections and thus suppress lasing; the output is taken from the opposite end. For operation, the injected current is increased until Stimulated emission and hence amplification occur, but because there is high loss at one end of the device, no optical feedback takes place, and hence no laser oscillations build up. Because of stimulated emissions, single-pass amplification takes place which results into high optical output power with narrowing of spectral width to approximately 30-40 nm.

Most of the light emitted from LED is coupled into the optical fiber. The coupling efficiency can be improved by using lenses, specifically when the fiber core diameter is significantly larger than width of the emission region. There axe several lens coupling conhgurations such as

1. Spherimlly polished structures
2. Spherical-ended or tapered fiber coupling.
3. Truncated spherical micro lenses.
4. Integral lens structure.

Polymer LED (PLED)

PLEDs are the polymer light-emitting diodes. The polymer emits light when exposed to electricity. PLEDs are thin film displays that are created by sandwiching conjugated polymer between two proper electrodes at a short distance. Figure shows the schematic structure of the first single-layer PPV polymer LED device. PLEDs consist of a thin layer of PPV between two electrodes, deposited on a glass substrate. In the structure shown , layer of aluminium (or magnesium or calcium) is the cathode, acting as the electron injection layer and layer of indium/tin oxide is the anode, acting as the hole injection layer. The light-emitting layer is poly(p-phenylenevinylene) (PPV). It is the most widely used light-emitting polymer. The cathode is made up of aluminium or calcium.

The anode is made up of indium or tin oxide, which facilitates the easy injection of holes into the PPV layer. The recombination takes place at the layer interface giving rise to photon emission The anode material (indium/tin oxide) is transparent to light; it provides the route for the emitted light to exit through the device.

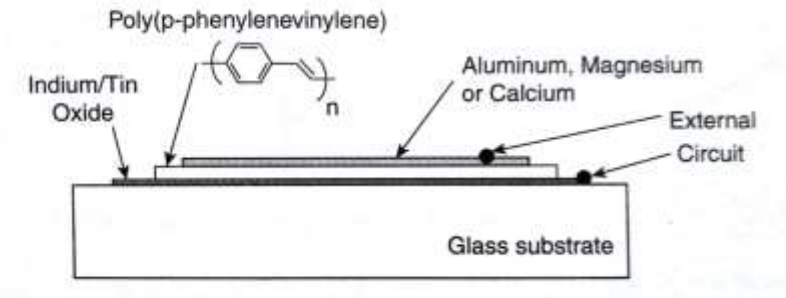


Fig: Polymer LED structure

The following are some advantages of polymer LED:

1. High brightness and long lifetime.
2. Low power consumption.

3. View angle can be large as 160°.
4. Permits flexible lighting and displays.
5. Much cheaper.
6. Useful to large area lighting.

LED Characteristics

LED is a very linear device and hence it tends to be more suitable for analog transmission. Output power versus forward current characteristics of LED is shown

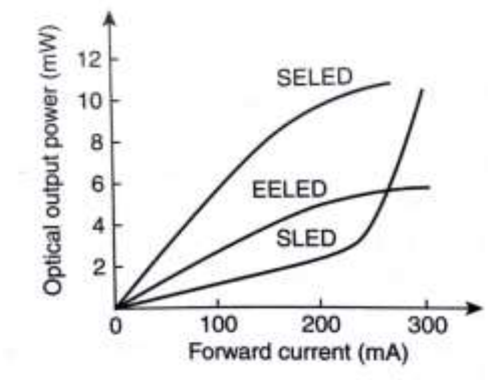


Fig: Output power Vs forward current characteristics

The surface emitter radiates significantly more optical power into the air than the edge emitter, and both devices are reasonably linear at moderate drive currents. SLED gives high output power for more forward current. Practically, LEDs do exhibit non-linearity; therefore, it is required to use some linearizing circuit to ensure linear performance.

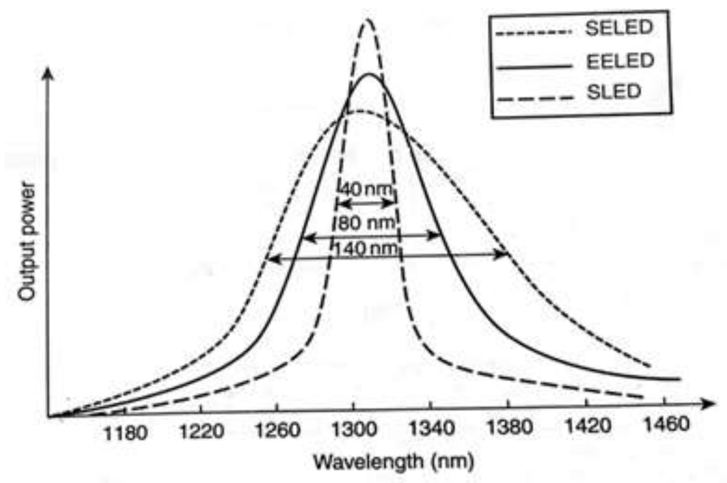


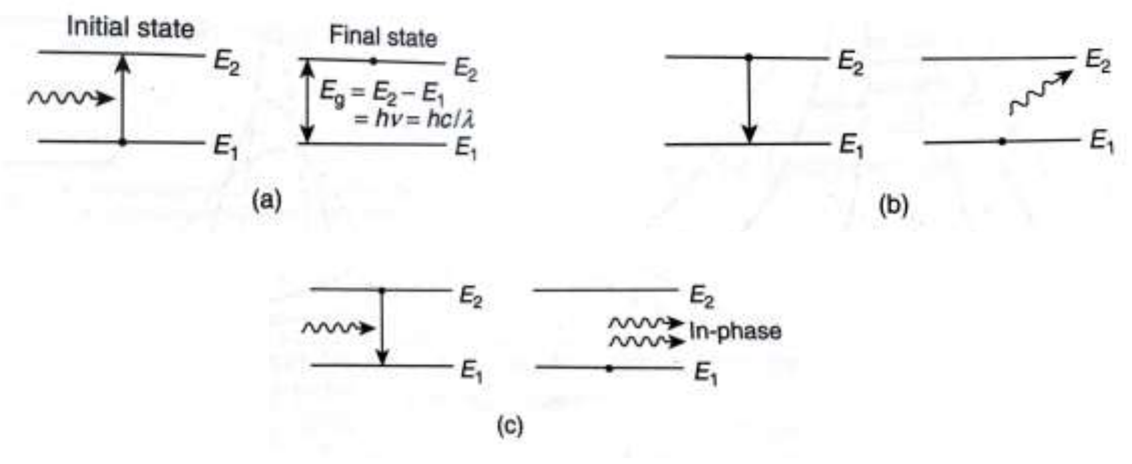
Fig: Spectral Response

The spectral width of the source is important as it determines the contribution to material dispersion. Low spectral Width allows increased data rate. Spectral responses of SELED, EELED, and SLED are shown in above figure. For super luminescent LED, spectral width as narrow as 30-40 mm is obtained.

LASER

Another important light source used in optical communication is the laser diode (LD). A basic LD structure is similar to that of edge-emitting LED. By adding additional structure for photon confinement, coherent light can be generated. The principle of semiconductor laser is based on external pumping and internal light amplification. When a laser has several energy states, external pumping excites carrier to a higher energy state. When they return to the ground state, they release energy and generate photons. Photon generation from external pumping is not sufficient for coherent light generation. An additional amplification mechanism is needed to multiply photons of the same frequency and phase. In a laser, this is made possible by a quantum phenomenon called stimulated emission. Several photon emission and absorption processes exist in two-level atomic system. When a carrier is pumped to the upper energy level, it can come back to the ground state either spontaneously or by stimulation.

An electron in an atom is excited from an energy level E1 to a higher energy level E2 by the absorption of a photon of energy $h\upsilon = E_2 - E_l$. The electron in higher energy level can come to lower energy level spontaneously or can be forced or stimulated by another photon for the downward transition. In this transition, a photon of energy Eg is released. In spontaneous emission, the electron falls down from energy level E2 to E1 and emits a photon of energy $h\upsilon = E_2 - E_l$ in a random direction as shown in Fig.(b). The transition is spontaneous and a random photon is emitted. In stimulated emission, an incoming photon of energy hv = E2-El Stimulates the whole emission process by forcing the electron at E2 to transit down to E1 as shown in Fig. (c). The emitted photon is in-phase with the incoming photon; it is in the same direction; it has the same polarization; and it has the same energy.



LASER STRUCTURES

The broad classification of laser is given in Fig.

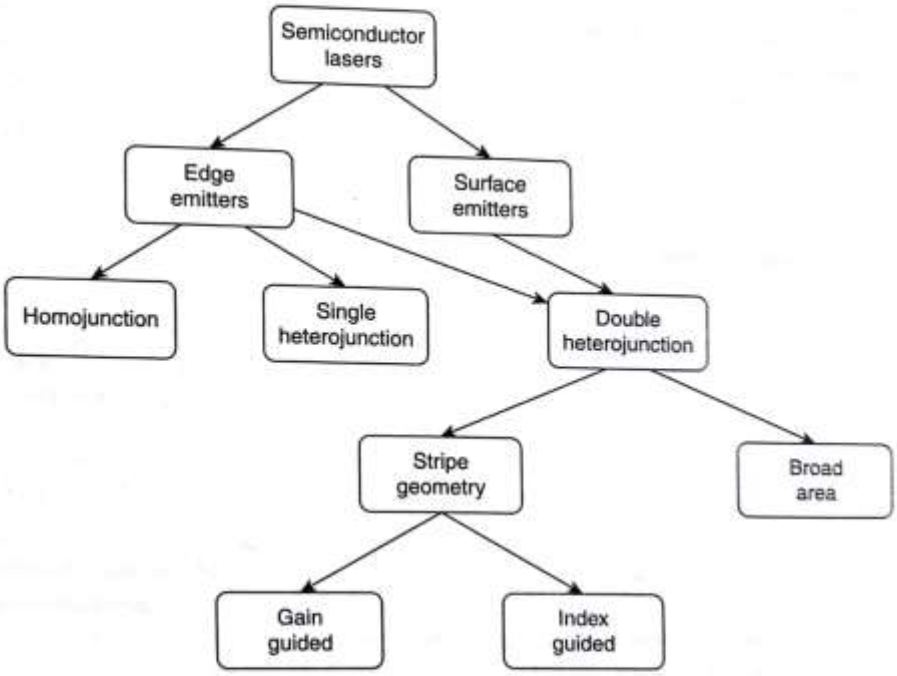


Fig: Classification of laser structures

1. Edge-emitting laser:
   The light emerges from the edge of the device, where the junction intersects the surface. The configuration is simple and easy to fabricate. Most laser diodes are edge emitters. They suffer from the drawbacks that the volume of material that can contribute to the laser emission is limited and they are difficult to package as 2-D arrays.

❖ Homo junction laser: One type of semiconductor material with different dopants is used to fabricate the pn junction shown in Fig. (a). The index of refraction depends on the impurity added and the doping level. The lightly doped material has the highest index of refraction and the more heavily doped p-type material has a lower refractive index. This produces the light pipe effect, which helps to confine the laser light to the active junction region. In this structure the index difference is low and much light is lost.

❖ Single heterojunction: The fraction of Ga in the p-type layer is replaced by Al to reduce the index of refraction, as shown in Fig. (b), Which results in better confinement of laser light to the optical cavity. This leads to lower losses, lower current, reduced damage, and longer lifetime for the diodes.

2. Surface-emitting laser: The light emerges from the surface of the chip rather than from the edge. The devices can be packed densely on a semiconductor wafer and it is possible to fabricate 2-D arrays easily.

❖ Double heterojunction: Only the junction region is composed of GaAs; both p and n-regions are of AJGaAs as shown in Fig.(c). Much better confinement is obtained in this structure. It leads to reduced loss but there are two additional difficulties. The optical radiation is so well confined that the output power may easily reach the damage threshold. The tight confinement also reduces the effective beam width of the output aperture of the laser. This increases the divergence angle in the direction perpendicular to the junction.

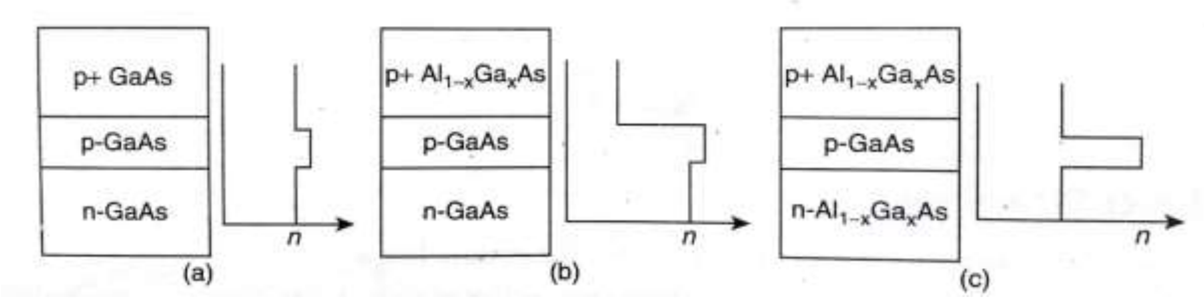


Fig: (a) Homojunction (b) Single hetero junction (C) Double hetero junction

In most modern semiconductor lasers, the current is injected only within a narrow region beneath a Stripe contact several um wide, in order to keep the threshold current low and to control the optical field distribution in the lateral direction.

Compared with broad-area lasers, where the entire laser chip is excited, the threshold current of lasers with stripe geometry is reduced roughly proportional to the area of contact.

The two types of stripe geometry structures are as follows:

1. Gain-guided laser: The current injection is restricted to a small region along the junction plane.
2. Index-guided laser: A built-in refractive index variation in the lateral direction is incorporated.

GAIN-GUIDED LASERS

The current injection is restricted to a narrow region beneath a Stripe as shown in Fig. The active region is planar and continuous. Lasing occurs only in a limited region of the active layer beneath the Stripe contact where high density of current flows. This horizontal confinement of light wave propagating through the active region is thereby accomplished by the small refractive index variation produced by the current-generated population inversion. If the light wave spreads in the horizontal plane outside of the horizontal dimensions of the stripe, it will be absorbed by the unexcited region of the active layer. In the vertical directions, the lower refractive indices of the surrounding layers reflect the optical wave back into the active region.

The current restriction serves several purposes.

1. It allows continuous-wave (CW) operation with reasonable low threshold currents (10-100 mA).
2. It can allow fundamental-mode operation along the junction plane, which is necessary for applications where the optical wave is coupled into a single-mode optical liber.
3. The requirements for heat sinking are low.

Such lasers are termed as ***gain-guided lasers*** because the optical intensity distribution in the lateral direction is determined by the gain profile produced by carrier density distribution.

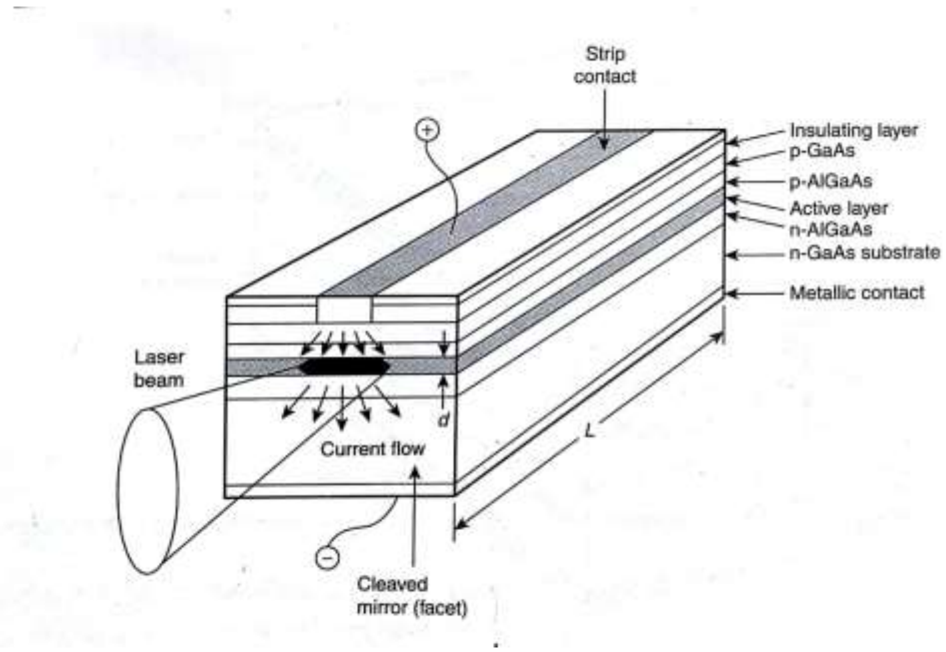


Fig: Gain Guided Laser

INDEX-GUIDED LASERS

The transversal mode control in laser diodes can be achieved using index guiding along the junction plane. The mode control is necessary for improving the optical wave current linearity and the modulation response of lasers. .The active region is surrounded by materials with lower refractive indices in both the vertical (y) and lateral (x) transverse directions. The active region is buried in lower refractive indices layers (e.g., InP) 6n all sides as shown in Fig. For this reason, these lasers are called ***buried-heterostructure*** lasers. The lateral index step along the junction plane is about two magnitudes larger than the carrier induced effects. As a result, the lasing characteristics of buried-heterostructure lasers are primarily determined by the rectangular waveguide that confines the mode inside the buried region. The transverse dimensions of the active region and the index discontinuities are chosen so that only the lowest order transverse modes can propagate in the waveguide. These index-guided devices produce beams with much higher beam quality, but are typically limited in power to only a few hundred milli watts. Another important feature of this laser is the confinement of the injected carriers to the active region

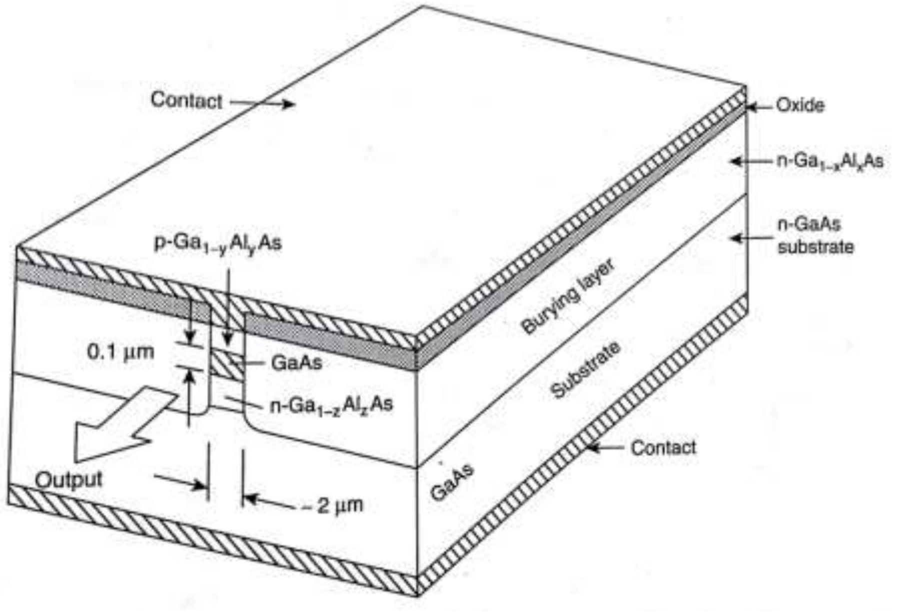


Fig: Index Guided Laser

LASER CHARACTERISTICS

1. Temperature dependence: Generally, the threshold current tends to increase with temperature as shown in Fig..

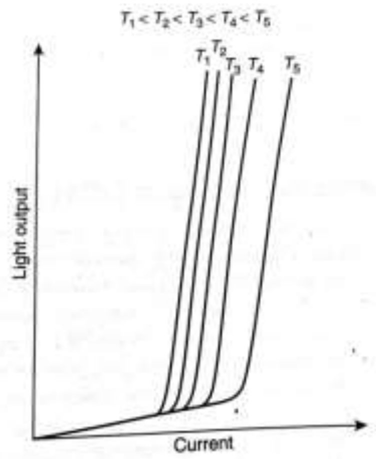


Fig: Variation of threshold current with temperature for laser

The temperature dependence of threshold current density j^{th} is approximately exponential and it is given by

$$J_{th} \propto e^{\frac{T}{T_0}}$$

where T is the device absolute temperature and To is the threshold temperature coefficient.

2. Mode hopping: In single-mode laser diode, the peak emission wavelength exhibits 'jumps" at certain temperatures as shown in Fig

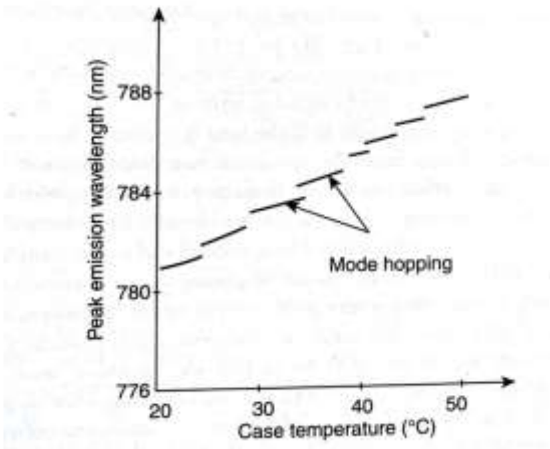


Fig: Peak wavelength versus case temperature charax showing mode hopping output spectrum of single mode laser diode

A jump corresponds to a mode hop in the output. That is, at a new operating temperature, another mode fulfils the laser oscillation condition which means a discrete change in the laser oscillation wavelength. The peak emission wavelength increases slowly with temperature due to slight increase in refractive index and cavity length with temperature.

3. Dynamic response: When a current pulse is applied to the device, it results into switch on delay (t_d) followed by high frequency damped oscillations known as relaxation oscillations as shown in Fig.

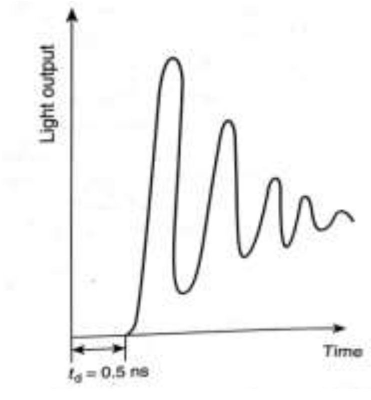


Fig: Dynamic Behaviour of laser

Consequently, the laser output can comprise several pulses as the electron density is repetitively built up and quickly reduced, thus causing relaxation oscillations. At higher data rates above 100 Mbps, this behaviour can deteriorate the pulse shape since t d = 0.5 ns and relaxation oscillation can last twice td.

4. Noise: The random Intensity fluctuations caused by temperature variation create a noise called ***relative intensity noise*** (RIN). Typically, RIN for single-mode

semiconductor laser lies in the range of 130 to 160 dB/Hz. It decreas as the junction current level I increases. Mode partition noise is a phenomenon associated with multi-mode semiconductor lasers when the modes are not stabilized. Temperature changes can cause the relative intensities of various longitudinal modes in laser's output spectrum to vary from one pulse
to next, even though the total output power from a laser is maintained nearly constant.

NOISE IN LASER DIODES

The optical output from a LASER diode is not constant at a particular level but has fluctuations in the light intensity levels. These fluctuations manifest themselves as noise in the transmission and are carried to the receiver end too. There are various sources of generation of noise in a LASER diode.

- ***Reflection Noise***:

This type of noise introduced into the LASER diode output due to the Fresnel reflections of the output light of the LASER diode at the tip of the optical fiber. Fresnel reflection is the phenomenon of reflection of a portion of light incident on a planar interface between two homogeneous media having different refractive indices. It is independent of the angle of incidence of light. When the output of the LASER diode is perfectly aligned to the perfectly flat tip of the optical fiber, part of the light energy is reflected back into the LASER diode and the phase of this reflected light depends on the relative separation between the LASER diode output and the tip of the optical fiber. Due to variation in mechanical vibrations or environmental factors the relative distance between the LASER diode output end and the optical fiber may vary and so does the phase of the reflected signal from the fiber tip. These variations in the phase of the reflected signal produce vibrations in the output of the LASER diode causing noise in the transmitted signal. This type of noise is, hence, the reflection noise.

- **Mode Partition Noise:**

In principle, although the output photonic flux emitted from the LASER has a precise wavelength that satisfies both the gain and the phase condition to get amplified between the two reflecting regions of the LASER, yet in practice, the output of a LASER has a finite spectral width. The spectral distribution of the LASER (as already shown) is given by the following figure.

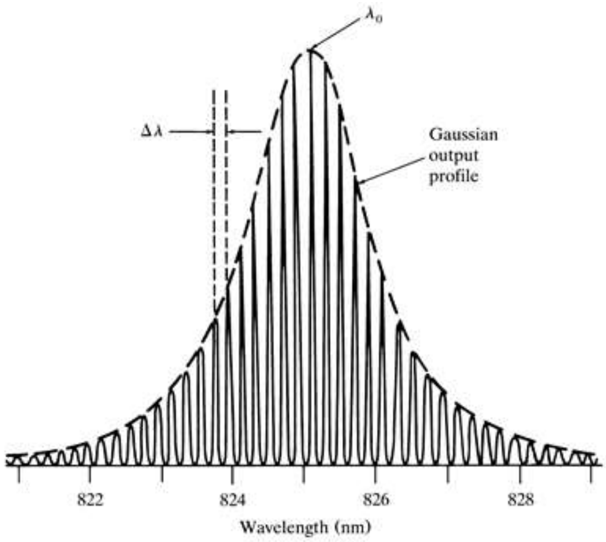


Figure: Spectral Distribution of Fabry-Perot cavity

However, one should note that the above spectral characteristic is actually an average power representation with respect to time. In other words, although the total power in the output may be constant with time, yet the power level of the different wavelength components in the output of the LASER does not remain the same all the time. The power level of the different wavelength components in the LASER output vary as a function of time (the total power remaining the same) and only when they are averaged over a time interval, the spectral distribution of the LASER output looks like figure above. These variations in the power levels of the different wavelength components of the output spectrum, cause different wavelengths to have the maximum power level at different instants of time. This leads to generation of noise in the transmission and is known as the mode partition noise.

- **Speckle Noise**:

The different frequency components in the optical output of the LASER diode move with different velocities inside the optical fiber due to dispersion phenomenon. This causes the output of the optical fiber at the receiving end to contain several small bright and dark regions called speckles of light. These speckles are shown in the figure below which shows the optical fiber output at the receiving end of the optical fiber.

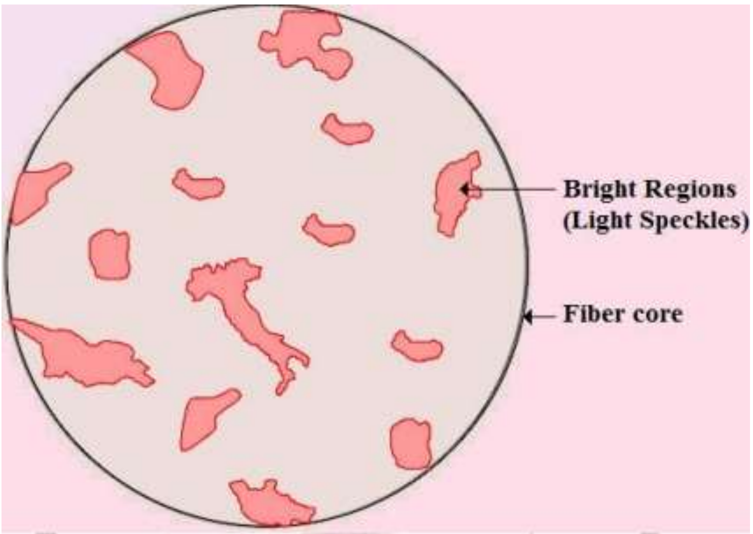


Figure : Speckle Pattern

These speckles are produced by the constructive and destructive interferences of the fields of different frequency components in the optical signal as they travel along the optical fiber. The pattern of the bright and dark regions produced at the output side of the optical fiber is called the speckle pattern. Speckle patterns are characteristic to any coherent light. Since the total power in the cross-section of the fiber core is constant, the speckle pattern is rather a redistribution of power over the cross-section of the optical fiber core. However, due to temperature variations, the different wavelength components in the optical signal undergo different phase changes with respect to time and so; the speckle pattern slowly varies with respect to time. This effect coupled with the non-uniform power detection capability of the photo-detector over its entire cross-section creates fluctuations in the output signal produced at the receiver. This is because, due to variation in the speckle pattern with respect to time, the once dark region now gets converted into a bright region and vice versa. So, the detector output varies accordingly since it has non-uniform power acceptance over the cross-section of the detector and thus noise creeps in. This noise is called the speckle noise. Along with the above three practical sources of noise, the relaxation oscillations produced at the receiver output also contributes to introducing some noise into the optical transmission.

AMPLIFIED SPONTANEOUS EMISSION

In any laser amplifier, we need to have some laser-active ions in excited (metastable) states as a precondition for stimulated emission. Unavoidably, we then also get some spontaneous emission. The resulting fluorescence light goes into all directions and mostly leaves the fiber on the side. (With an infrared viewer, one can see the pumped fiber "glowing".)

A tiny part of the fluorescence light is captured by the fiber core and propagates together with any pump and signal along the fiber (in both directions). Importantly, it can then experience a similar gain as any signal. As fiber amplifiers often reach a high gain (tens of decibels), the guided part of the light from spontaneous emission is strongly amplified. We call that amplified spontaneous emission (ASE). The resulting power can become much larger than the power radiated into all other directions, even though only a minor part of the fluorescence is captured by the core.

The consequences of amplified spontaneous emission are:

- We may obtain a substantial output power in any wavelength region where the amplifier gain is high, even if we do not inject any input signal. That ASE light is relatively broadband; it is actually used in some super luminescent sources.
- If ASE copropagates with a signal, it constitutes a broadband noise for that signal.
- Strong ASE can cause substantial gain saturation: via stimulated emission, it lowers the excitation density and thus the amplifier gain. It causes a kind of soft gain clamping: more pump power still increases the gain, but only slightly, as the ASE powers grow rapidly with increasing gain.

Note that the gain clamping by ASE is most unwelcome when we need to amplify signals at wavelengths far from the gain maximum. Essentially, ASE limits the peak gain, and our signal gain may be much weaker than that. There are even cases where a device cannot work at all because of ASE. For example, it is not easy to make efficient high-power erbium-doped fiber lasers emitting at 975 nm, because it can be hard to suppress ASE at longer wavelengths.

MODULE III
OPTICAL DETECTORS

3.1 INTRODUCTION

A photo-detector is a device which absorbs light and converts the optical energy to measurable electric current. Detectors are classified as

- Thermal detectors
- Photon detectors

3.1.1 THERMAL DETECTORS :

When light falls on the device, it raises its temperature, which, in turn, changes the electrical properties of the device material, like its electrical conductivity. Examples of thermal detectors are thermopile (which is a series of thermocouples), pyro-electric detector etc.

3.1.2 PHOTON DETECTORS:

Photon detectors work on the principle of conversion of photons to electrons. Unlike the thermal detectors, such detectors are based on the rate of absorption of photons rather than on the rate of energy absorption. However, a device may absorb photons only if the energy of incident photons is above a certain minimum threshold. Photon detectors, in terms of the technology, could be based on
Vacuum tubes - e.g. photomultipliers
Semiconductors - e.g. photodiodes
For optical fiber applications, semiconductor devices are preferred because of their small size, good responsivity and high speed.

3.2 CHARACTERISTICS OF DETECTOR

- Sensitivity has to be matched to the emission spectra of the optical transmitter,
- There should be a linear relationship between the intensity of incident signal and the electrical output signal of the Photodetector.
- High quantum efficiency/high spectral sensitivity.
- Fast response time to obtain high data rate operation.
- Stability of performance irrespective of ambient conditions, such as temperature. Reliability and robustness.
- Long life.
- Low noise.
- Low cost.

3.3 PHYSICAL PROCESSES IN LIGHT DETECTION

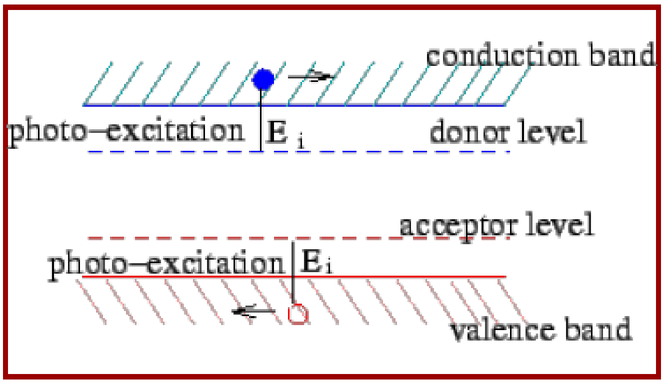
Detection of radiation is essentially a process of its interaction with matter. Some of the prominent processes are

- photo-conductivity
- photo-voltaic effect

- photo-emissive effect

3.3.1 PHOTOCONDUCTIVITY :

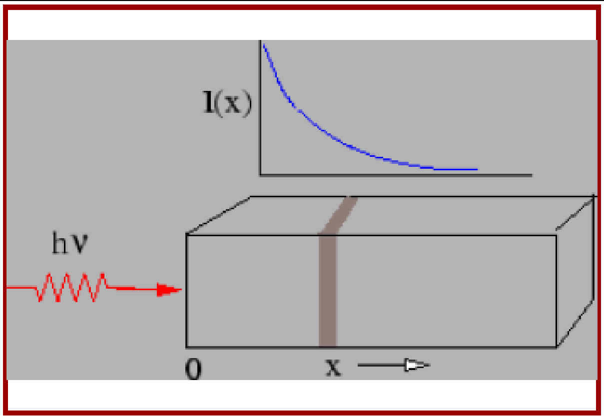
A consequence of small band gap (Δ) in semiconductors is that it is possible to generate additional carriers by illuminating a sample of semiconductor by a light of frequency greater than (Δ/h) . This leads to an increased conductivity in the sample and the phenomenon is known as **intrinsic photoconductivity** . The effect is not very pronounced at high temperatures except when the illumination is by an intense beam of light. At low temperatures, illumination results in excitation of localized carriers to conduction or valence band.
Even when an incident photon does not have sufficient energy to produce an electron-hole pair, it can still produce an excitation at the impurity centres by creating a free electron - bound hole pair (for excitation at donor level) or a free hole - bound electron (for acceptor level). If is the impurity ionization energy, the radiation frequency for extrinsic photoconductivity should be at least $\frac{Ei}{h}$

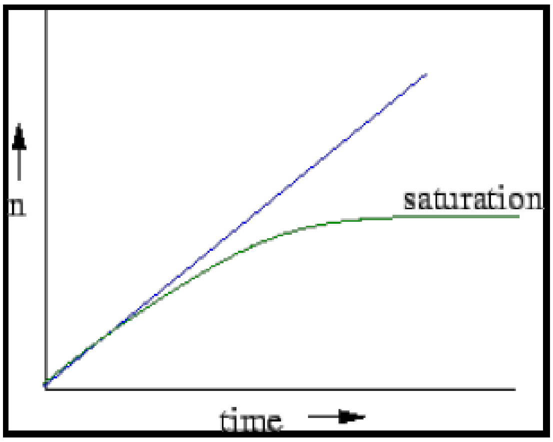


Consider a thin slab of semiconductor which is illuminated by a beam of light propagating along the direction of its length (x-direction). Let ***I*** be the radiation intensity (in watts/m) at a position ***x*** from one end of the semiconductor.
If $\alpha =$ absorption coefficient per unit length, the power absorbed per unit length is . The change in the intensity with distance along the sample length is given by

$$\frac{dI}{dx} = -\alpha I$$

Which has solution $I = Io \times e^{-\alpha x}$





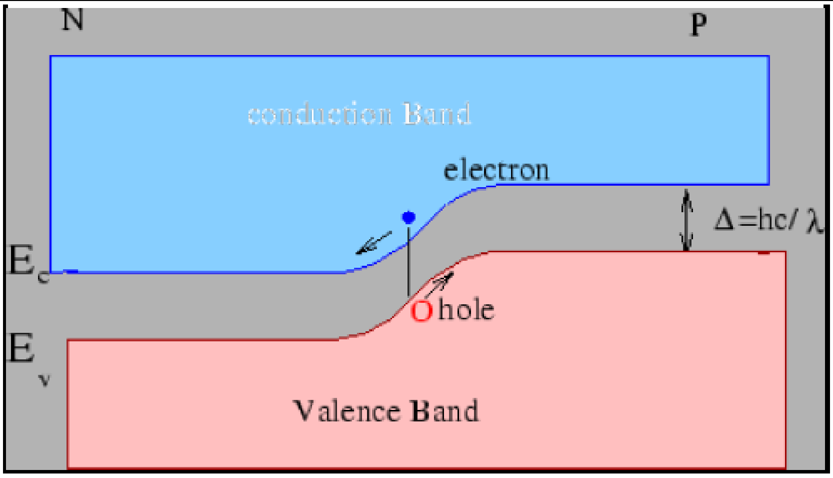
If we define η as the **quantum efficiency** , i.e. the fraction of absorbed photons that produce electron-hole pairs, the number of pairs produced per unit time is given by

$$\Delta n = \Delta p = \frac{\eta \alpha I}{h\vartheta}$$

In principle, the process of illumination will lead to a continued increase in the number of carriers as the amount of energy absorbed (Δn and Δp) will increase linearly with time. However, the excited pairs have a finite life time ($10^{-7} to\, 10^{-2}$ s). This results in recombination of the pairs. The relevant life time is that of minority carriers as a pair is required in the process. Recombination ensures that the number of excess carriers does not increase indefinitely but saturates.

3 .3.2 PHOTOVOLTAIC EFFECT :

Photo-voltaic effect can occur in a material which has a space charge layer, e.g. in a p-n junction.
A photon of sufficient energy can be absorbed by the detector material to excite an electron from the valence band to the conduction band. The excited electron may be observed through its contribution to the current. A photovoltaic detector can be operated without application of a bias voltage.



3.3.3 Photoemissive Process :

In a photoemissive process (also known as **external photo-effect**) incident radiation causes electron emission from photocathode which are to be collected by an anode. Photoemissive detectors have an advantage over other detectors as they have faster speed, higher gain and low noise. However, their spectral range is somewhat limited as the incident photon must have sufficient energy to eject electrons from the photocathode. Photoemissive detectors are, therefore, natural choices in the ultraviolet range.

3.4 PERFORMANCE PARAMETERS :

The performance of a detector is described in terms of certain **figures of merit** .

3.4.1 Responsivity :

Responsivity of a detector is given as the ratio of the generated photocurrent (I) to the amount of optical power (Po) incident on the detector

$$R = \frac{I}{P_0}$$

The unit of responsivity is amperes/watt.

3.4.2 Quantum Efficiency :

A detector is not capable of collecting all the photons and converts them to electron-hole pairs. The number of electrons produced per incident photon is defined as the **quantum efficiency** , which is usually expressed as a percentage.

$$\eta = \frac{No.of\ electrons\ produced}{No.of\ incident\ photons} \times 100\%$$

If I= photocurrent in the external circuit and Po= the incident optical power

$$\eta = \frac{I/q}{Po/h\vartheta}$$

Using this in the expression for the responsivity, we get

$$R = \frac{I}{P_0} = \frac{q\eta}{h\vartheta} = \frac{q\eta\lambda}{hc}$$

The responsivity, therefore, depends on the wavelength λ. For an ideal photodetector, $\eta = 1$ and R is linear with λ.

3.4.3 Spectral Response :

The spectral response of a detector is is given by the manner in which the output signal of the detector varies with the change in the wavelength of the incident radiation. As the quantum efficiency depends on the wavelength, the response is not linear as would be the case if η=1.

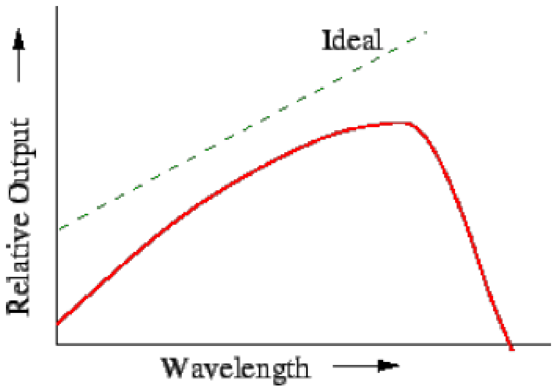
The energy of the photon must be sufficient to excite an electron across the energy barrierΔ. If Δ is in eV, the maximum wavelength that the detector would respond to is

$$\lambda_{max}(in\ nm) = \frac{1240}{\Delta(eV)}$$

However, the response does not fall off abruptly to zero for values of λ above the threshold. This is because, due to thermal energy of the molecules, the absorption coefficent α of the material of the device is found to be given by

$$\alpha = \alpha_0 e^{E/\Delta}$$

Where E is the incident photon energy. For $\lambda > \lambda_{max}$, $E<\Delta$ so that the absorption of radiance becomes smaller.



3.4.4 Noise Equivalent Power :

Source of noise in a detector is thermal fluctuation. Charged particles are always in a state of motion. Even when no radiation is incident on a device, a background current, whose magnitude could be in nano-amperes or pico-amperes, is generated. This is known as **dark current** . In order that a detector may be able to differentiate between such random noise and an incoming signal, the power of the signal must be greater than the noise signal. In a detector design, one defines **signal to noise ratio (SNR)** as

$$SNR = \frac{Signal\ Power}{Noise\ Power}$$

Noise equivalent power (NEP) is an important figure of merit for a detector. NEP is defined as the rms incident power which gives rise to a current (or voltage) whose rms value is equal to the rms value of the current (voltage) due to noise effects.

For a detector, the NEP is usually specified at particular wavelength and temperature. The bandwidth for the incident radiation for the measurement of NEP is generally taken as 1 Hz.

Noise power within a bandwidth Δ_f of is expected to be proportional to Δ_f itself. Since the current (voltage) is proportional to the square root of the power, the noise current (voltage) is proportional to $\sqrt{\Delta f}$. The unit of NEP is, therefore, watts/$\sqrt{Hz}$.

3.4.5 Detectivity and Dee Star (D*)

Both these terms are frequently used interchangibly, though some definitions make a difference between the two. D* is essentially the inverse of NEP normalized to unit area of the detector.

$$D^* = \frac{\sqrt{A}}{NEP}$$

The unit of D* is $m(Hz)^{1/2}$/W.
(Detectivity is often defined as the inverse of NEP.)

3.5 TYPES OF PHOTODIODES

3.5.1 PN PHOTODIODE

It is the simplest structure and is always operated in reverse-bias condition. The depletion region is formed a shown in Fig.3.5.1(a).

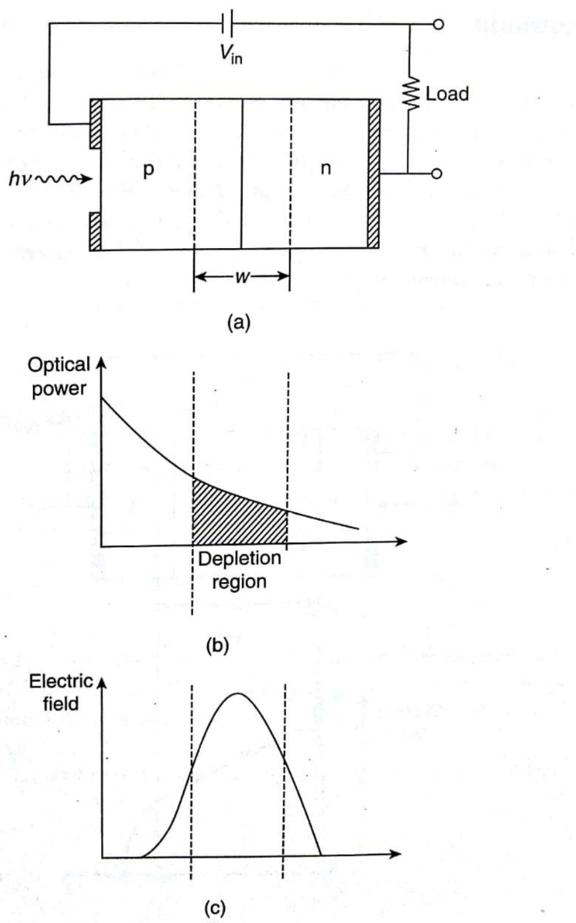


Fig: 3.5.1 (a) Structure of PN photo diode with reverse biased condition (b) Optical Power variation (c) Electric field variation.

The width of the depletion region depends on the doping concentration. Wider depletion regions can be obtained by having lower doping concentration. Incident photons of energy hv are absorbed inside the depletion region as well as the diffusion region. The photons absorbed within the depletion region generate EHPs and drift under the influence of the electric field. The resulting flow of photocurrent constitutes the response of the photodiode to the incident optical power. The response time is governed by the transit time τ_{drift}. It is given as

$$\tau_{drift} = \frac{\omega}{v_{drift}}$$

Where ω is the depletion region width and v_{drift} is the average drift velocity.

The structure of a pn photodiode is shown in Fig. 3.5.2. The incident photons are also absorbed outside the depletion region. The electrons generated in the p-region have to diffuse to the depletion region before they can drift to the n-region under the built-in electric field. Similarly, the holes generated in the n-region have to diffuse to the depletion region for their drift toward the p-region. The diffusion process is slow as compared to drift process and hence limits the response of the photodiode. Therefore, most of the photons should be absorbed in the depletion region; hence, it is made as long as possible by decreasing the doping in the n-region. This width is normally 1-3 µm. The detection wavelength range of silicon photodiode is 400-700 nm and for germanium i is 700-900 nm.

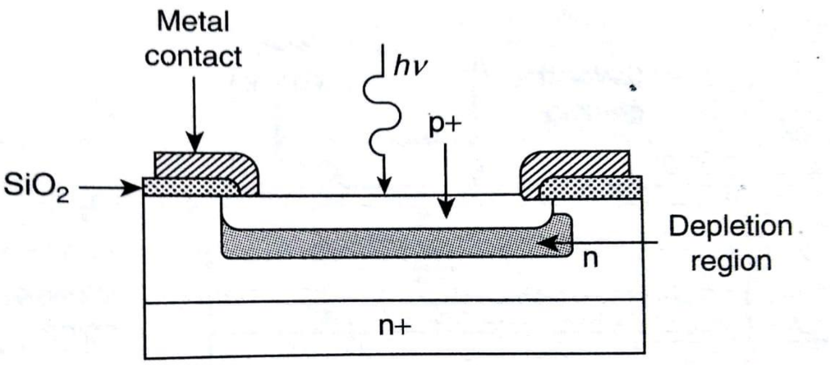


Fig: 3.5.2 A PN photo diode

3.5.2 PIN PHOTODIODE

The diffusion component of a pn photodiode can be reduced by decreasing the widths of the p-region and the n-region and increasing the width of the depletion region. By this, most of the incident photons are absorbed inside it as shown in Fig. 3.5.3. It also allows longer wavelength operation, where the light penetrates more deeply into the wider depletion region, typically 5-50 pm. The n-material is very lightly doped, so that it can be considered as intrinsic region and inserted between p and n-regions. This creates the PIN structure (Fig 3.5.4). The middle layer offers very high resistance, hence most of the voltage drop occurs across it. Most of the incident photons are absorbed inside the intrinsic region. Therefore, the drift component of photocurrent dominates when compared to the diffusion component.

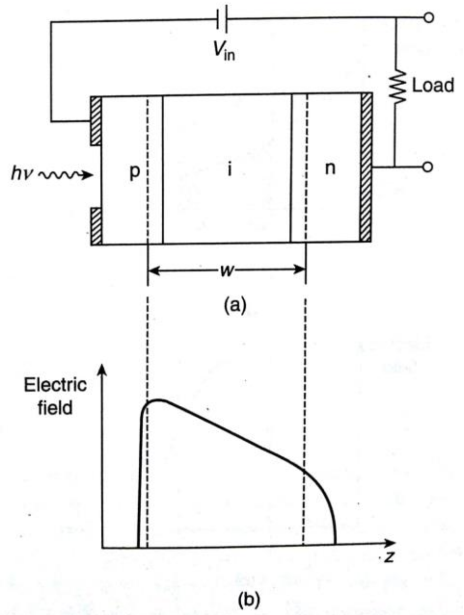


Fig 3.5.3 Structure of PIN photodiode in reverse bias condition.(b) Electric field variation.

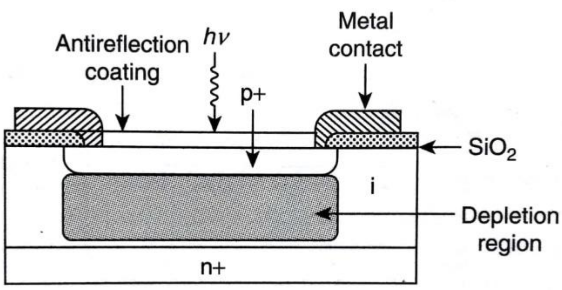


Fig 3.5.4 A PIN photo diode

The two very thin layers of negative and positive charges separated by intrinsic Si of width w -form a structure similar to parallel-plate capacitor. The junction or depletion layer capacitance of: PI N diode: is given by

$$C_{depletion} = \frac{\varepsilon_s A}{\omega}$$

Where A is the cross- sectional area, ε_s is the permittivity of conductor, ω is the width of intrinsic semi-conductor

Three main factors limit the speed of response of a photodiode. These are

1. Drift time of carriers through the depletion region. The speed of response of a photodiode is fundamentally limited by the time it takes photo-generated carriers to drift across the depletion region. When the field in the depletion region exceeds a saturation value, the carriers may be assumed to travel at a constant (maximum) drift velocity ***vd***. The longest transit time, t_{drift}, is for carriers which must traverse the full depletion layer width w and is given by:

$$t_{drift} = \frac{\omega}{v_d}$$

A field strength above 2 x 10^4 V cm^{-1} in silicon gives maximum (saturated) carrier velocities of approximately 10^7 cm s^{-1}. Thus the transit time through a depletion layer width of 10 μm is around 0.1 ns.

2. Diffusion time of carriers generated outside the depletion region. Carrier diffusion is a comparatively slow process where the time taken, tm, for carriers to diffuse a distance d may be written as:

$$t_{diff} = \frac{d^2}{2D_c}$$

where Dc is the minority carrier diffusion coefficient. For example, the hole diffusion time through 10 pm of silicon is 40 ns whereas the electron diffusion time over a similar distance is around 8 ns.

3. Time constant incurred by the capacitance of the photodiode with its load. A reverse-biased photodiode exhibits a voltage-dependent capacitance caused by the variation in the stored charge at the junction. The junction capacitance Cj is given by:

$$C_j = \frac{\varepsilon_s A}{\omega}$$

RISE TIME

It is measured by applying a step light input to the photodiode and is defined **as the time required for the output to change from 10% to 90% of the steady output level**. The rise time depends on the incident light wavelength and load resistance as follows:

$$t_r = \frac{0.35}{f_c}$$

where fc; is the cutoff frequency.

3.5.3 AVALANCHE PHOTODIODE

One limitation of the PIN photodiode is the lack of internal gain. Incident photon produces only one EHP.

In an APD, similar to photodiodes, the incident photons produce EHPs. However, the APD is operated with a large reverse bias, which crates the high-field region within the device. This accelerates the photon- generated electrons, which acquire so much kinetic energy that they collide on bound electrons in the valence band and create secondary hole-electron pairs. This process is called as impact ionization. If the field created is high enough,due secondary carrier pairs create new EHPs. This is called the avalanche effect. Thus, the carriers get multiplied, which results in a large photocurtent.

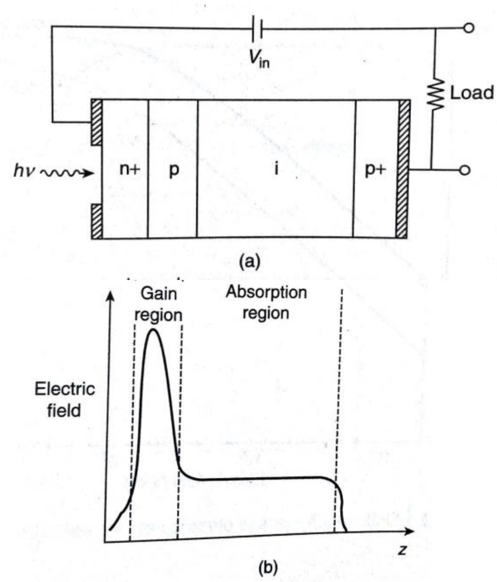


Fig: (a) Reach-through APD (b).Electric field variation

A simplified schematic of silicon reach-through APD is shown in Fig.(a). The n+ layer is a thin layer; the photons to be detected fall on this layer through the window. There are three p-type layers of different doping level next to n+ layer. The first is a thin p-type layer and second layer is a thick, lightly doped p-type layer. Which is almost intrinsic. The third layer is a heavily doped p-layer. Under no-bias condition, the depletion layer does not extend across the intrinsic layer. The diode is reverse-biased to increase the field in the depletion region. If a sufficient reverse-bias is applied, the depletion in the p-layer widens to reach through to the intrinsic layer: hence it is named as reach-through APD.

The electric field distribution across the junction is shown in Fig. (b). It is maximum at n+p junction, then decreases slowly through the p-layer and the field vanishes at the end of narrow depletion layer in the p+ layer. The nearly uniform field in intrinsic region separates the hole-electron pairs and drifts them toward the n+ and p+ layers. When these electrons reach the p-layer, they experience greater electric field. They acquire sufficient kinetic energy, greater than Eg to impact ionize some of the Si covalent bonds and release another EHP. These electrons further cause another impact ionization and release more EHPs. This chain multiplication process leads to an avalanche of impact ionization process. Thus, one electron entering the p-layer can generate more number of EHPs, which contribute to the multiplied photocurrent. Hence we can say that this photodiode possess internal gain mechanism.

Thus, the photo-generation takes place in the intrinsic region, whereas avalanche multiplication takes place in the p-region. The avalanche multiplication is a statistical process and leads to carrier-generation fluctuation that leads to excess noise in the avalanche multiplied photocurrent. The avalanche multiplication factor M of an APD is defined as

$$M = \frac{Multiplied\ output\ photocurrent}{initial\ or\ primary\ unmultiplied\ photocurrent} = \frac{I_{output}}{I_{photo}} = \frac{I_0}{P_{in}R} = \frac{I_0}{P_{in}\frac{\eta e\lambda}{hc}} = \frac{I_0 hc}{P_{in}\eta e\lambda}$$

$$M = \frac{1}{1 - \left(\frac{V_{in}}{V_{BR}}\right)^n}$$

where V_{BR} is avalanche breakdown voltage, Vin is the reverse-biased voltage, and n is characteristic index. The speed of reach-through APD depends on following three factors:

- The time it takes for the photo-generated electrons to cross the absorption region (intrinsic region) to the multiplication region (p-region).
- The time it takes for the avalanche process to build up in the p-region and generate EHPs.
- The time it takes for the last hole released in the avalanche process to transit through the intrinsic region.

The response time of APD is longer than PIN structure because of multiplicative process.

3.5.3.1 Drawbacks of APDs

APDs suffer from the following drawbacks:

- The fabrication cost is high due to complex structure.
- The avalanche multiplication is a statistical process and hence leads to carrier-generation fluctuation which leads to excess noise in the avalanche multiplied photocurrent.
- It requires high bias voltages around 50-400 V.
- Gain is temperature-dependent; hence, temperature compensation is necessary for stable operation.

3.5.4.FUNDAMENTAL PHOTO DIODE CIRCUIT

The photodiode shown in Fig. (a) is unbiased. The photocurrent I_{photo} produced by incident photons is converted into output voltage by connecting load resistor RL. The output vo tage (V_{OUT}) is given as **Vout= Iphoto x R_L**. Output voltage is proportional to the amount of incident light when $V_{OUT} < V_{OC}$, V_{OC} is the open terminal voltage, that is, when RL = 0.

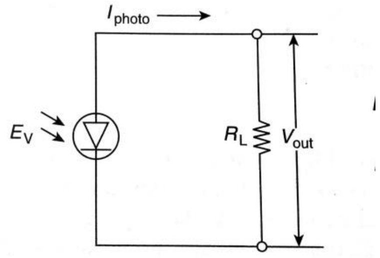
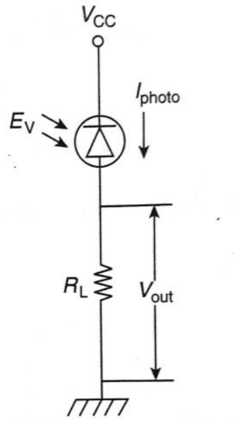


Fig.(a) Unbiased Photo diode circuit



Fig(b): Photo diode with bias

Figure (b) shows a circuit in which the photodiode is reverse-biased by V_{CC}. The photo current (I_{photo}) is converted into an output voltage by the load resistor R_L. The output voltage V_{OUT} is given as $V_{OUT} = I_{photo} \times R_L$:
Output voltage is proportional to the amount of incident light when $V_{OUT} < (V_{0C} + V_{CC})$..
Features of a circuit used with a reverse-biased photodiode are as follows:

1. High-speed response.
2. Wide-proportional range of output.

Therefore, this circuit is generally used.

5.5. PHOTO DETECTOR NOISE

The different figure of merit used to assess the noise performance of optical detectors is

1. Noise equivalent power (NEP)
2. Detectivity (D).
3. Specific detectivity (D*).

5.5.1 Noise equivalent power (NEP)

In many design applications. the designer is concerned with the minimum detectable power of photo diode. The minimum incident power on a photodiode required to generate a photon current equal to the total photo diode noise current is defined as the noise equivalent power, or NEP. As a mathematical expression,

$$NEP = \frac{\text{RMS noise current (A)}}{\text{Phatodiode sensitivity (A/W)}}$$

The NEP is dependent on the bandwidth of the measuring system, frequency of modulated signal, detector area , and operating temperature. In order to remove the bandwidth dependence, the figure is divided by the square root of the bandwidth. This gives an NEP density in W/Hz. Since the power-to-current conversion of a diode depends on radiation wavelength, the NEP figure is always quoted at a particular wavelength.

There are several sources of noise in photo detectors. These include ***shot noise*** from the detector ***dark current*** ,***shot noise*** from the ***photocurrent***, ***Johonson noise*** from thermal fluctuations in the detector impedance. And ***flicker noise*** that is inversely proportional to the measurement frequency (also referred to as "1/f" noise). APDs also have excess noise" that depends on the ratio of the ionization coefficients for electrons and holes and the avalanche gain.

The shot noise current produced by the reverse leakage current of a device is given by the formula

$$I_s = (2ei_D B)^{\frac{1}{2}}$$

where I_S is the shot noise current, ***e*** is the electronic charge (1.6 X 10^{-19} coulomb), ***B*** is the bandwidth of system. and i_D is the dark leakage current (amps).

3.5.2 Dark Current

Dark current is a small current which flows when a reverse voltage is applied to a photodiode in dark condition (no light). This is a major source of noise in applications where reverse voltage is applied to photodiode .In contrast to this, the applications where no reverse voltage is applied, noise resulting from shunt resistance is predominant.

3.5.3 Shunt Resistance (R_{sh})

It is the voltage-to-current ratio in the vicinity of 0 V:

$$Rsh = \frac{10mV}{i_D}$$

where i_D is the dark current at Vin = 10 mV. The Johnson or thermal noise contribution is provided principally by the shunt resistance of the device. The Johnson noise current is given by

$$I_j = \left[\frac{4kTB}{R_{sh}}\right]^{\frac{1}{2}}$$

where Ij is the Johnson noise current , (A, RMS), k is the Boltzmann constant (1.33×10^{-23} J/K)T is temperature (K), and R_{sh} is the shunt resistance giving rise to noise

The total noise current is the quadrature sum of the individual noise current contributions:

$$I_N = \left(I_s^2 + I_J^2\right)^{1/2}$$

$$NEP = \frac{I_N}{R}$$

Shot noise is the dominant component for a reverse-biased photodiode especially for a large area device operated at a high voltage. If a device is operated with zero bias, then the Johnson noise dominates, since the dark current tends to zero. It is usually the case when operating in this mode that noise current is reduced to such a degree that the NEP, and hence the minimum detectable signal, is reduced in spite of some loss of absolute sensitivity.

The detectivity D is defined as the inverse of NEP

$$D = \frac{1}{NEP}$$

The specific detectivity D* is a parameter which takes into account the area of the photo-detector.

The specific detectivity $D^* = DA^{1/2}$

3.6. RECEIVER SENSITIVITY

Among a group of optical receivers, a receiver is said to be more sensitive if it achieves the same performance with less optical power incident on it. The performance criterion for digital receivers is governed by the bit-error rate (BER).
BER defined as the probability of incorrect identification of a bit by the decision circuit of the receiver. Hence, a BER of 2×10^{-6} corresponds to on average 2 errors per million bits. A commonly used criterion for digital optical receivers requires the BER to be below 1×10^{-9}.
The ***receiver sensitivity*** is defined as the minimum average received power P_{rec} required by the receiver to operate at a BER of 10^{-9}.

$$BER \approx \frac{e^{(-Q^2/2)}}{Q\sqrt{2\pi}}$$

Where

$$Q = \frac{I_1 - I_0}{\sigma_1 + \sigma_0}$$

I_1 = Maximum current variation of received pulse
$\sigma_1 = standard\ deviation\ at\ I_1$
I_0 = Minimum current variation of received pulse
$\sigma_0 = standard\ deviation\ at\ I_0$

Minimum power received

$$P_{rec} = \frac{Q}{R}\left[qF_A Q\Delta f + \frac{\sigma_T}{M}\right]$$

$F_A = amplifier\ noise\ figure$
$\Delta f = Effective\ noise\ bandwidth$ $\sigma_T = RMS\ thermal\ current$
$M = gain\ of\ detector$ $R = responsivity$

$$(P_{rec})_{pin} \approx \frac{Q\sigma_T}{R}$$

$$(P_{rec})_{APD} \approx \left[\frac{q\Delta f}{R}\right] Q^2$$

3.7 OPTICAL RECEIVERS

3.7.1 IDEAL PHOTO RECEIVER

Photodetector structures convert the incident optical power to the photocurrent. This is the very first stage of the optical receiver. This raw electrical signal needs limiter processing to extract the original information. The weak photo-current requires amplification and conversion to voltage. The converted signal may be analog or digital depending upon the type of system

The next stages are as follows: . _

1. **Amplification**: The power of the received optical signal is less than 10 µW. The detected signal is in micro ampere range which is to be amplified for further signal processing. Before that, it needs the conversion from current to voltage. The receiver may have one or more amplification stages. The special low-noise

amplifier for weak input is used for pre-amplification. Further amplifier may be added to amplify the signal to high level.

2. **Equalization**: Detection and amplification may distort the received signal. All the frequencies are not amplified by the same factor. Therefore, equalization circuit takes care of this and equalizes this difference or unevenness in amplification.
3. **Filtering**: This stage removes the undesired frequencies (e.g., noise or harmonics) and improves the signal-to-noise ratio.
4. **Discrimination**: This circuit generates digital pulses by comparing the signal with discrimination level as shown in Figs.(c) and (d). The decision circuit produces ON pulse if signal level is above discrimination threshold and OFF pulse if signal level is below discrimination threshold.
5. **Re-synchronization**: This circuit recreates the clock signal and puts the discriminated pulses in correct time slot.

The sources of noise at photo detector and amplification stage are as follows:

1. Quantum noise.
2. ***Dark current***: When no light is falling on the photo-detector, a small current flows through the circuit. This current under no light or dark condition is called the dark current. Ideally no current should flow. Practically a good photo-detector should have dark current as less as possible.
3. Excess noise due to random fluctuations (only for APB).
4. Thermal noise due to bias resistor.
5. Amplifier noise.

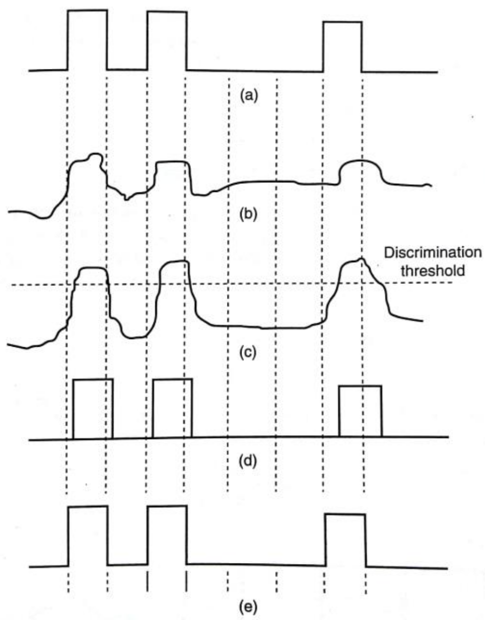


Figure: (a) Original digital signal (b) Photo detected signal (c) Amplified signal (d) Discriminated signal (e) Re-synchronized signal

3.7.1 1 .EQUIVALENT CIRCUIT OF OPTICAL FIBER RECEIVER

In the equivalent circuit of optical fiber receiver shown in Fig., i_{det} represents the optical detector as a current source, ***Cd*** is the detector capacitance, R_L is the detector load Resistance, i_t is the thermal noise current, i_{Ts} is the total shot noise current, R_a is the amplifier input resistance, ***Ca*** is the amplifier input capacitance, and i_{amp} is the amplifier noise current.

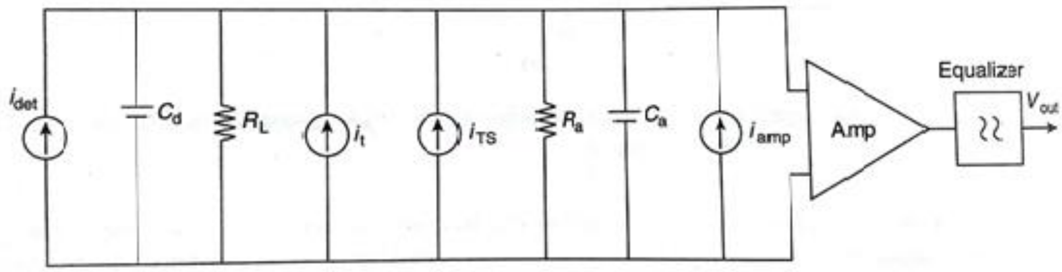


Fig: Equivalent circuit of optical fiber receiver

3.7.1 .2 RECEIVER AMPLIFIER CONFIGURATIONS

There are three commonly used amplifier configurations, as follows:

1. Low impedance front end:

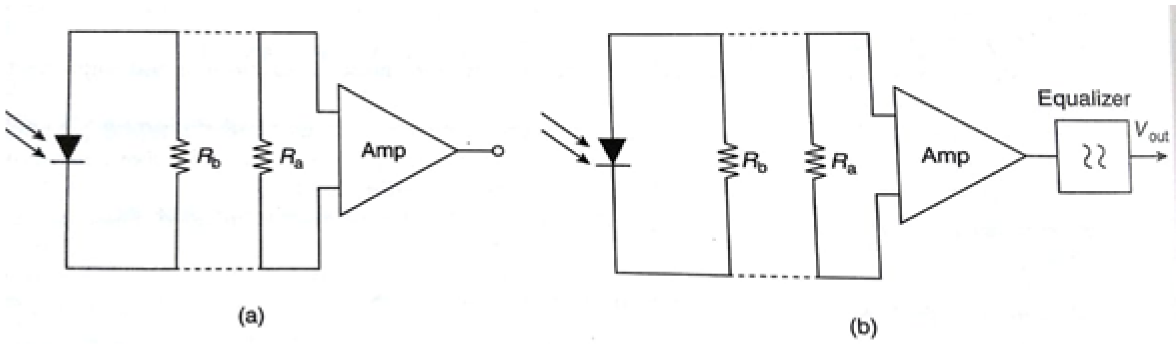


***Fig: (a) Low impedance front end (b) High impedance front end*.**

In Fig. Ra is the amplifier input resistance and Rb is the detector bias resistor.The total load resistance of photo diode is

$$R_{TL} = \frac{R_a R_b}{R_a + R_b}$$

Bandwidth and noise are the important parameters in the design of receiver. From the equivalent circuit the front-end total capacitance is

$$C_T = Cd + Ca$$

and if the load resistance is R_{TL}, then the post-detection bandwidth B is given as

$$B \geq \frac{1}{2\pi R_{TL} C_T}$$

From the above equation, it is clear that to increase the post-detection bandwidth B, R_{TL} should be reduced. However, increase in B and decrease in R_{TL} increases the thermal noise, which is undesirable. It severely limits the sensitivity of receiver. Thus, the circuit is impractical for long-distance communication.

2. **High impedance front end**:

In this circuit, the effect of thermal noise is reduced by increasing the detector bias resistor and input impedance of amplifier. However, the frequency response is degraded. The detector output is integrated over long time constant and then restored by differentiation with the help of equalizer as shown in Fig.(b). Thus, this structure gives much better sensitivity as compared to low impedance front-end configuration, but needs equalization and has limited dynamic range.

3. **Transimpedance front end**:

In transimpedance front-end configuration, a low noise, high input impedance amplifier with negative feedback is used to overcome the drawbacks of the high impedance front-end configuration. It operates in a current mode amplifier, and the high input impedance is reduced by negative feedback .This configuration provides much greater bandwidth as well as reduced thermal noise.

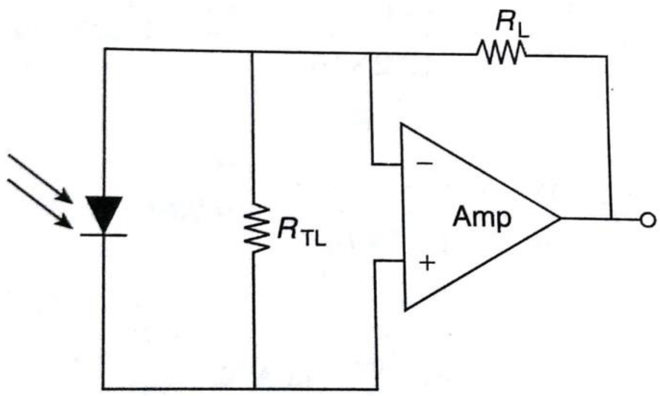


Fig: Transimpedance front end.

3.7.2 QUANTUM LIMIT OF DETECTION

The minimum number of photons required to be detected per bit for achieving the desired BER is called the ***quantum limit of detection*** of the receiver.

For calculating the quantum limit of detection, let us assume ‘P(t)’ be the transmitted optical power during a bit-interval and ‘η’ be the efficiency factor related to the generation of electron-hole pairs in the material of the photo-detector. If 'hν' be the energy of one photon, the number of electron-hole pairs generated (N) is given by:

$$N = \frac{\eta}{h\nu}\int_0^{\tau} P(t)dt$$

the probability of 'n' electron-hole pairs being generated during any bit interval is given by the Poisson's distribution as shown below:

$$P(n) = N^n \frac{e^{-N}}{n!}$$

The probability that no electron-hole pairs are generated during a bit interval is given by substituting n=0 in the equation

$$P(0) = N^0 \frac{e^{-N}}{0!} = e^{-N}$$

For an acceptable system, the BER should at most be 10^{-9}. That is:

$$e^{-N} \leq 10^{-9}$$

$$N \approx 21$$

So for the best possible receiver with no thermal noise, there should be at least 21 photons, on average, incident onto the photo-detector during one bit interval for an acceptable BER. This is the quantum detection limit of the receiver.

However, in practice, this is too small a number and the actual number of photons per bit ranges from a few hundred to a few thousand. Also, in practice, the quantum limit of detection of a practical receiver would be a lot smaller than 21 because of the presence of thermal and other kinds of noises which deteriorate the receiver performance.

The quantum limit of detection gives the average number of photons that required to be transmitted per bit-duration for achieving the desired BER. Therefore, if the bit-duration decreases (i.e. if data rate increases), the quantum limit of detection (number of photons per bit) would remain the same but the number of photons per second would increase and the average power would, thus, increase. Thus the average power is proportional to the data rate.

$$P_{received} \;\alpha\; \boldsymbol{B}$$

INTENSITY MODULATED (IM) SYSTEM

A modulation scheme in which an information signal changes the driving current and the latter modulates the amplitude of the output light is called intensity modulation (IM). At the receiver end, modulated light is directly converted into electrical current by a photodiode; that is, the receiver provides direct detection (DD). In short, the method is called intensity modulation/direct detection (IM/DD)

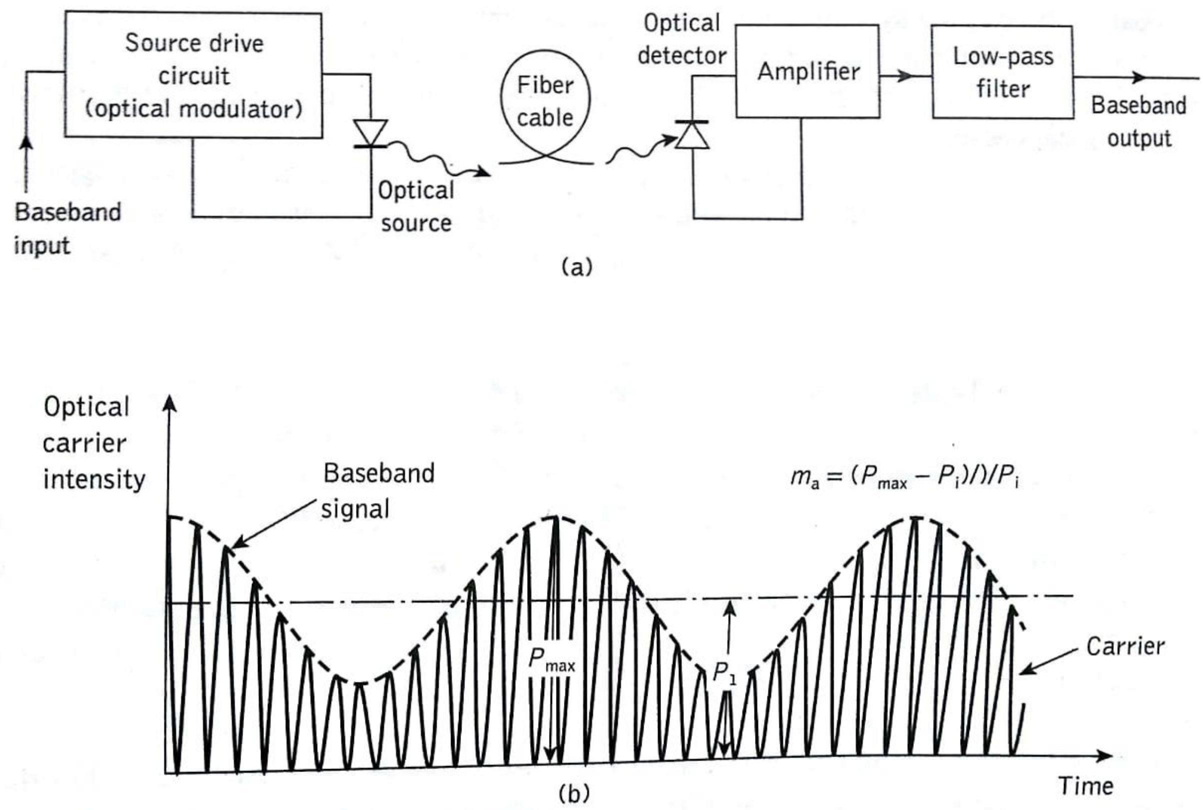


Fig: (a) Analog system employing direct intensity modulation (b) Time domain representation

The transmitted optical power

$$P_{opt}(t) = P_i(1 + m(t))$$

Where P_i is the average un-modulated carrier power , m(t) intensity modulating signal.

$$m(t) = m_a cos\omega_m(t)$$

$P_{opt}(t) = P_i(1 + m_a cos\omega_m(t))$ it is the transmitted signal.

At the receiver side

The secondary photo current I(t) generated at an APD with multiplication factor M is given by

$$I(t) = I_p M(1 + m_a cos\omega_m(t))$$

Where primary photo current with an unmodulated carrier I_p is given by

$$I_p = \frac{\eta e}{hf} P_0$$

The mean squire signal current

$$\overline{i_{sig}^2} = \frac{1}{2}(m_a M I_p)^2$$

The total average noise in the system is composed of quantum, dark current and thermal (circuit) noise components. The noise contribution from quantum effects and detector dark current may be expressed as the mean square total shot noise current for the APD receiver $\overline{i_{SA}^2}$ is given in following equation ;where the excess avalanche noise factor is written following Eq. as F (M) such that:

$$\overline{i_{SA}^2} = 2eB(I_p + I_d)M^2 F(M)$$

where B is the effective noise or post-detection bandwidth.

Thermal noise generated by the load resistance R_L and the electronic amplifier noise can

be expressed in terms of the amplifier noise figure $\boldsymbol{F_n}$ referred to R_L and thus the total mean square noise current, $\overline{i_N^2}$ may be written as:

$$\overline{i_N^2} = 2eB(I_p + I_d)M^2 F(M) + \frac{4KTBF_n}{R_L}$$

The SNR defined in terms of ratio of the mean square signal current to mean squire noise current for APD receiver is given by

$$\left(\frac{S}{N}\right)_{rms} = \frac{\overline{i_{sig}^2}}{\overline{i_N^2}} = \frac{\frac{1}{2}(m_a M I_p)^2}{2eB(I_p + I_d)M^2 F(M) + \frac{4KTBF_n}{R_L}} \dots\dots\dots\dots(APD)$$

When unity gain photo detector (PIN) is used then

$$\left(\frac{S}{N}\right)_{rms} = \frac{\overline{i_{sig}^2}}{\overline{i_N^2}} = \frac{\frac{1}{2}(m_a I_p)^2}{2eB(I_p + I_d) + \frac{4KTBF_n}{R_L}} \dots\dots\dots\dots(PIN)$$

The SNR for video transmission include the ratio of luminance to composite video ,b; then

$$\left(\frac{S}{N}\right)_{p-p} = \frac{\overline{i_{sig}^2}}{\overline{i_N^2}} = \frac{(2 m_a I_p b)^2}{2eB(I_p + I_d) + \frac{4KTBF_n}{R_L}} \dots\dots\dots\dots(PIN)$$

COMPARISON BETWEEN PIN & APD

SL.NO	PARAMETERS	PIN	APD
1	Sensitivity	Less Sensitive(0-12dB)	More Sensitive (0-15dB)
2	Biasing	Low reverse bias voltage (5-10V)	High reverse bias voltage (20-400V)
3	Wave length region	30-1100nm	400-1000nm
4	Gain	No internal Gain	Internal Gain
5	S/N Ratio	Poor	Better
6	Detector Circuit	Simple	More Complex
7	Conversion efficiency	0.5 to 1 Amps/Watt	0.5 to 100 Amps/Watt
8	Cost	Cheaper	More expensive
9	Support circuitry required	None	High voltage & temperature compensation

MODULE IV

DIGITAL TRANSMISSION SYSTEMS

4.1 DESIGN OF INTENSITY MODULATED DIRECT DETECTION(IMDD) LINKS

A modulation scheme in which an information signal changes the driving current and the latter modulates the amplitude of the output light is called intensity modulation (IM). At the receiver end, modulated light is directly converted into electrical current by a photodiode; that is, the receiver provides direct detection (DD). In short, the method is called intensity modulation/direct detection (IM/DD)

4.1.1 LINK DESIGN

The user generally specifies the distance over which the information is to be sent and the data rate to be transmitted. The Designer then has to find the specification of the system components.

The designer generally has to define some additional criteria either as per the standards or as per the user specifications.

The Design criteria are given in the following.

1. **Primary Design Criteria**
   Data Rate
   Link length
2. **Additional Design Parameters**

- Modulation format eg. Analog/digital

Depends upon the type of signals user want to transmit. For example if it is a TV signal, then may be analog transmission is more suited as it requires less bandwidth and better linearity. On the other hand if data or sampled voice is to be transmitted, digital format may be more appropriate. The digital signals have to be further coded to suite the transmission medium and also for error correction.

- System fidelity: BER, SNR

The system fidelity defines the correctness of the data received at the receiver.

For digital transmission it is measured by the Bit Error Ratio (BER) . The BER is defined as

$$BER = \frac{Number\ of\ bits\ in\ error}{Total\ number\ of\ bits\ transmitted}$$

In optical system the BER has to be less than 10^{-9} . For analog system the quality parameter is the Signal-to-noise (SNR) ratio. Also there is a parameter called the inter-modulation distortion which describes thelinearity of the system.

- Cost : Components, installation, maintenance

Cost is one of the important issues of the link design. The cost has three components, components, installation and maintenance. The component and the installations cost are the initial costs. Generally the installation cost is much higher than the component cost for long links. This is especially true for laying the optical cable. It is therefore appropriate to lay the cables keeping in view the future needs. The optical link is suppose is supposed to work for at least 25years. The maintenance costs are as important as the initial cost. An initial cheaper system might end up into higher expenses in maintenance and therefore turn out to be more expensive as a whole.

- Upgradeability

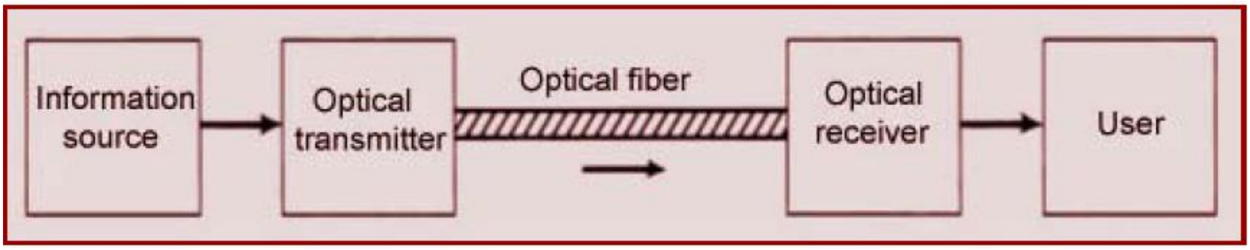
The optical fiber technology is changing very rapidly and the data rates are increasing steadily. The system should be able to adopt new technology as well as should be able to accommodate higher data rates with least possible changes.

- Commercial availability

Depending upon which part of the world one is, the availability of the components and the systems may be an issue.

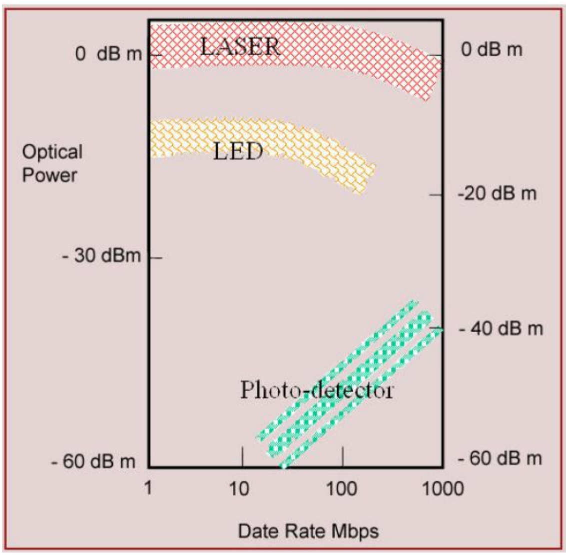
DESIGN OF A SIMPLE POINT-TO-POINT OPTICAL LINK.

A simple point to point link is shown in the following Fig.



The link has primarily 3 components to design.
1. Optical Transmitter.
2. Optical Fiber
3. Optical receiver

The Fig. shows the typical optical power which LEDs and and Lasers can deliver and the photo-detector needs for a BER of 10^{-9}



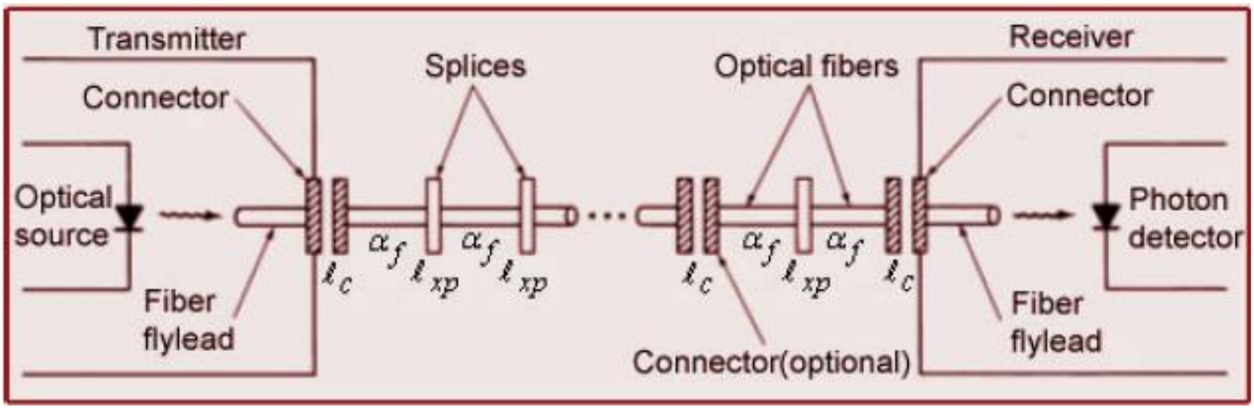
As the data rate increases the power delivering capacity of the source reduces and at the same time the power requirement of the detector increases.
The following table gives the combination of the sources and fibers for different link capacity and distance.

1-10m	10m-.1km	.1-1km	1-3km	3-10km	10-50km	50-100km	>100km	
						LD		10k
	SLED					MM		10-100K
		MM						100K-1M
					LD	GI		1-10M
			LED					10-50M
			GI			LD		50-500M
LD		LD				SM		500M-1G
MM		GI						>1G

Considering the cost, speed etc, first choose the laser and the detector. Also the type of fiber is chosen from the above table. Generally a multi-core fiber is laid even if the immediate requirement is only one or two fibers.
The link design then reduces to finding locations of the repeater on a long link.

Two calculations are carried out in the link design

The Fig. show the power loss model of an optical fiber link. The power is lost in various components like, fiber, connectors, splicing.



The fiber loss depends upon the wavelength and also the physical conditions of the fiber. The fiber loss is generally higher than that the specified by the manufacturers. This is primarily due to micro-bending of the fiber. Also the micro-bending loss is higher for 1550nm compared to 1310nm. Therefore the over all loss could be higher at 1550nm than at 1310nm, although intrinsically silica glass has minimum loss at 1550nm. Typical loss at 1550nm may lie in the range 0.4-0.5 dB/km.

The splice loss could be between 0.05-0.1 dB per splice.
The connector loss is higher and could be 0.2-0.3 dB per connector.

POWER BUDGET CALCULATIONS

Ps = Power from the Transmitter in dBm
Pr = Sensitivity of receiver in dBm for given BER

- Maximum permissible loss

$$\alpha_{max} = P_s - P_r$$

$$\alpha_{max} = \alpha_{fiber} + \alpha_{conn} + \alpha_{splice} + \alpha_{Syst}$$

$$\alpha_{conn} = Nc \times lc \quad ; Nc = Number\ of\ connectors; lc = loss\ of\ connector;$$

$$\alpha_{splice} = Ns \times ls \quad ; Ns = Number\ of\ splicers; ls = loss\ of\ splicer;$$

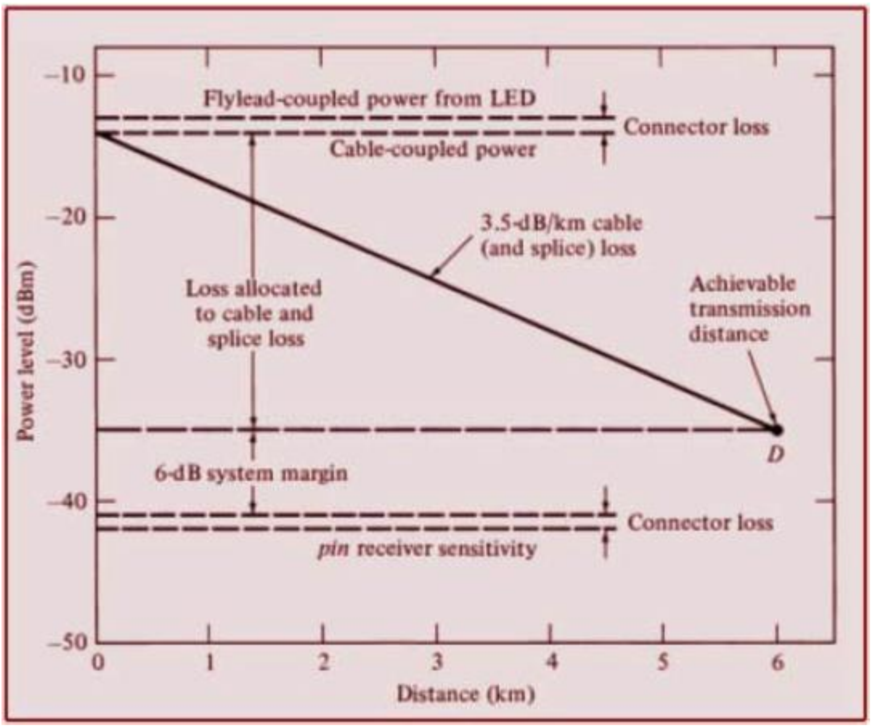
$$\alpha_{Syst} = 6dB\ normally$$

$$\alpha_{fiber} = \alpha_{max} - (\alpha_{conn} + \alpha_{splice} + \alpha_{Syst})$$

- Power limited link length

$$L_{Pmax} = \frac{\alpha_{fiber}}{Loss/Km}$$

Beyond this distance the SNR is below the acceptable limit



System margin is generally taken to be 6 dB to accommodate deterioration of components over time.

RISE TIME BUDGET CALCULATION

- Rise time analysis gives effective bandwidth of the link

$$t_{sys} = \sqrt{t_{tx}^2 + D^2{\sigma_\lambda}^2L^2 + {t_{rx}}^2}$$

- For satisfactory operation of the link (for NRZ format)

$$t_{sys} \leq 0.7T_b$$

$$L_{RT_{max}} = \frac{1}{D\sigma_y}\sqrt{(0.7T_b)^2 - ({t_{tx}}^2 + {t_{rx}}^2)}$$

Beyond this distance the signal distortion is unacceptable

- Rise time of a system or component = 1/bandwidth

Here,

- t_{sys}= Total system rise time.
- t_{tx} = Transmitter rise time
- t_{rx}= Receiver rise time. Generally $t_{rx} >> t_{tx}$.
- D = Dispersion of the fiber
- σ_λ= Spectral width of the transmitter
- L= Length
- T_b= Data bit duration = $\frac{1}{Data\ Rate}$

Note: For RZ data the system rise time t_{sys} should be $\leq 0.35T_b$.

- In the link design two lengths, the power budget length L_{Pmax} and the rise time budget $L_{RT_{max}}$ length are calculated.
- The repeater has to be installed at a distance $\min(L_{Pmax}, L_{RT_{max}})$.

Generally, the links are power limited and the repeaters are installed at L_{Pmax}. Typical

- repeater length is about 50-60 km in practice.

Example : 1

Let us take typical parameters for a link.
Data rate = 1 GHz. ; DFB Laser spectral width = 0.1nm ;
SM fiber dispersion at 1550nm = -20 ps/km/nm = -0.02 ns/km/nm
Rise time of the receiver = 0.1 nsec ; Rise time of the transmitter = 0.1nsec
Fiber loss = 0.4dB/km ; Transmitter power -3 dBm
Min Detectable power -40 dBm ; Neglect splice and connector losses.

$$T_b = \frac{1}{Data\ Rate} = \frac{1}{1GHz} = 1nsec$$

$$L_{RT_{max}} = \frac{1}{D\sigma_y}\{(0.7T_b)^2 - ({t_{tx}}^2 + {t_{rx}}^2)\}^{1/2}$$

$$L_{RT_{max}} = \frac{1}{0.02 \times 0.1}\{(0.7 \times 1)^2 - (0.1^2 + 0.1^2)\}^{1/2} = 178Km$$

$$\alpha_{max} = P_s - P_r = -3 - (-40) = 37dB$$

$$\alpha_{fiber} = \alpha_{max} - \left(\alpha_{conn} + \alpha_{splice} + \alpha_{Syst}\right) = 37 - (0 + 0 + 6) = 31dB$$

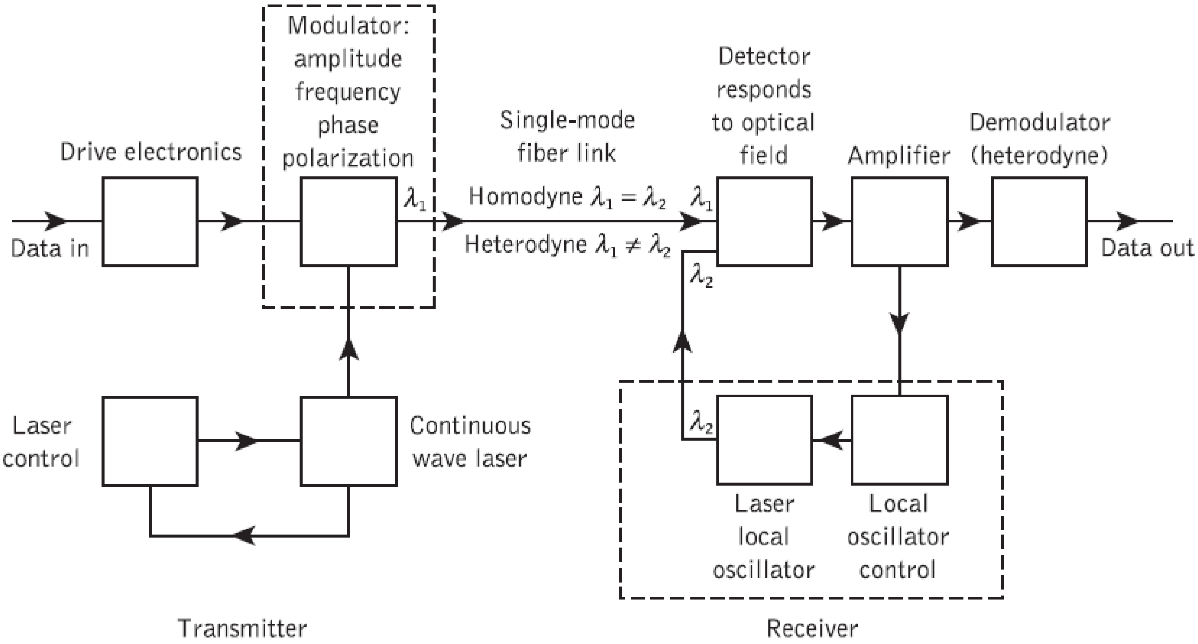
$$L_{Pmax} = \frac{\alpha_{fiber}}{\frac{Loss}{Km}} = \frac{31}{0.4} = 77.5Km$$

Since $L_{Pmax} < L_{RT_{max}}$, the link is power limited and the repeater has to be installed at a distance of less than 77.5Km

Questions for practice

Refer Text Book : Fiber optic communication system –Systems & Components by Mishra & Ugale page nos. 283-288

4.2 BASIC COHERENT SYSTEM



The dashed lines enclose the main elements which distinguish the coherent system from its IM/DD equivalent. At the transmitter a CW narrow-line width semiconductor laser is shown which acts as an optical frequency oscillator. An external optical modulator usually provides amplitude, frequency or phase shift keying of the optical carrier by the information signal.

At the receiver the incoming signal is combined (or mixed) with the optical output from a semiconductor laser local oscillator. The combined signal is then fed to a photo detector for direct detection in the conventional square law device. When the optical frequencies (or wavelengths) of the incoming signal and the local oscillator laser output are identical, then the receiver operates in a homodyne mode and the electrical signal is recovered directly in the baseband. For heterodyne detection, however, the local oscillator frequency is offset from the incoming signal frequency and therefore the electrical spectrum from the output of the detector is centred on an intermediate frequency (IF) which is dependent on the offset and is chosen according to the information transmission rate and the modulation characteristics. This IF, which is a difference signal (or difference frequency), contains the information signal and can be demodulated using standard electrical techniques.

The electrical demodulator is required in particular for an optical heterodyne detection system which can utilize synchronous or asynchronous/ nonsynchronous electrical detection.
Synchronous or coherent demodulation implies an estimation of phase of the IF signal in transferring it to the baseband. Such an approach requires the use of phase-locking techniques in order to follow phase fluctuations in the incoming and local oscillator signals. Alternatively, asynchronous or noncoherent (envelope) IF demodulation schemes may be employed which are less demanding but generally produce a lower, performance than synchronous detection techniques .

Optical homodyne detection is by definition, however, a synchronous demodulation scheme and as the detected signal is brought directly into the baseband, then optical phase estimation is required.

4.2.1 COHERENT DETECTION PRINCIPLES

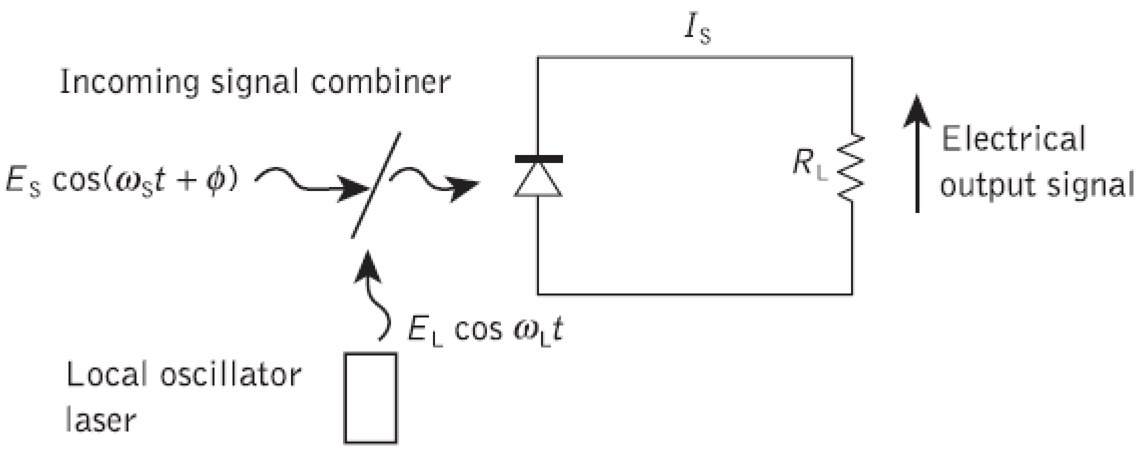


Figure: Basic coherent receiver model

A simple coherent receiver model for ASK is displayed in Figure. The low-level incoming signal field e_S is combined with a second much larger signal field e_L derived from the local oscillator laser. It is assumed that the electromagnetic fields obtained from the two lasers (i.e. the incoming signal and local oscillator devices) can be represented by cosine functions and that the angle $\Phi = \Phi_s - \Phi_L$ represents the phase relationship between the incoming signal phase Φ_s and the local oscillator signal phase Φ_L defined at some arbitrary point in time. The two fields may be written as

$$e_S = E_S \cos(\omega_S t + \Phi) \quad \text{and} \quad e_L = E_L \cos(\omega_L t)$$

where E_S is the peak incoming signal field and ω_S is its angular frequency, and E_L is the peak local oscillator field and ω_L is its angular frequency. The angle $\Phi(t)$ representing the phase relationship between the two fields.

For heterodyne detection, the local oscillator frequency ωL is offset from the incoming signal frequency ω_S by an intermediate frequency such that:

$\omega_S = \omega_L + \omega_{IF}$

where ω_{IF} is the angular frequency of the IF, the IF is usually in the radio-frequency region and may be a few tens or hundreds of megahertz.

By contrast, within homodyne detection there is no offset between ω_S and ω_L and hence $\omega_{IF} = 0$. In this case the combined signal is therefore recovered in the baseband. The two wave fronts from the incoming signal and the local oscillator laser must be perfectly matched at the surface of the photo detector for ideal coherent detection. This factor creates the normal requirement for polarization control of the incoming optical signal.

In the case of both heterodyne and homodyne detection the optical detector produces a signal photocurrent I_p which is proportional to the optical intensity (i.e. the square of the total field for the square-law photodetection process) so that:

$$I_p \propto (e_S + e_L)^2$$

$$I_p \propto [E_S(\cos \omega_S t + \varphi) + E_L \cos \omega_L t]^2$$

$$\begin{aligned}[E_S^2 \cos^2(\omega_S t + \phi) &+ E_L^2 \cos^2 \omega_L t + 2E_S E_L \cos(\omega_S t + \phi)\cos \omega_L t] \\ = [\tfrac{1}{2}E_S^2 &+ \tfrac{1}{2}E_S \cos(2\omega_S t + \phi) + \tfrac{1}{2}E_L^2 + \tfrac{1}{2}\cos 2\omega_L t \\ &+ E_S E_L(\cos \omega_S t + \phi - \omega_L t) + E_S E_L \cos(\omega_S t + \phi + \omega_L t)]\end{aligned}$$

Removing the higher frequency terms oscillating near the frequencies of $2\omega S$ and $2\omega L$ which are beyond the response of the detector and therefore do not appear in its output, we have:

$$I_p \propto \tfrac{1}{2}E_S^2 + \tfrac{1}{2}E_L^2 + 2E_S E_L \cos(\omega_S t - \omega_L t + \phi)$$

Then recalling that the optical power contained within a signal is proportional to the square of its electrical field strength, expression may be written as:

$$I_p \propto P_S + P_L + 2\sqrt{P_S P_L} \cos(\omega_S t - \omega_L t + \phi)$$

where PS and PL are the optical powers in the incoming signal and local oscillator signal respectively.

$$I_p = \frac{\eta e}{hf}[P_S + P_L + 2\sqrt{P_S P_L} \cos(\omega_S t - \omega_L t + \phi)]$$

where η is the quantum efficiency of the photo detector, *e* is the charge on an electron, *h* is Planck's constant and *f* is optical frequency. When the local oscillator signal is much larger than the incoming signal, then the third a.c. term in Eq. may be distinguished from the first two d.c. terms and I_p can be replaced by the approximation I_S where

$$I_S = \frac{\eta e}{hf}[2\sqrt{P_S P_L} \cos(\omega_S t - \omega_L t + \phi)]$$

Equation allows the two coherent detection strategies to be considered. For heterodyne detection $\omega_S \neq \omega_L$

$$I_S = \frac{2\eta e}{hf}\sqrt{P_S P_L} \cos(\omega_{IF} t + \phi)$$

For the special case of homodyne detection, however, $\omega S = \omega L$ and therefore Eq. reduces to:

$$I_S = \frac{2\eta e}{hf}\sqrt{P_S P_L} \cos \phi$$

Or

$$I_S = 2R\sqrt{P_S P_L}\cos\phi$$

where R is the responsivity of the optical detector. In this case the output from the photodiode is in the baseband and the local oscillator laser needs to be phase locked to the incoming optical signal.

When the local oscillator signal power is much greater than the incoming signal power then the dominant noise source in coherent detection schemes becomes the local oscillator quantum noise. In this limit the quantum noise may be expressed as shot noise.

$$\overline{i_{SL}^2} = 2eBI_{pL}$$

Substituting for I_{pL} ,where the photocurrent generated by the local oscillator signal is assumed to be by far the major contribution to the photocurrent, gives:

$$\overline{i_{SL}^2} = \frac{2e^2\eta P_L B}{hf}$$

The detected signal power S, being the square of the average signal photocurrent

$$S = \left(\frac{\eta e}{hf}\right)^2 P_S P_L$$

Hence the SNR for the ideal heterodyne detection receiver when the local oscillator power is large (ignoring the electronic preamplifier thermal noise and photo detector dark current noise terms) may be obtained

$$\left(\frac{S}{N}\right)_{\text{het-lim}} = \left(\frac{\eta e}{hf}\right)^2 P_S P_L \Big/ \frac{2e^2\eta P_L B}{hf} = \frac{\eta P_S}{hf2B} = \frac{\eta P_S}{hfB_{IF}}$$

IF amplifier bandwidth B_{IF} is assumed to be equal to $2B$ (i.e. $B_{IF} = 2B$)

Hence the SNR limit for optical homodyne detection is:

$$\left(\frac{S}{N}\right)_{\text{hom-lim}} = \frac{\eta P_S}{hfB}$$

4.2.2 SENSITIVITY OF COHERENT RECEIVER

BER and Sensitivity of coherent systems depends on modulation format and demodulation scheme used by coherent receiver.

Modulation Format	Bit-Error Rate	N_p	$\bar{N}_p$
ASK heterodyne	$\frac{1}{2}\text{erfc}(\sqrt{\eta N_p/4})$	72	36
ASK homodyne	$\frac{1}{2}\text{erfc}(\sqrt{\eta N_p/2})$	36	18
PSK heterodyne	$\frac{1}{2}\text{erfc}(\sqrt{\eta N_p})$	18	18
PSK homodyne	$\frac{1}{2}\text{erfc}(\sqrt{2\eta N_p})$	9	9
FSK heterodyne	$\frac{1}{2}\text{erfc}(\sqrt{\eta N_p/2})$	36	36
Direct detection	$\frac{1}{2}\exp(-\eta N_p)$	20	10

Table 1 : Sensitivity of synchronous receiver

Modulation Format	Bit-Error Rate	N_p	$\bar{N}_p$
ASK heterodyne	$\frac{1}{2}\exp(-\eta N_p/4)$	80	40
FSK heterodyne	$\frac{1}{2}\exp(-\eta N_p/2)$	40	40
DPSK heterodyne	$\frac{1}{2}\exp(-\eta N_p)$	20	20
Direct detection	$\frac{1}{2}\exp(-\eta N_p)$	20	10

Table 2 : Sensitivity of asynchronous receiver

4.2.3 SENSITIVITY DEGRADATION

Sensitivity of practical systems may degrade due to phase noise, intensity noise, polarization mismatch and fiber dispersion.

1. **Phase Noise**

An approach to solve the phase-noise problem is designing special receivers known as phase-diversity receivers . Such receivers use two or more photo detectors whose outputs are combined to produce a signal that is independent of the phase difference $\emptyset_{IF} = \emptyset_s - \emptyset_{LO}$; . This technique works quite well for ASK, FSK, and DPSK formats. Figure shows schematically a multiport phase-diversity receiver. An Optical component known as an ***Optical hybrid*** combines the signal and local-oscillator inputs and provides its output through several ports with appropriate phase shifts introduced into different branches. The output from each port is processed electronically and combined to provide a current that is independent of $\emptyset_{IF}$. In the case of a two-port homodyne receiver, the two output branches have a relative phase shift of 90°, so that the currents in the two branches vary as $I_p cos\emptyset_{IF}$, and $I_p sin\emptyset_{IF}$. When the two currents are squared and added, the signal becomes independent of $\emptyset_{IF}$. In the ease of three-port receivers, the three branches have relative phase shifts of 0, 120 °, and 240°. Again, when the currents are added and squared, the signal becomes independent of $\emptyset_{IF}$.

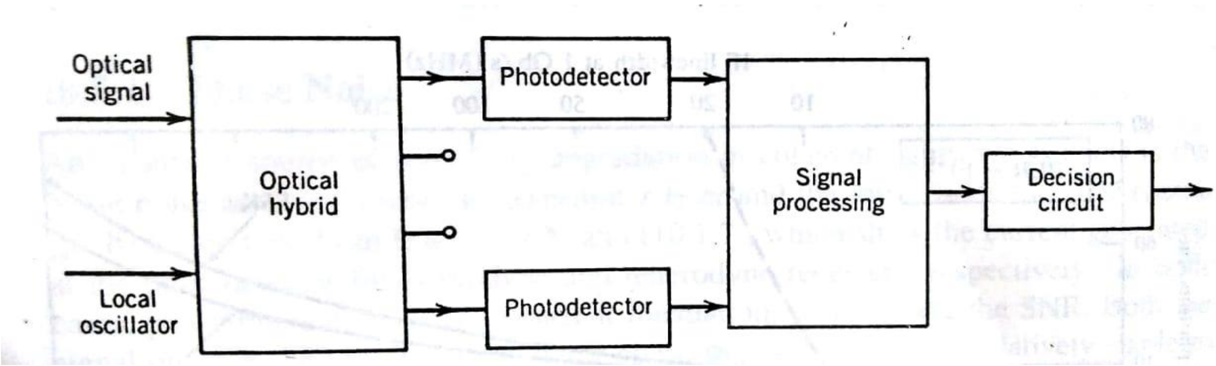


Figure : Phase diversity receiver

2. Intensity Noise

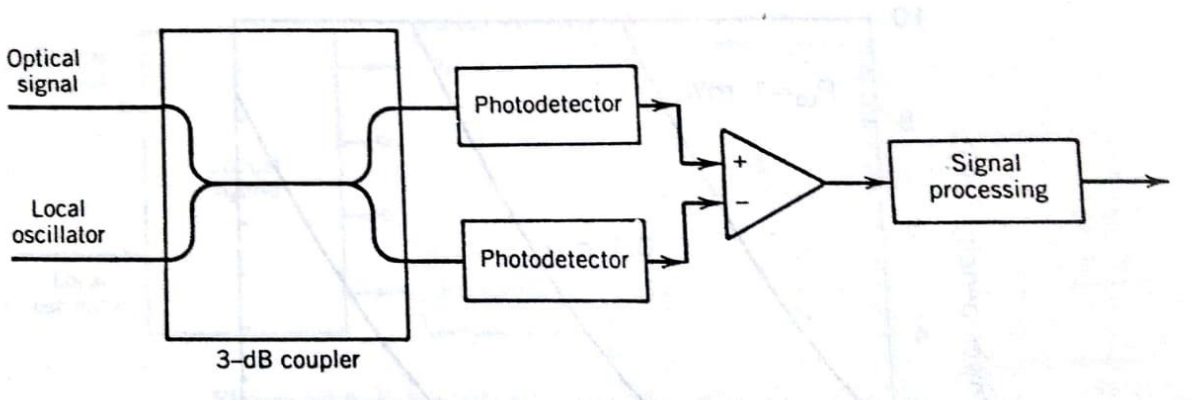
A solution to the intensity-noise problem is offered by the balanced coherent receiver made with two photo detectors. Figure shows the receiver design schematically. A 3-dB fiber coupler mixes the optical signal with the local oscillator and splits the combined optical signal into two equal parts with a 90° relative phase shift. The operation of a balanced receiver can be understood by considering the photocurrents **I⁺** and **I⁻**, generated in each branch. Using the transfer matrix of a 3-dB coupler, the currents **I⁺** and **I⁻** are given by

$$I^{+} = \frac{1}{2}R(P_s + P_{LO}) + R\sqrt{P_S P_{LO}}\cos(\omega_{IF}t + \emptyset_{IF})$$

$$I^{-} = \frac{1}{2}R(P_s + P_{LO}) - R\sqrt{P_S P_{LO}}\cos(\omega_{IF}t + \emptyset_{IF})$$

Where $\emptyset_{IF} = \emptyset_s - \emptyset_{LO} + {}^{\pi}/_{2}$

The subtraction of the two currents provides the heterodyne signal. The dc term is eliminated completely during the subtraction process when the two branches are balanced in such a way that each branch receives equal signal and local-oscillator powers. More importantly, the intensity noise associated with the dc term is also eliminated during the subtraction process. The reason is related to the fact that the same local oscillator provides power to each branch. As a result, intensity fluctuations in the two branches are perfectly correlated and cancel out during subtraction of the photo currents I+ and I-. It should be noted that intensity fluctuations associated with the ac term are not cancelled even in a balanced receiver. However, their impact is less severe on the system performance because of the square-root dependence of the ac term on the local-oscillator power.



Balanced receivers are commonly used while designing a coherent lightwave system because of the two advantages offered by them. First, the intensity-noise problem is nearly eliminated. Second, all of the signal and local-oscillator power is used effectively. A single-port receiver rejects half of the signal power P_S (and half of P_{LO}) during the mixing process. This power loss is equivalent to a 3-dB power penalty. Balanced receivers use all of the signal power and avoid this power penalty. At the same time, all of the local-oscillator power is used by the balanced receiver, making it easier to operate in the shot-noise limit.

3. Polarization mismatch

The most commonly used approach solves the polarization problem by using a two-port receiver, with two branches process orthogonal polarization components. Such receivers are called polarization-diversity receivers as their operation is independent of the polarization state of the signal received.

Figure shows the block diagram of a polarization-diversity receiver. A polarization beam splitter is used to separate the orthogonally polarized components which are processed by separate branches of the two-port receiver. When the photocurrents generated in the two branches are squared and added, the electrical signal becomes polarization independent. The power penalty incurred in following this technique depends on the modulation and demodulation techniques used by the receiver. In the case of synchronous demodulation, the power penalty can be as large as 3 dB. However, the penalty is only 0.4-0.6 dB for optimized asynchronous receivers.

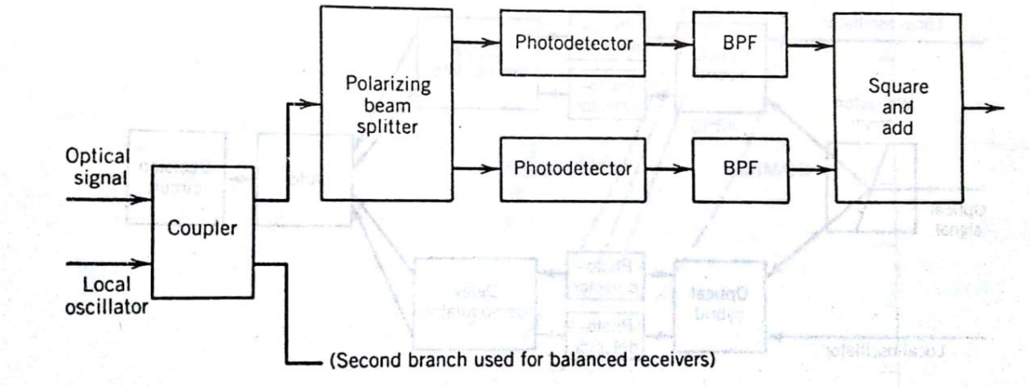


Figure: Polarization –diversity coherent receiver

4. Fiber dispersion

Dispersion becomes a major limiting factor for systems designed with standard fibers when transmission distance is increased using optical amplifiers. Dispersion management would solve this problem. Electronic equalization can be used for compensating dispersion in coherent systems . The basic idea is to pass the intermediate-frequency signal through a filter whose transfer function is the inverse of the transfer function associated with the fiber.

4.3 COMPARISON BETWEEN IMDD & IMCD SYSTEMS

SL.NO	PARAMETERS	IMDD	IMCD
1	Name	Intensity modulated direct detection system	Intensity modulated coherent detection system
2	Eye diagram	Less open eye	More open eye. (The more open the eye the better is the quality of the received signal)
3	sensitivity	Low sensitivity	High sensitivity
4	Gain	Low gain	High gain
5	Power penalty	low	high
6	Unamplified transmission distance	low	high
7	Splitting ratio	low	high

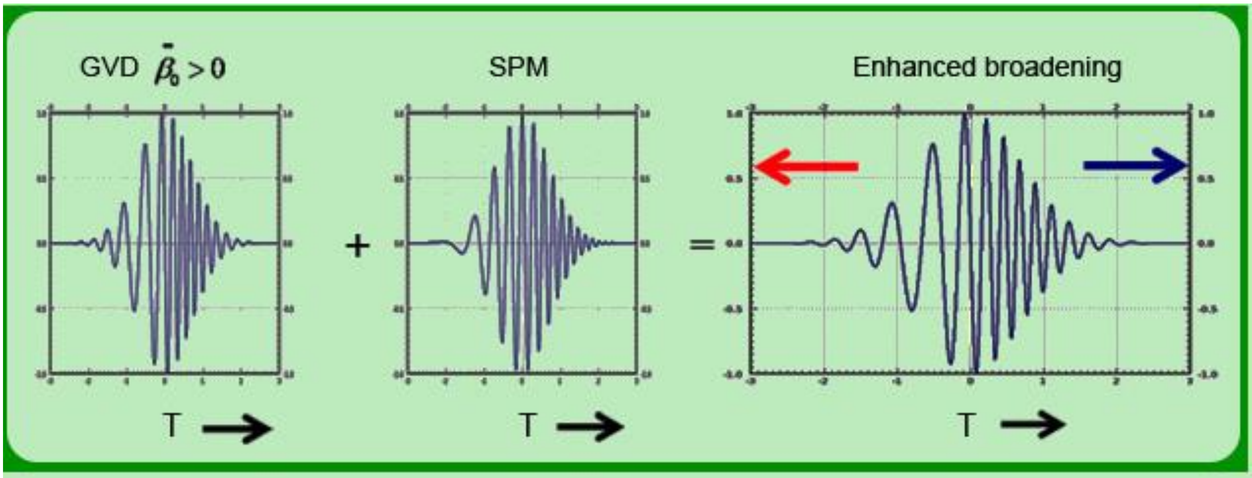
The higher receiver sensitivity, higher splitting ratio and a long unamplified transmission reach makes coherent detection scheme a technology of choice for application in FTTH technology.

4.4 SOLITON SYSTEMS

We can use SPM to compensate for dispersion-caused pulse Spread to keep the pulse width constant over the entire transmission distance. ***Such a pulse, having a constant width, is called a soliton***. A soliton either keeps its width constant or changes it periodically, but its width never exceeds a given value. A soliton, then, is essentially a nonlinear effect because it is based on SPM.

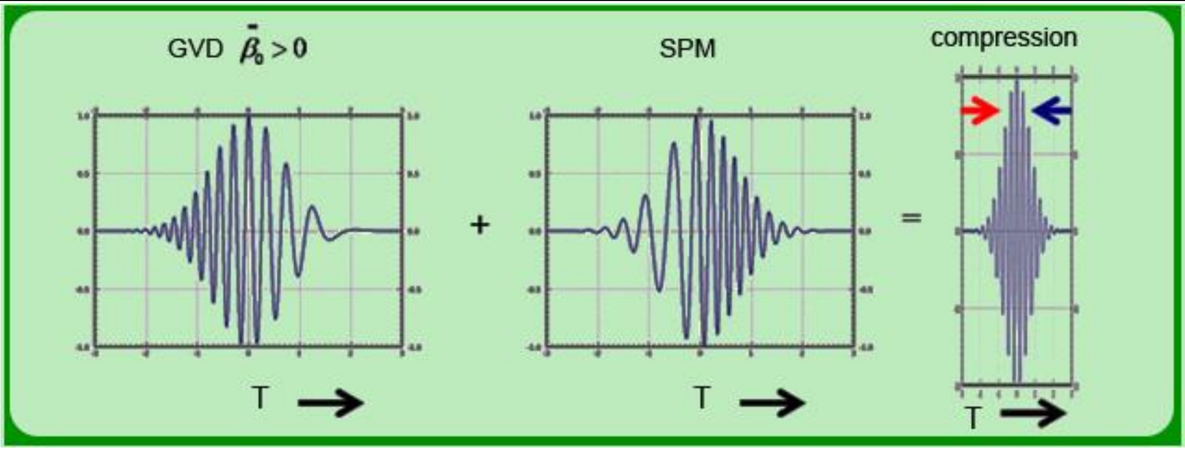
Role of positive GVD and SPM:

SPM leads to the spectrally enriched positively chirped pulse by lowering of the leading edge frequencies i.e. red shifted, and raised for the trailing edge frequencies i.e. blue shifted. Consequently, propagation through a medium with positive GVD, the high frequency components in the trailing edge of the pulse will increasingly lag behind the low frequency components in the leading edge upon propagation as if these two end are being pull apart. This results in the enhanced temporal broadening of the pulse.



Role of -ve GVD and SPM

The positive chirp of spectrally enriched pulse produced by SPM can be removed with subsequent pulse compression. In this case, the high frequency components from the back end try to catch with the low frequency component from the front end due to negative GVD. Consequently, the pulse is compressed as shown in figure



If the two effects, balance each other, the pulse will retain a constant shape which moves like a particle and result in a pulse which retains its shape on propagation which is dynamically and structurally stable like a particle and is called a fundamental soliton. Such a particle like state of the pulse will have strong implications for the transport of signal or information. It is also possible that it rebuilds its shape periodically in space. This is the case of higher order solitons.

4.4.1 SOLITON TRANSMISSION

The soliton pulse able to keep its shape and width steady as a result of mutual compensation of dispersion-broadening and self-phase-modulated narrowing processes.

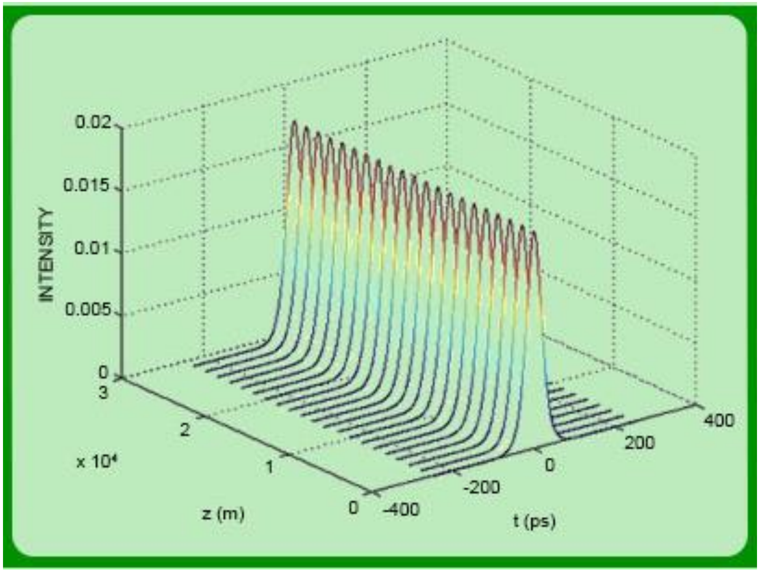


Figure: soliton propagation in one soliton period.

Solitons can be transmitted over a very long fiber link without amplification and dispersion compensation, they look like the most promising transmission technology.

The major challenge in the development of commercial soliton transmission systems is accomplishing soliton transmission over already installed multimillion-mile networks of a standard fiber.

LONG DISTANCE SOLITON TRANSMISSION SYSTEM

Desirable attributes of a communication system are

- Large data bit rates.
- Low transmission losses.
- Easy scalability.

Since transmission bandwidth or the data bit rate of a communication system is proportional to the carrier wave frequency, light waves being the highest frequency waves are therefore, the best suited candidates as information carrier. Further, the availability of low loss fibers, fiber amplifiers and high speed optical modulators has made the optical communication a reality.

Long distance communication systems like submerged trans-Atlantic communication link require that the integrity definition of the data bits or optical pulses is maintained. However, pulse broadening by group velocity dispersion effect in optical fibers will spoil this definition. This can be managed by using repeater stations at regular periods to recover the data bits and retransmit these. Too frequent use of repeater stations add to the complexity and cost of the system. Optical nonlinearity can be exploited to compensate the broadening effects of the group velocity dispersion and generate soliton pulses in optical fibers which maintain their shape with propagation. The long distance soliton communication can, therefore, have great prospects. Nakazawa et-al of NTT(Japan) demonstrated 10Gbits soliton transmission over 1 million kilometer in a land mark paper. Many refinements have been reported since then. The obvious wave length choice for soliton system is 1500nm fiber window as it offers lowest 1.55µm and –ve GVD.

For a typical fiber having A_{eff} **=50µm** operating λo= 1500nm the soliton power, energy and period are given by

$$P = \frac{1.34D}{(\Delta t)^2} W; E = \frac{1.53D}{(\Delta t)} pJ \text{ and } Z_0 = \frac{0.42(\Delta t)^2}{D} Km$$

$$\Delta t - FWHW \text{ in } ps$$

$$D - ps/nm/Km$$

$$\text{taking } D = 1 ps/nm/km \text{ gives}$$

$$P = \frac{1.34D}{(\Delta t)^2} W; E = \frac{1.53}{(\Delta t)} pJ \ and \ Z_0 = 0.42(\Delta t)^2 Km$$

To achieve high bandwidths, soliton pulse duration should be small. However smaller duration soliton requires large peak powers and energy. The choice of input pulse width then will depend upon the semiconductor laser source.

As an example let us consider the duration of soliton pulses $\Delta t = 25ps$

$P_1 = 2.1 mW$

$\Rightarrow P = 2.1mW$ Achievable using semiconductor laser sources

$\Rightarrow Z_0 = 263km$ need amplification for $Z_0 > A_{eff}$

To avoid soliton- soliton interaction of adjacent pulse (e.g. 11000 type pattern) separation between solitons should be several times the soliton width(say times) i.e.

$5 \times \Delta t = 125 ps$

$$data \ BW = \frac{1}{125ps} = 8GHz$$

There are several factors that affect the performance of the long distance soliton system. In the following we address some of these limitations and remedies to overcome these.

4.4.2 LIMITATIONS OF SOLITONS

1. FIBER LOSS:

The power requirement of the fundamental soliton of given pulse width is

$$P_1 = \frac{0.776 \lambda^3 D A_{eff}}{\pi^2 C n_2 \tau^2}$$

If fiber loss is small over soliton period, Zo, then pulse will adiabatically adjust its width to conform to power requirement for N=1 Soliton. However, this limits the communication distance. To overcome this limitation, one can use the distributed Raman gain amplification .Taking fiber loss to be 0.2dB/km, 3 dB loss will result after propagation distance L=15 km. Also when input power drops by a factor of 2, the soliton will become a normal dispersive pulse i.e. non-soliton propagation. Hence for long distance it is necessary to amplify the signal periodically.

Solitons arise as a balance of the phase shifts arising from nonlinearity & dispersion

- The balance occurs for $Z_0 > L$

By making length of fiber amplifier $L_a < Z_0$ so that the phase change in each amplifier segment is small, average dispersion can be cancelled by the average nonlinear phase shift. Hence Soliton System can even be realized with lumped amplification which can be easily realized using Erbium doped fiber amplifiers arranged periodically in a chain.

The significance of Er doped fiber amplifier is that

- It can provide amplification for signal in the low loss region of 1520-1580 nm range.
- Pump power are modest ~tens of mw.
- Pumping possible with 1480 nm In Ga As/ in gap MQW Lasers.
- Gain of up to 25dB.

The gain factor of the amplifier has to be such that the gain $\boldsymbol{g = e^{\alpha Z_a}}$ exactly compensates the loss.
For a fiber having loss of

$$0.2 \text{ dB/km} \rightarrow \alpha = 0.046/km$$

Let

$$z_a = 0.1 \times Z_0 = 0.1 \times 263 km$$
$$= 25 \ km$$
$$\Rightarrow g = 3.16$$

To compensate for the loss we need to launch power greater than necessary for exciting N=1 soliton.
Thus to have "average N=1 " soliton it can be shown that we require

$$N = \left[\frac{\ln g}{1 - \frac{1}{g}} \right]^{1/2}$$
$$\Rightarrow N = 1.3$$

For the example of 25ps fundamental soliton N=1 in a lossless system, one requires

$$P_1 = 2.1 mW$$

Therefore power required for N =1.3 soliton is

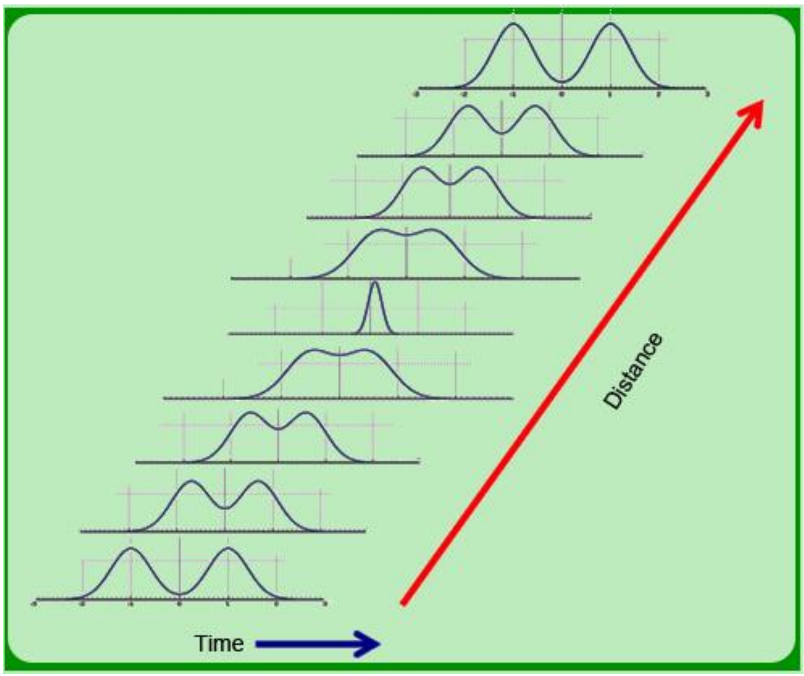
$$P_N = N^2 P_1 = (1.3)^2 \times 2.1 mW = 3.55 mW$$

2.SOLITON- SOLITON INTERACTIONS

Maximum data rate is determined by how close two adjacent pulse/bits can be packed. To determine how close two solitons can propagate without interacting one needs to solve nonlinear Schrödinger equation numerically with initial condition

$$u(z=0,t) = \text{sech}(t-\Delta) + \text{sech}(t+\Delta)e^{j\theta}$$

where Δ is their initial separation and θ is their relative phase. Note that $\Delta = 0$ $gives\ N = 2$ bound soliton while $\Delta = \infty$ will correspond to two independent single solitons. Evolution of two co-propagating solitons with $\Delta = 3.5$ is shown in figure . It can be seen that these collapse and separate with an oscillation period $Z_0 e^{\Delta}$
This process is referred as "Brother Soliton".



If the relative phase "θ" between adjacent solitons is such that $\theta \neq 0$ then they experience repulsive force.

Propagation over Length $L_c = \frac{\pi}{2}e^{\Delta}$ results in collapse of two in-phase soliton and distance Δ apart at input. By choosing the soliton travel length $L_T < L_C$ soliton collapse can be avoided. In practice soliton separation has to be 5-10 X soliton width. Hence using 1 ps soliton data transmission rates ~100-200 G bits /s can be realized. 10 ps soliton will provide data rates of 10-20 Gbits/s and 25ps soliton will enable only 4-8Gbits/s data rates.

1. AMPLIFIER INDUCED PULSE JITTER & THE GORDON-HAUS (GH) EFFECT

The soliton central frequency can also affected by ASE induced by optical amplifiers. ASE induced noise produce random frequency variations (σ_{jitter}),which can be translated into time variations at the pulse output. This phenomenon is called Gordon–Haus effect. Soliton transmission is susceptible to Gordon –Haus effect, which results in a reduction of overall system transmission capability.

The soliton pulses are affected by two sources.

- Fluctuation of pulse energy of soliton
- Pulse arrival time at the end of fiber.

The Gordon-Haus effect is due to the combination of fluctuations in the center frequency of optical pulses with the timing. Therefore, a change in the center frequency causes a change in group velocity, which in turn affects the pulse timing.

Gordon and Haus considered the noise in a fiber-optic link in periodically spaced fiber amplifiers. In these amplifiers, it is assumed that they have a wavelength-independent gain that introduces a quantum noise. This noise randomly causes a shift in the optical center frequency. With more and more shift in the center, the timing deviations of pulses accumulate. The cumulative effect of these deviations causes growing timing errors.

The Gordon-Haus analysis was based on soliton pulse propagation for long-haul data transmission. This jitter can be suppressed considerably by using regularly spaced optical filters, or amplifiers having a limited gain bandwidth. In case of mode locked lasers there is an effect of timing drift, due to the Gordon-Haus jitter.

The perturbing Gordon-Haus effect can be reduced considerably by adopting the following measures.Use narrow-band frequency-guiding filters periodically distributed along the transmission line. Key is that the filters are opaque to noise but transparent to solitons.

Use post- transmission dispersion compensation. This can reduce jitter up to a factor of 2.

4.4.3 ADVANTAGES OF SOLITON BASED COMMUNICATION SYSTEMS

Solitons are unaffected by an effect called PMD due to the imperfection in the circular symmetry fiber which leads to a small and variable difference between the propagation constants of orthogonal polarized modes. This dispersion becomes a major problem over long distances and at high data rates.

- Solitons are well matched with all optical processing techniques. Our long term goal is to create networks in which all of the key high-speed functions, including routing, demultiplexing and switching are performed in the optical domain. So the signals need not be converted into an electrical form on the way. Most of the devices and techniques designed for these tasks work only with well-separated optical pulses, which are particularly effective with solitons.
- If the solitons are controlled properly they can be more robust than NRZ pulses. Schemes have been devised that can not only provide control over the temporal positions of the solitons, but also remove noise added by amplifiers. Such schemes would allow the separations between amplifiers to be many times greater than in the schemes that are used with NRZ pulses. The particle nature of solitons can be employed for sliding-frequency guiding optical filters along the link. With these cantered at slightly reducing wavelengths along the path, the soliton is capable of following this change without any degradation.
- The use of in-line saturable absorbers, which work in the time domain to suppress noise. The particle feature of solitons *is* also very useful to perform various all optical functions such as switching.
- Yet another and very important particle feature is the fact that solitons tend to stay together in presence of a walk-off between different polarization components - so called PMD. The soliton PMD robustness may be a key to success when upgrading existing fiber links to high speed.
- Solitons would replace the traditional NRZ with RZ modulations, which are used in almost all commercial terrestrial WDM systems. Typically the design of a conventional WDM system involves an effort to increase the power as much as possible to counteract attenuation and noise without introducing too much nonlinearity. Thus NRZ and RZ systems are often called linear system. Recent advancements in soliton communication with 3.2T b/s have been demonstrated.

4.4.4 APPLICATIONS OF SOLITONS

The effects due to nonlinearity and dispersion are destructive in OFC but useful in Optical Soliton Fiber Communication (OSFC) systems.
The soliton type pulses are highly stable. Their transmission rate is more than 100 times better than that in the best linear system. They are not affected by the imperfections in the fiber geometry or structure. Soliton can be propagated without any distortion if the nonlinear characteristics like amplitude, intensity of the pulse-depending on velocity and the dispersion characteristics like frequency-depending on velocity of the media, are balanced. Soliton can also be multiplexed at several wavelengths without interaction between the channels, though they usually suffered in Non Return to Zero (NRZ) systems. Nowadays, most of the communication systems use RZ format, for example Transoceanic Transmission (TOT) where the transmission rate is 10 G b/s per channel, transmits the information transfer in dispersion managed fibers. This format is the only stable form for pulse propagation through the fiber in the presence of fiber nonlinearity and dispersion in all optical transmission lines with minimum loss.

In dispersion managed fibers, a large pulse width is allowed, pulse height is reduced and nonlinear interactions between adjacent pulses as well as among different wavelength channels are reduced . Not only in he field of communication, solitons also find application in the construction of optical switches , soliton laser, pulse compression and the like.

MODULE V

OPTICAL AMPLIFIERS

In long distance communication systems, the attenuation in fibers and various losses due to optical components (such as multiplexers and couplers) are compensated by inserting regenerative repeaters at equidistant points. Due to the cumulative loss of signal strength, the signal becomes too weak to be detected; the signal strength has to be restored before the signal gets buried under background noise. This task is accomplished by a regenerative repeater.

5.1 BASIC CONCEPT

A regenerative repeater converts the optical signal to an electrical signal and restores the signal, that is, it compensates for signal loss and dispersion, and converts the signal back into an optical signal for further transmission.

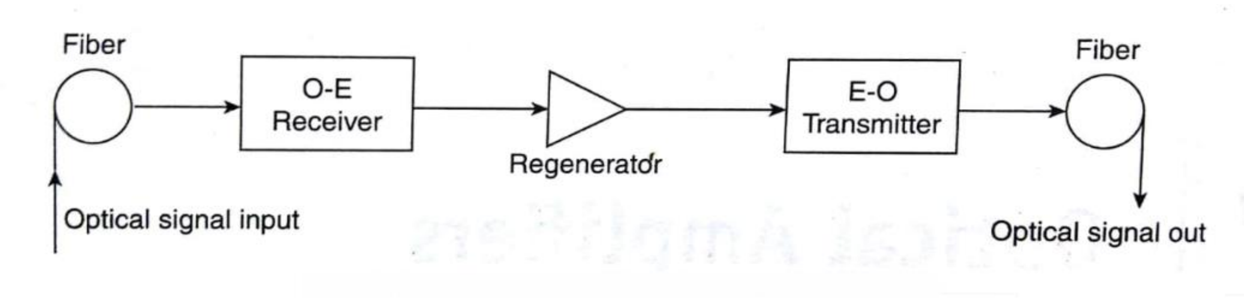


Figure 5.1 : Block Diagram of repeater.

The various functional blocks involved in regenerative repeaters are shown in Fig. the job of repeater is different than being only an amplifier. A repeater receives the signal, converts it to an electrical signal, re-clocks and re-shapes it, amplifies it, and converts it back to an optical signal before coupling the signal back in the optical fiber. It is important to mention that this process is code and timing-sensitive. The repeaters have to be designed to handle the transmission code and the timing scheme. This process works well for moderate-speed, single-wavelength operation; it is very complex and expensive for high-speed, multiple-wavelength systems. Many researchers have worked hard to find an amplifying device which works in the entire optical domain.

Optical amplifiers have many advantages over repeaters, such as:

1. Optical amplifiers are insensitive to the bit rate or signal formats. Thus, a system using optical amplifiers can be more easily upgraded to a higher bit rate, without replacing the amplifier.

2. Optical amplifiers have fairly large gain bandwidths and as a consequence, a single amplifier can simultaneously amplify several wavelength division multiplexing (WDM) signals, in contrast to a separate regenerator for each wavelength.

Thus, optical amplifiers have become an essential component in high-performance optical communication systems.

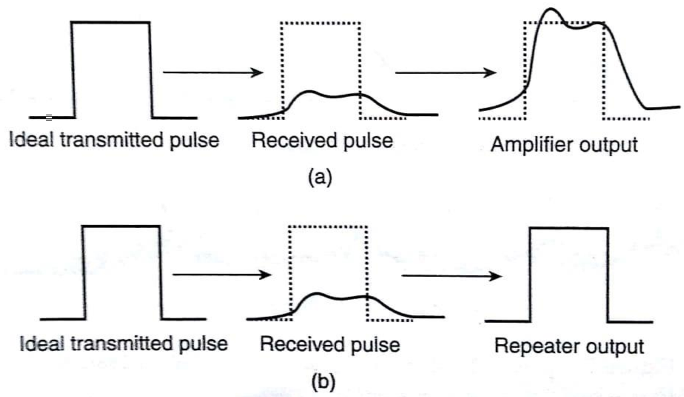


Figure 5.2 : (a) Amplifier Function (b) Repeater Function.

5.2 APPLICATIONS

Optical amplifiers can be used 1n both linear and non-linear modes of operation. The common applications are

1. **In-line optical amplifiers**: Optical amplifiers are used as optical linear repeaters in a long-haul transmission system. In optical transmission systems that use single longitudinal mode lasers, the effects of fiber dispersion may be small, and the main limitation on repeater spacing is the signal attenuation as a result of fiber loss. Such systems do not require a complete regeneration of the signal at each repeater, and linear amplification of the signal is sufficient. Thus, linear optical amplifiers can be used as repeaters. The gain of each amplifier is chosen to compensate exactly for the signal loss incurred in the preceding

$$G = e^{+\alpha L}$$

2. **Preamplifier**: Optical amplifiers are used as pre-amplifiers to boost weak optical signals before detection. Use of a semiconductor laser amplifier before a photodetector to linearly amplify the optical signal can increase the detection sensitivity. The improvement can be particularly significant for bit rates in excess of 1 Gbit/s.

3. **Power amplifier**: Power or booster amplifiers are placed immediately after an optical transmitter to boost the transmitted power. The amplifier inputs are generally -8 dBm or greater, and the power amplifier gain must be greater than 5 dB in order for it to be more advantageous than using a pre-amplifier at the receiver. For example, this boosting technique, when used along with an optical pre-amplifier at the receiving end, can enable repeater-less undersea transmission up to distances of 200-250 km. It can also be used as an optical gain block to compensate for losses in splitting networks, for example, to provide fan-out capability for future optical networks.

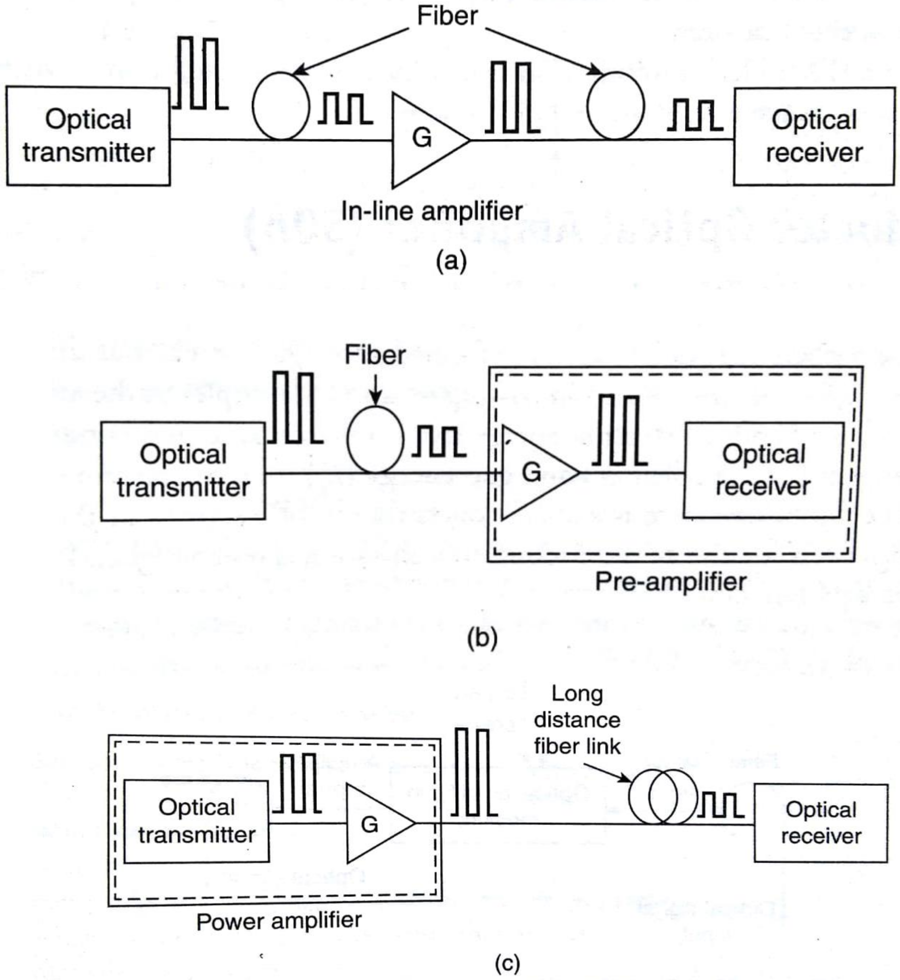


Figure 5.3 : (a) In-line amplifier (b) Pre amplifier (c) Power amplifier

5.3 TYPES OF OPTICAL AMPLIFIERS

An optical amplifier is a single in-line component as shown in Fig.5.4. It does not require electrical-to-optical and optical-to-electrical conversions, in contrast to a repeater. All optical fiber amplifiers increase the power level of incident light through stimulated emission or an optical power transfer process. Here, the device absorbs the energy supplied from an external source, called a pump. The pump supplies energy to electrons in an active medium and raises them to higher energy levels to produce population inversion. The incoming signal photon triggers these excited electrons to drop to lower levels through a stimulated emission process. One incoming trigger photon stimulates many excited electrons to emit photons of equal energy, thus producing an amplified optical signal.

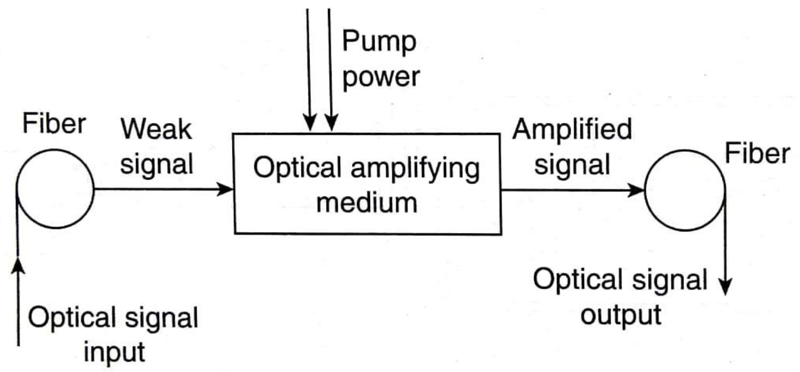


Fig.5.4 : block diagram of Optical amplifier

Two main categories of optical amplifiers are as follows:

1. **Cavity amplifier /semiconductor optical amplifiers (SOAs)**: Here amplification is done by simulated emission from injected carriers.
2. **Fiber amplifiers (PA):** Here amplification is provided by stimulated Raman scattering or doping with rare-earth materials, such as erbium (Er) or thulium

5.3.1 SEMICONDUCTOR OPLTICAL AMPLIFIER (SOA)

The S0A is basically a pn junction as shown in Fig. 5.4 .Light is amplified through stimulated emission when it propagates through the active region. The depletion region formed at the Junction acts as the active region The two ends of the active region are given an anti-reflection coating to eliminate ripples in the amplifier gain.

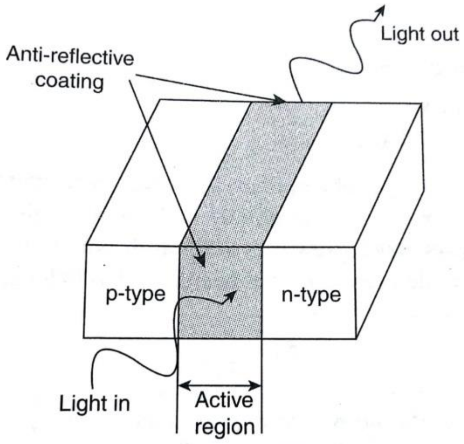


Figure: 5.4 Block diagram of SOA

A semiconductor consists of two bands of electron energy levels: valence band and conduction band. The bands are separated by an energy difference called as band gap energy (Eg.) In a p type semiconductor material shown in Fig. 5.5 at thermal equilibrium there is a small concentration of electrons in the conduction band. However, in the population inversion condition, the electron concentration is much higher. Population inversion is achieved by forward biasing a pn junction.

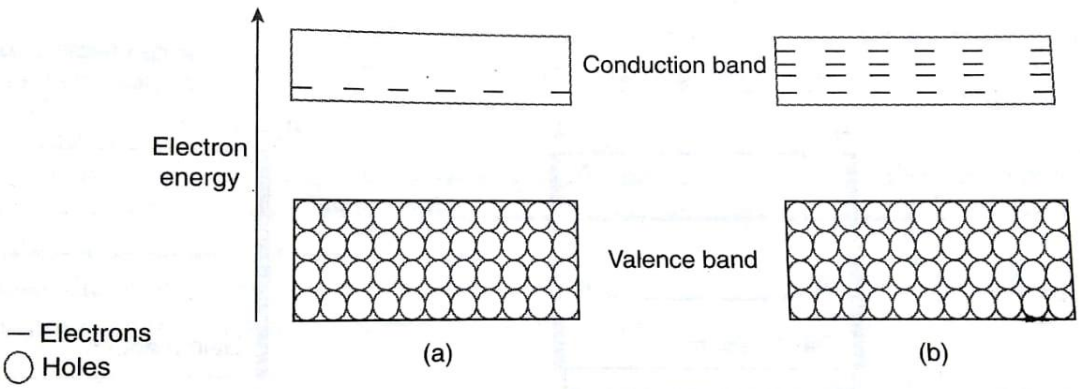


Fig. 5.5 Energy bands and electron concentration in p-type semiconductor at (a) Thermal equilibrium (b) Population inversion

In a pn junction the holes diffuse from the P-type semiconductor to the n-type semiconductor, and electrons diffuse from the n-type semiconductor to the p-type semiconductor and form a depletion region. When the junction is forward-biased the width of depletion region reduces and there is a drift of electrons from n type region to p-type region. which increases the electron concentration in the conduction band of p type region. This results in population inversion with sufficiently high forward bias.in this case pn junction act as an optical amplifier.

The following are the characteristics of a SOA

1. Polarization dependent requires a polarization maintaining fiber.
2. Relatively high gain ~20 dB.
3. Output saturation power 5-10 dBm.
4. Large bandwidth.
5. Can operate in the 800, 1,300, and 1,500 nm wavelength regions.
6. Compact and can be easily integrated with other devices.
7. Can be integrated into arrays
8. High noise figure and crosstalk levels due to non-linear phenomena such as 4-wave mixing.

5.3.1.1 Types of SOA

SOAs can be classified into two main groups:

1. Fabry-Perot amplifiers (FPAs).
2. Traveling wave amplifiers (TWAs).

The main difference between the two types of amplifiers is the facet reflectivity, as shown in Fig. 5.6 In FPAs. the facet reflectivities are of the order of 0.01 to 0.3 and a highly resonant amplifier is formed. The transmission characteristic comprises very narrow pass bands as shown in Fig.5.7. The mode zero corresponds to peak gain wavelength and the mode spacing $\delta\lambda$ can be obtained as follows:

$$\delta\lambda = \frac{\lambda^2}{2nL}$$

FPAs are normally biased below the normal lasing threshold current, and light entering one facet appears amplified at the other facet, together with inherent noise. These devices are very sensitive to fluctuations in bias current. temperature, and signal polarization. Because of their resonant nature and high internal field. they are used in non-linear applications such as pulse shaping and bistable elements.

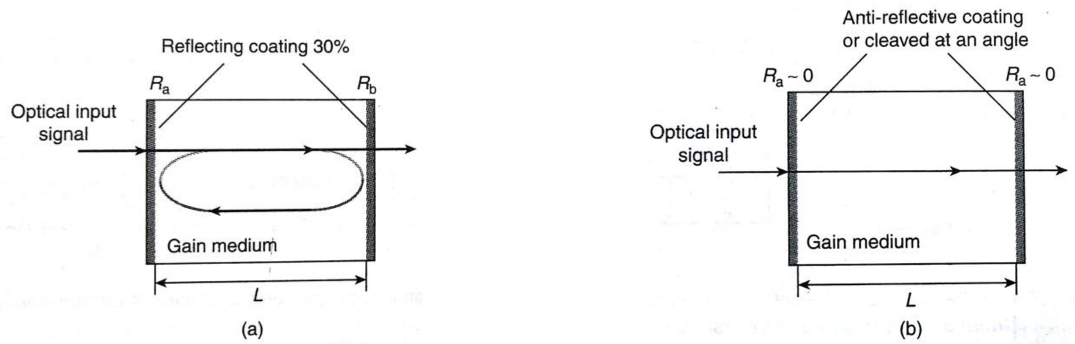


Fig 5.6 (a).Fabry-perot amplifier (b). Travelling wave amplifier

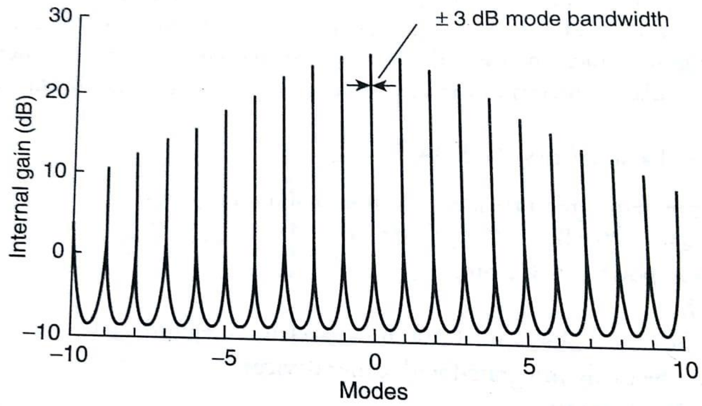


Fig: 5.7 Fabry-Perot amplifier pass band

In traveling wave SOAs, to eliminate or reduce the end reflectivities, a thin layer of silicon oxide or silicon nitride is applied on the end facets. The reflectivities are reduced to l x 10^{-3} or less; this operates the traveling wave amplifier (TWA) in the single-pass amplification mode. The effects of this are: suppressed resonance, increased spectral bandwidth, and increased lasing current threshold. This also makes the transmission characteristics less dependent upon fluctuations in bias current, temperature, and input signal polarization. Hence, TWAs are superior to FPAs, particularly for linear applications. When compared to an FPA, a TWA requires significantly higher bias currents for operation. The narrow spectral bandwidth of FPAs provides inherent noise filtering, which is not obtained with TWAs. Therefore, they are subject to increased level of noise.

5.3.2 RAMAN AMPLIFIER

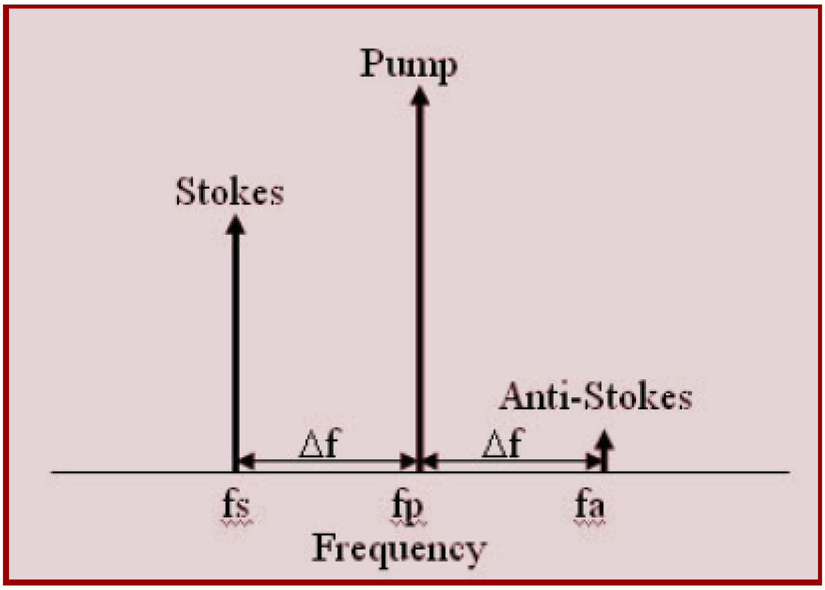
Raman scattering, especially if it is stimulated, is a very important non-linear effect because it affects the SNR in a WDM system. It can also be used for amplification of the optical signals in a long haul optical communication link.

Incase of spontaneous Raman scattering, a small portion of the incident light is transformed into a new wave with lower or higher frequency. This transformation is because of the interaction of the photon with the vibrational modes of the material. The transformation efficiency of spontaneous Raman scattering is very low. Typically photons 1 part per million are transformed to the new wavelength per cm length of the medium.
Contrary to spontaneous Raman scattering, stimulated Raman scattering can transform a large fraction of the incident light in the new frequency-shifted wave.

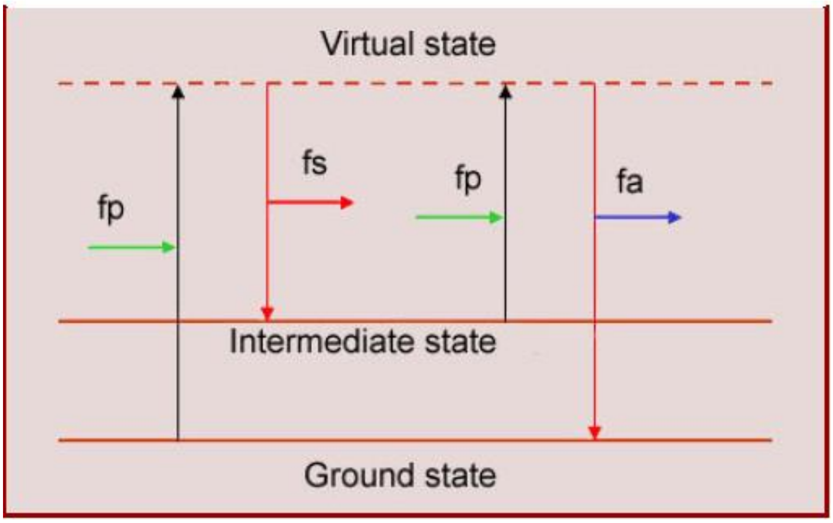
ORIGIN OF RAMAN SCATTERING

In principle, spontaneous Raman scattering can be observed in any material. If a medium is irradiated by an intense monochromatic light and if the scattered light is studied with a spectrometer, the scattered light shows new wavelengths in addition to the original wavelength.
The wave which irradiates the material is called the Pump wave, the waves with lower frequencies are called the Stokes waves, and the waves with higher frequency are called

the Anti-Stokes waves.
The intensity of the Stokes waves is many orders of magnitude higher than the intensity of the anti-Stokes waves as shown in Fig.



The origin of the generation of the new frequencies lies in the energy exchange between the photons and the material molecules. The quantum-mechanical energy diagram for Raman scattering is shown in Fig.



In the Stokes generation process, the incoming photon of frequency f_p excites a molecule from the ground state to the virtual state. The molecule returns to the intermediate state releasing a Stokes photon of frequency f_s . Since the energy difference between the virtual and intermediate levels is smaller then the energy difference between the ground an the virtual states, the frequency of the Stokes photon is lower than the incident photon ($f_s < f_p$).
In the anti-Stokes generation process, the incoming photon of frequency f_p excites a

molecule from the intermediate state to the virtual state. The molecule returns to the ground state releasing a anti-Stokes photon of frequency f_a . Since the energy difference between the virtual and intermediate levels is smaller then the energy difference between the ground an the virtual states, the frequency of the anti-Stokes photon is higher than the incident photon ($f_a > f_p$).

If energy difference between the intermediate level and the ground level is , $\Delta E = h\Delta f$ where is the Planck's constant, then we get

$$f_s = f_p - \Delta f = f_p - \frac{\Delta E}{h}$$

Energy ΔE is the vibrational energy and in the stokes generation process it is delivered to the molecule.

In anti-Stoke generation process, the molecule supplies vibrational energy to the photon increasing the total energy of the incident photon. In thermal equilibrium, the density of molecules in the intermediate state is much smaller than the density in the ground state, and therefore the number of anti-Stokes photons is much smaller compared to that of the Stokes photons.

The vibrational energy depends upon the molecular resonances.

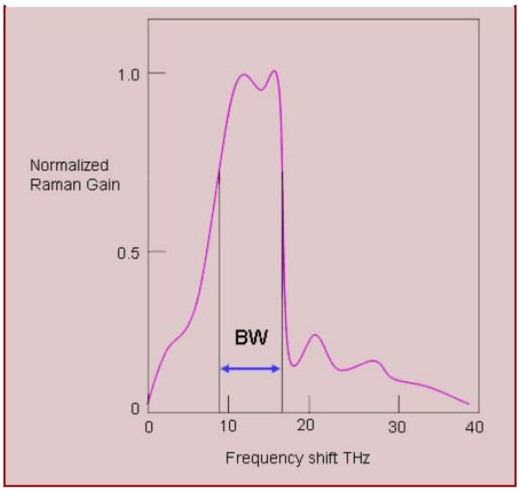
The Raman scattering depends upon particular material resonances. In crystalline material these resonances show a very narrow bandwidth. Therefore the frequencies of the Stokes and the anti-Stokes waves reflect material property. This fact made the Raman scattering a useful tool in the filed of spectroscopy.

Raman Scattering in Optical Fibers

The basic material used in optical fibers is glass which is not crystalline but is amorphous in nature. The molecular resonance frequencies of the vibrational modes in glass are overlapped with each other to give a rather broad frequency band. The optical fibers therefore show Raman scattering over a large frequency range.

The energy conversion process between the pump and the Stokes is characterized by a parameter called the Raman Gain , g_R. The Raman gain depends mainly on the material composition of the fiber core and contained dopants.

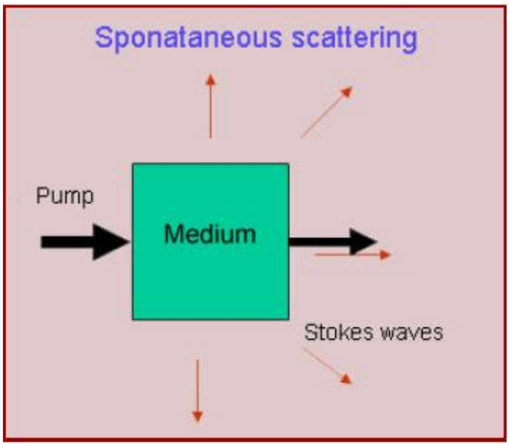
A typical Raman gain spectrum of silica glass fiber is shown in Fig.

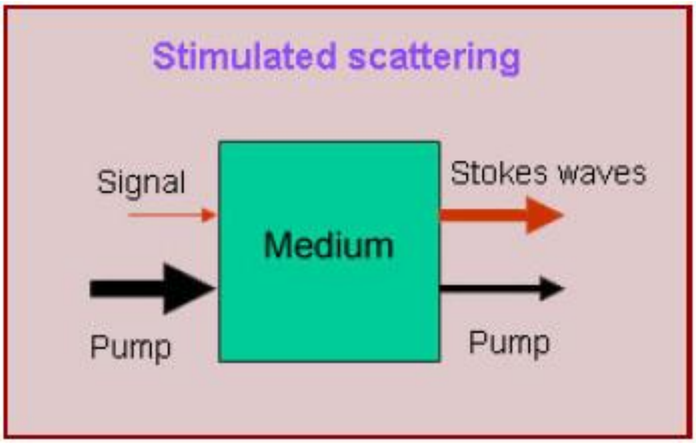


The Raman gain for silica glass has one main and many small side maxima.
If minor peaks in the spectrum are includes, the Raman gain has a wide bandwidth of about 40 THz.
The maximum gain is practically constant over a bandwidth from 9THz to 16THz. The mean of the high gain region is around **13THz (** which at 1550nm wavelength corresponds to Δλ=112nm) . The maximum Raman gain in pure glass is .$g_{Rmax} = 1.9 \times 10^{-13} m/W$
Raman gain is inversely proportional to the wavelength of the pump and depends on the polarization of the wave. The Raman gain is much higher for parallel polarization (when the pump and the stokes waves have same polarization) compared to that for the perpendicular polarization (i.e. when the pump and the Stokes waves have orthogonal polarization).
In optical fiber however, due to birefringence, the polarization states of the pump and the Stokes wave change continuously and if the fiber is long enough, the effective Raman gain is the mean of the parallel and perpendicular gains. So in a fiber we may say that the Raman gain is polarization independent.
Raman scattering can be seen in the forward as well as backward direction. In optical communication the forward Raman scattering is of importance since it causes cross talk in a multi channel WDM system. Backward scattering can be exploited for signal amplification in Fiber Raman Amplifier.

FIBER RAMAN AMPLIFIER

For optical amplification we need stimulated Raman scattering. The basic difference between spontaneous and stimulated Raman scattering is shown in Fig.





If the intensity of the incident field is below a threshold, spontaneous scattering occurs The important thing to note is, the stimulated process can be used for light amplification. If a small signal at Stokes frequency is present along with the pump, the signal gets amplified keeping all the characteristics of the input signal.
The differential equations governing the intensities of the pump and the Stokes waves are

$$\frac{dI_s}{dz} = g_R I_p I_s - \alpha_s I_s \quad \text{..........................(A)}$$

$\frac{dI_p}{dz} = -\frac{\omega_p}{\omega_s} g_R I_p I_s - \alpha_p I_s$ ……………………..(B)

where I_p, I_s are the intensities of the pump and the signal respectively. ω_p, ω_s are the frequencies and α_p, α_s are the attenuation constants of the pump and the stokes waves.

The equations show that the Stokes grows exponentially with distance whereas the pump decays exponentially with distance.
In first approximation it is generally assumed that the pump depletion due Raman scattering is small. The first term on the RHS in equation (B) can be neglected. The pump then decays along the fiber due to fiber attenuation and its intensity is given by

$I_p = I_p(0)e^{-\alpha_p Z}$ ………………………………..(C)

Introducing I_p in (A) we get intensity of the Stokes wave as

$$I_s = I_s(0)\exp\left[g_R I_p(0) L_{eff} - \alpha_s z\right]$$

Where L_{eff} is the effective interaction length of the pump and is given as

$$L_{eff} = \frac{1 - e^{-\alpha_p z}}{\alpha_p}$$

For long fibers

$$L_{eff} = \frac{1}{\alpha_p}$$

The threshold for stimulated scattering is defined as input intensity I_{pth} value of the pump for which Stoke wave shows gain in the fiber. The Raman gain process then must exceed the fiber loss to give

$$g_R I_{pth} L_{eff} \approx \alpha_s z$$

Assuming that the length of the fiber is approximately L_{eff} , we can get threshold intensity for Stimulated Raman Scattering (SRS) as

$$I_{pth} \approx \frac{\alpha_s}{g_R}$$

For a SM fiber typically the core effective area is 80μm^2,$\alpha \approx 0.2dB/km$ and , Raman gain Is 7×10^{-14} mW, the Raman threshold power

$$P_{th} = I_{pth} A_{eff} \approx 53mW.$$

Note:
The threshold given above just tells that above this pump power the ther will be gain for any signal above the noise. However still the Stokes power is orders of magnitude smaller than the Pump.

If we define the threshold as the input power for which the output powers of pump and Stokes are equal, then its value is approximately

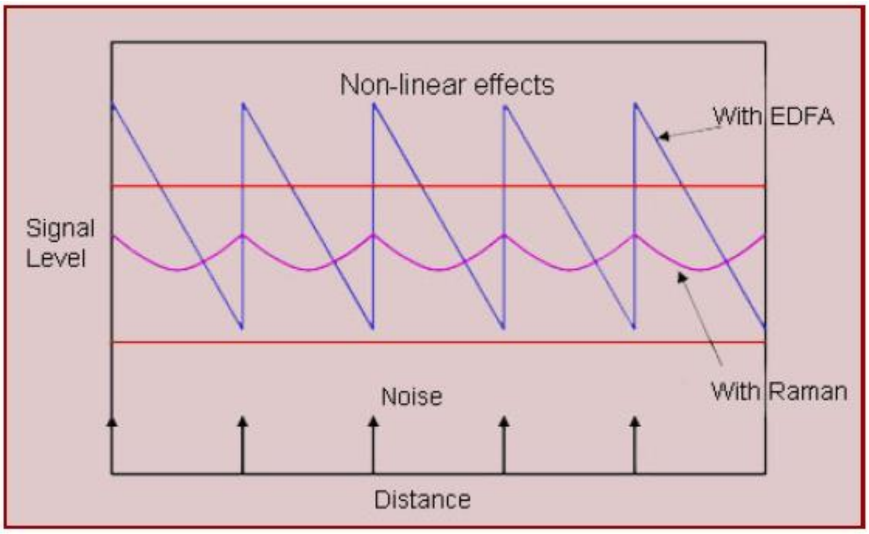
$$I_{th} = \frac{16}{g_R L_{eff}}$$

Typical power to achieve this threshold intensity in a SM fiber is about 1 W.

Raman amplification has renewed interest in recent years due to several reasons:

1. Laser diodes which deliver the required power at several wavelengths are commercially available.
2. Using Raman amplification the whole transmission bandwidth of the optical fiber can be exploited. (The EDFA) makes use of a very small fraction of the transmission window).
3. In an optical fiber multiple Raman processes can go on simultaneously. That means using multiple pumps, ultra wideband amplifiers can be realized.
4. **Most Important:** It is a distributed amplifier as compared to the EDFA or the semiconductor optical amplifier (SOA).

The signals levels on a long haul optical link with EDFA and with Raman amplification are shown in Fig. The arrows indicate the location of EDFAs or pumps for Raman amplification



It can be seen from the Fig. that the signal level for Raman amplification remains more or less constant at a level much higher than the noise floor in the system.

In case of EDFA the signal level reaches close to the noise floor just before the amplifier, and just after the amplifier it increases to such a high value that the non-linear effects like SPM, XPM, FWM become effective. In presence of non-linear effects the signal gets distorted. The lumped amplification system like the EDFA has worse noise as well as distortion performance.

PUMPING SCHEMES FOR RAMAN AMPLIFIER

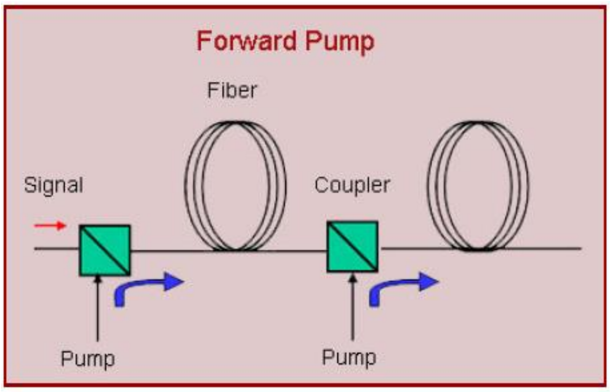
The Raman amplifier can be pumped with forward as well as backward pump since Raman gain is independent of the pump direction. The two schemes are shown in Fig.

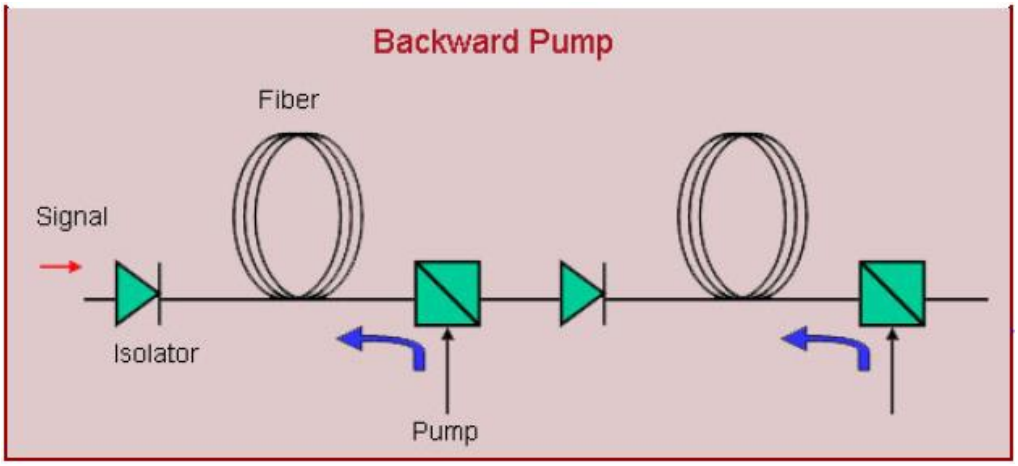
The forward pump scheme has two main drawbacks

1. The pump level is higher where signal is stronger giving increase of signal power at the beginning of the section
2. The residual co-propagating pump is to filtered.

The maximum length or gain beyond which the Raman amplifiers no longer improve the system performance is determined by the so called double Rayleigh back scattering (DRBS) multi-path interference (MPI) noise. This can be explained as follows.

Suppose a signal is amplified by a co-propagating pump. Due to Rayleigh scattering a part of the signal is scattered back. The SRS being direction independent amplifies the backward scattered signal. The scattered light becomes strong enough to generate double back scattered signal which travels with the pump. Superposition between the signal and the time delayed double back-scattered light leads to time dependent noise.





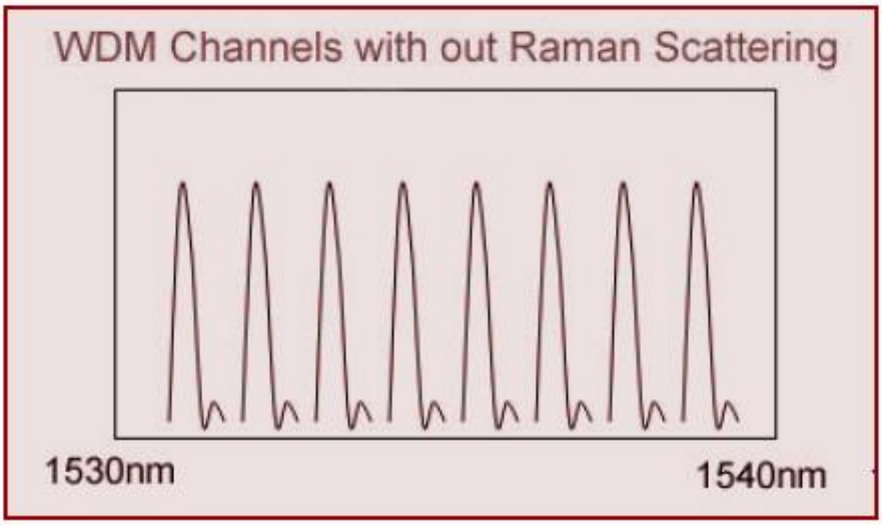
BROAD BANDING OF RAMAN AMPLIFIER

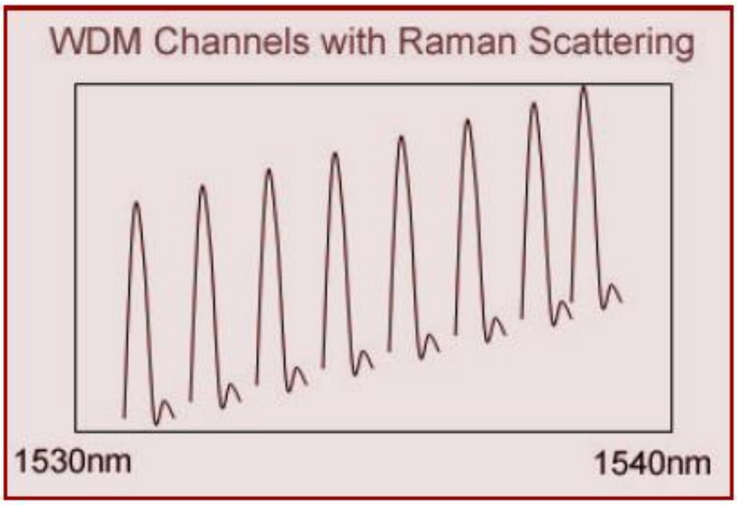
The Raman amplifier with single pump gives a bandwidth of about 7 THz which is approximately 60nm. The trans mission window of the fiber is about 400nm (1200nm to 1600nm). A broad band amplifier therefore is very desirable.
Using multiple pumps, wide band amplifiers with a very small gain ripple can be designed. It should be kept in mind however, that in a multiple pump scheme, there is exchange of power between the pump themselves due to Raman process.

IMPACT OF RAMAN SCATTERING ON WDM SYSTEM

If only one channel propagates on an optical fiber, the Raman effect is observable only if the input power of the channel is of the order of the threshold for the forward Raman scattering. Since the threshold is very high the SRS can be neglected in a single channel system.
A completely different behavior can be seen in WDM systems. Here the initial Stokes wave is not generated by the spontaneous process because the waves of right frequency shifts are already present in the system. Further the input power of the Stokes wave is more or less same as the input power of the pump (the channels of shorter wavelengths act as pump for the channels of the longer wavelengths).
Since the Raman gain peaks around 13THz frequency shift, channels separated by about 100nm influence each other maximally. In other words, channels from different bands like L, C influence each other more. Nevertheless, channels within a band also influence each other though to a lesser extent.

For DWDM system the Raman interaction is very complicated. Every wavelength acts as a pump for wavelengths longer than it, and as Stokes wave for a wavelength shorter than it. Hence Due to Raman scattering every channel receives power and every channel loses power. There is systematic flow of power from higher frequency channels to the lower frequency channels. So to start with if all channels had equal power, at the end the spectrum will be as shown in Fig.



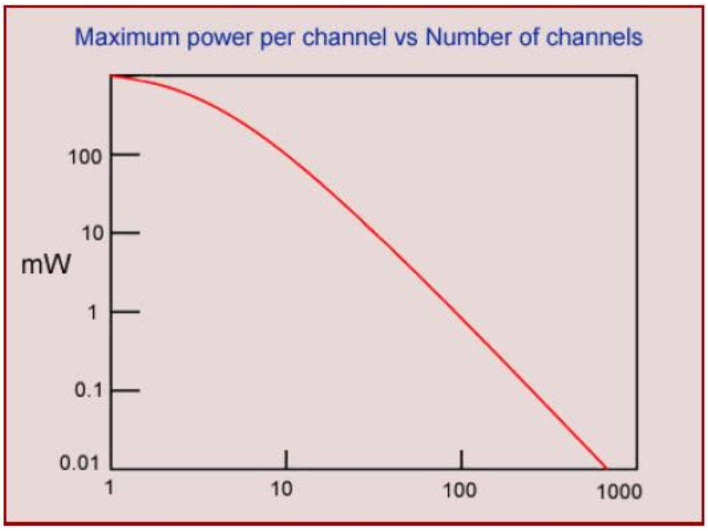


Decrease in channel power is a problem in WDM system as it reduces SNR and increase the BER.
The decrease in power of a channel can be estimated analytically assuming a triangular Raman gain profile from 0 to 15 THz. If the acceptable reduction in the channel power is 1dB, the power-bandwidth product,

$$[nP](N-1)\Delta f < 500W.GHz$$

Where ***n*** is the number of DWDM channels, ***P*** is the power per channel, and Δf is the channel separation.

If number of channels is small, the maximum power per channel decreases as 1/n, but if the number of channel is large, the power decreases as $\frac{1}{n^2}$. A plot of maximum power per channel as a function of number of channel is shown in Fig.



In a long haul system with periodic amplification, SNR performance in presence of Raman scattering has been estimated. If the acceptable decrease in SNR in the channel with smallest wavelength is 0.5dB, the number of transmittable channels N can be calculated using

$$n(n-1) = \frac{8.7 \times 10^{15}}{P\Delta f L_{eff}}$$

Where L_{eff} is the effective interaction length of the system with amplifiers.
The noise power in the system due to the amplifiers is

$$N = 2mhvn_{sp}B_o(G-1)$$

where $\boldsymbol{m}$ is number of amplifiers $m = \frac{L}{L_A}$ (L being the link length and L_A is the amplifier spacing), hv is the photon energy, n_{sp} is excess noise factor of the amplifier, Bo is the optical bandwidth of the receiver, and G is the gain of each amplifier.

If the required SNR is R, the average input power in each channel is

$$P = 2\left(\frac{L}{L_A}\right) hvn_{sp}Bo(G-1)R$$

For large number of channels, the channel capacity can be obtained as

$$C < \sqrt{\frac{1.8 \times 10^{14}}{2\left(\frac{L}{L_A}\right) hvn_{sp}L_{eff}(G-1)R}}$$

Here is assumed that channel spacing is 6 times the data rate and receiver filter bandwidth is 4 times the data rate.

5.3.3 RARE-EARTH-DOPED FIBER AMPLIFIERS

Optical long-haul data transmission systems today usually operate in the C-band. from 1530 to 1570 nm. The standard amplifier for these systems is the erbium-doped fiber amplifier (EDFA), which provides gain more or less in the whole C-band. For high data rate links, dense wavelength division multiplexing (DWDM) systems with increasing bit-rates per channel and decreasing channel spacing are used. Of course, this process cannot be continued without limitations. Another approach to reach very high bit-rates without violating the l bit/s/Hz limit is the usage of transmission bands besides the C and L-bands. The usable range of the low-loss window of transmission fibers is usually considered to be 1200-1700 nm. Figure indicates the spectral position of a couple of rare-earth-doped fiber amplifiers in this window. Amplifiers in the $\boldsymbol{S^-}$ **and S^+**-bands are of the mat practical importance, on the one band due to their spectral location close to the C-band and on the Other hand because the dispersion compensation is more easy at shorter wavelengths than at the long wavelength edge of the transmission window. These S-band amplifiers use thulium for the active core instead of erbium and are therefore called thulium-doped fiber amplifiers (TDFA).

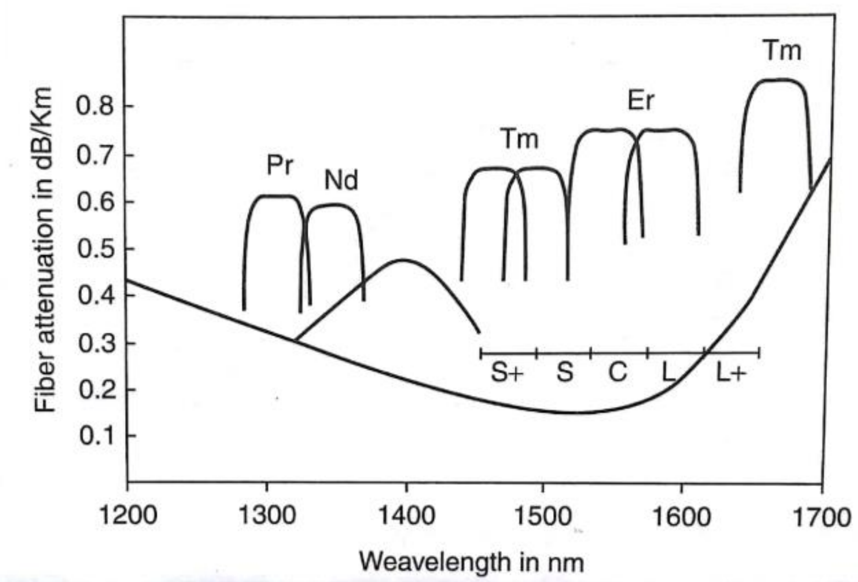
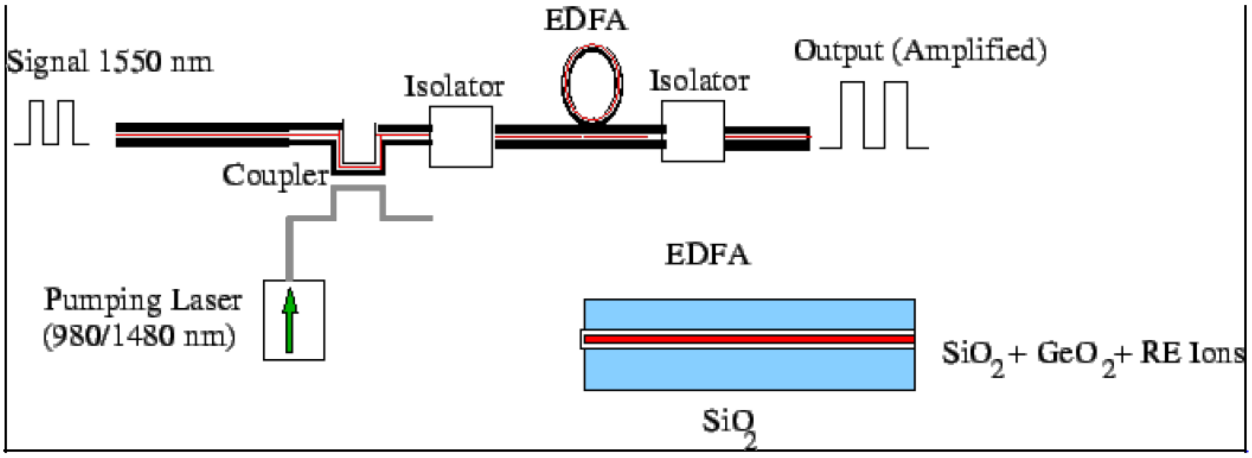


Figure: Rare earth doped fiber amplifiers in the low-loss window of transmission fibers.

5.3.3.1 ERBIUM-DOPED FIBER AMPLIFIER (EDFA)

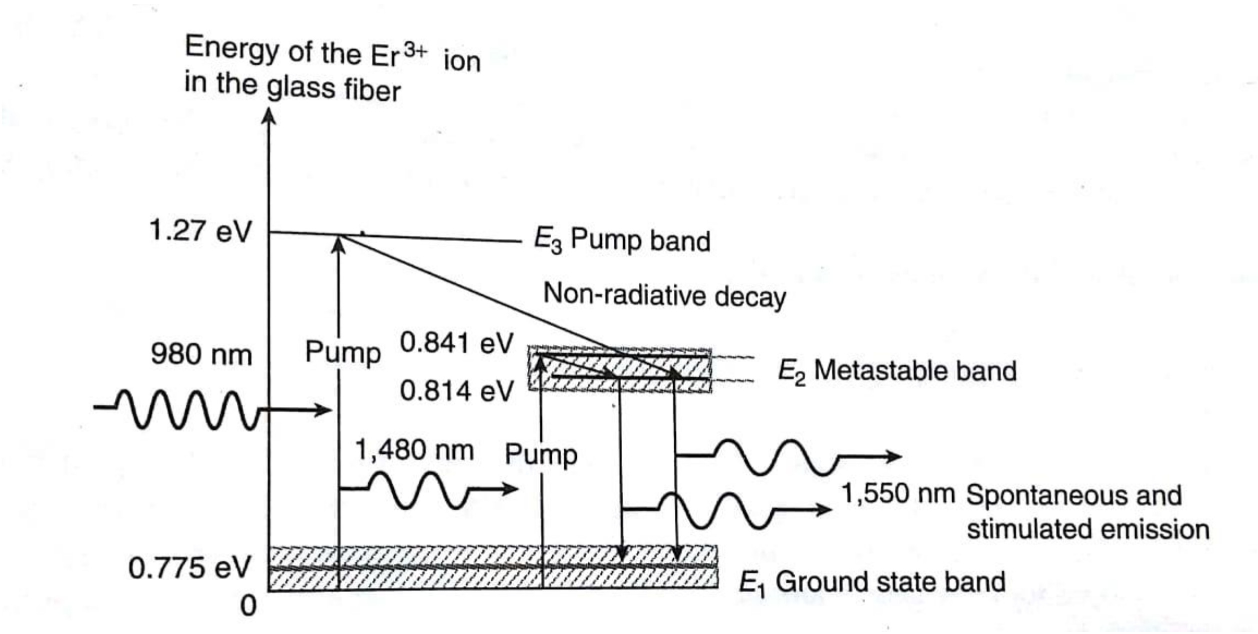
An EDFA is shown in Fig . It consists of a 10-30 m length of silica fiber whose core is lightly doped with ionized atoms of rare-earth elements such as erbium (Er^{3+}), ytterbium (Yb), thulium (Tm), or praseodymium (Pr), while the host fiber material can be standard silica, fluoride glass, or telluride glass. The operating region is decided by the host material and the doping element. For long-haul telecommunication applications, silica fiber doped with erbium is the most popular choice, which is known as erbium-doped fiber amplifier or EDFA.

Instead of using external current injection to excite electrons to higher energy levels, this amplifier uses optical pumping. The fiber is pumped using a pump signal from a laser, typically at a wavelength of 980 nm or 1480 nm.



The figure above shows a typical configuration of EDFA based communication system. The optical output is first passed through an optical isolator which prevents reflection, i.e. allows light to move from left to right. The coupler allows the pump input to be fed into the fiber with minimum loss

PRINCIPLE OF EDFA:



Three-level energy diagram of Er^{3+} is shown in Fig.. the energy levels are labelled as E1, E2, and E3 in order of increasing energy. These levels are actually bands of closely spaced energy levels that form a manifold due to the effect known as ***Stark splitting.***

- E3 is the pump band, 'with an energy difference of 1.27 eV from ground level. This energy corresponds to a wavelength of 980 nm.
- E2 is the metastable band. The term "metastable" means that the lifetimes for transitions from this state to the ground state are very long when compared to the lifetimes of the states that led to this level. The top of the metastable band has an energy difference of 0.841 eV from ground level, corresponding to a wavelength of 1480 nm. The bottom of the metastable band has energy difference of 0.814 eV from ground level, corresponding to a wavelength of 1530 nm.
- E1 is the ground state band.

  The upward arrow indicates wavelengths at which the amplifier can be pumped to excite the ions into the higher energy level. The 980 nm transition corresponds to the band gap between the E1 and E3 levels. The 1480 nm transition corresponds to the gap between the bottom of E1 and top of E2 band. The downward transition represents the wavelength of photons emitted due to spontaneous and stimulated emission.

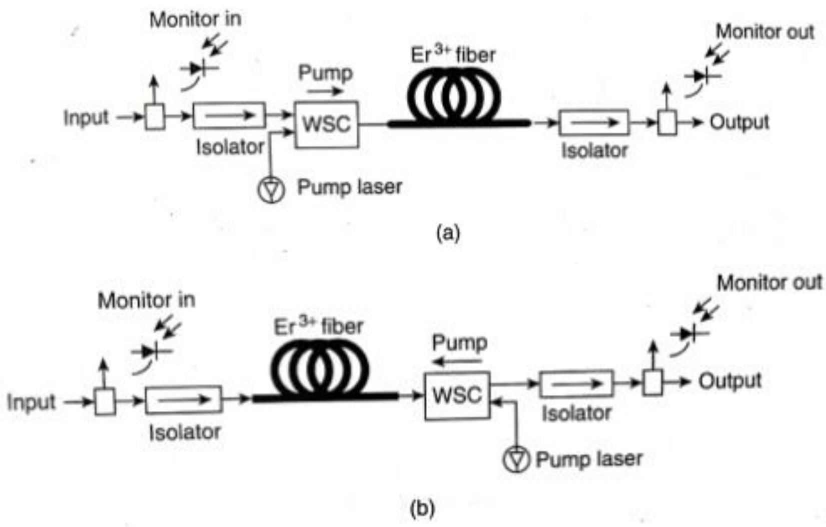
A pump laser emitting photons of wavelength 980 nm is used to excite ions from the ground state to the pump level. These excited ions decay very quickly (in about 1 μs) from pump band to the metastable band. During this decay, the excess energy is released as mechanical vibrations in the fiber. In the metastable state, the electrons of excited ions tend to populate the lower end of band and have a very long fluorescence time of about 10 ms.

Another wavelength (1480 nm) can also be used for pumping. Absorption of a 1480 nm pump photon excites an electron from E1 to top of E2, which is lightly populated. These electrons then tend to move down to the more populated end of E2. Some of the ions can decay back to ground level in the absence of external stimulating photon flux. This phenomenon is known as ***spontaneous emission*** and adds to the amplifier noise. In the stimulated emission process, a signal photon triggers an excited ion to drop to the ground state, thereby emitting a new photon having the same energy, wave vector, and polarization as the incoming signal photon.

In a two-energy-level atomic system, only an optical signal at the frequency fc satisfying $hf_c = E_2 - E_1$ is amplified. If these levels are spread into bands, all the frequencies that correspond to the energy difference between some energy in the E2 band and some energy in the El band can be amplified. In an EDFA, the set of frequencies that can be amplihed by stimulated emission from E21 band to the El band corresponds to the wavelength range ' 1525-1570 nm, a bandwidth of 50 nm.

EDFA ARCHITECTURE

The complete setup of an optical fiber amplifier in different configurations is shown in Fig.



(a)

(b)

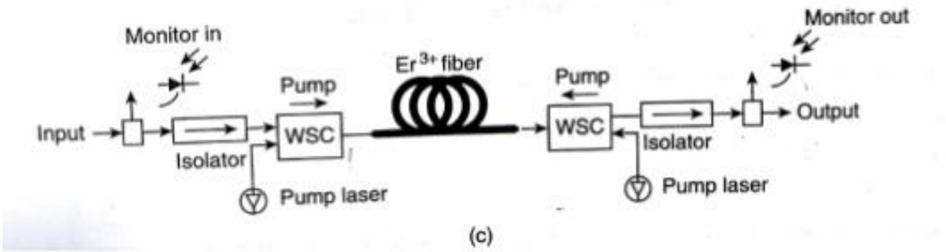


Fig: Different configurations of EDFA. Here WSC is the wavelength selective coupler

It consists of a doped fiber, one or more pump lasers, a passive wavelength coupler, an optical isolator, and tap couplers at the input and output sides to monitor the input and output. The dichroic coupler couples the pump and signal optical powers into the fiber amplifier. The optical isolator prevents the amplified signal from reflecting back into the device. The three possible configurations of an EDFA are as follows:

- Co-directional pumping.
- Counter-directional pumping.
- Dual pumping.

In co-directional pumping, the pump light is injected from the same direction as the signal flow. However, in counter-directional pumping, the pump power is injected in the opposite direction to the signal flow. This arrangement allows higher gain. but co-directional pumping gives better noise performance. The dual pumping scheme can be employed for more gain of around +35 dB, which 13 almost double that of s1ngle pumping scheme(+17dB)

AMPLIIIER GAIN AND EFFICIENCY

The populations at the various levels within a band are different; therefore, EDFA gain becomes a function of the wavelength. The gain flattening of EDFAs has been a research issue in recent years, with the development of high capacity WDM optical communication systems. For single-channel systems, the gain variation is not a problem. However, as the number of channels increases, transmission problems arise, because a conventional EDFA has intrinsic non-uniform gain. They typically present gain peaking at about 1530 nm and the useful gain bandwidth may be reduced to less than 10 nm as shown in Fig.

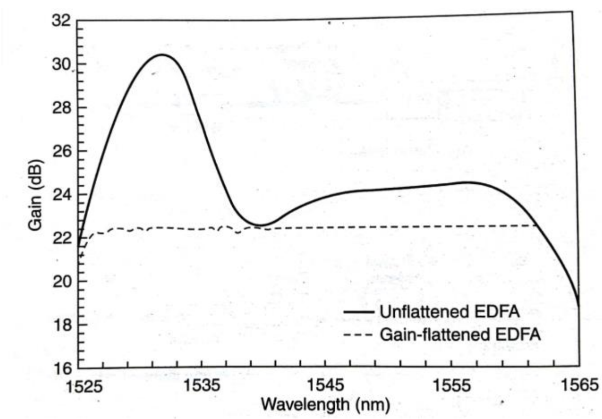


Figure ; Gain Band of EDFA

The gain of EDFAs depends on a large number of device parameters such as erbium-ion concentration, amplifier length, core radius, and pump power. To increase the gain bandwidth of an amplified light wave system, several methods can be used, but equalizing optical filters operating as spectrally selective loss elements appear to be the best solution.

The factors controlling the degree of gain uniformity are as follows:

- Concentrations of the active ion (erbium).
- Optical gain flattening filter.

An additional (second) pump laser can also be used at each end of the fiber one pump beam propagates with signal beam, while the other propagates against it. This ensures that population inversion and gain remain constant along the fiber.

Gain equalization can be accomplished in several ways:

- Long period fiber gratings.
- Chirped fiber Bragg gratings.
- Thin film filters

The input and output powers of an EDFA can be expressed in terms of the principle of energy conservation as

$$P_{signal\ out} \leq P_{signal\ in} + \frac{\lambda_p}{\lambda_s} P_{pump\ in}$$

where $P_{Pump\ in}$ is the input pump power, and λ_p and λ_s are the pump and signal wavelengths, respectively. We can rewrite the above equation as

$$G = \frac{P_{signal\ out}}{P_{signal\ in}} \leq 1 + \frac{\lambda_p}{\lambda_s} \frac{P_{pump\ in}}{P_{signal\ in}}$$

$$Thus$$

$$P_{signal\ in} = \frac{\frac{\lambda_p}{\lambda_s} \times P_{pump\ in}}{G - 1}$$

Maximum output signal power depends on the ratio $\frac{\lambda_p}{\lambda_s}$. Thus the power conversion efficiency (PCB) is defined as

$$PCE = \frac{P_{signal\ out} - P_{signal\ in}}{P_{pump\ in}}$$

NOISE IN EDFA

The dominant noise generated in an EDFA is amplified spontaneous emission (ASE). This is generated due to the spontaneous recombination of electrons and holes in the amplifier medium. This recombination gives rise to a broad spectral background of photons that get amplified along with the optical signal. The output spectrum for an EDFA amplifying a signal at 1540 nm with a pumping signal at 1480 nm is shown in Fig. along with ASE.

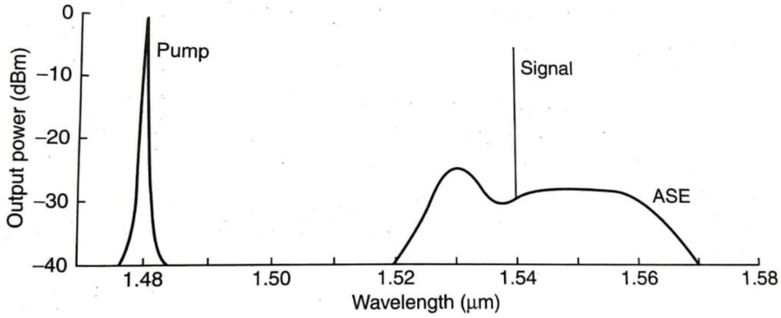


Fig: Output spectrum of EDFA amplifying signal at 1540nm with pumping signal at 1480nm

The total optical held is sum of signal field Es and the spontaneous emission field En. The total photodetector

current $\boldsymbol{i_{total}}$ is proportional to the square of the electric field of the optical signal. Mathematically,

$$i_{total} \propto (E_s + E_n)^2 = E_s{}^2 + E_n{}^2 + 2E_sE_n$$

Here the first term arises due to the signal, the second term due to noise, and the third term is a beat signal (mixing component) between signal and noise. Signal degradation comes from beat signals generated at noise-noise and noise-signal interferences. Each "slice" of noise can interfere with another "slice" to generate a beat signal at frequencies that are combinations of the sum and difference of the input frequencies as indicated in Fig.

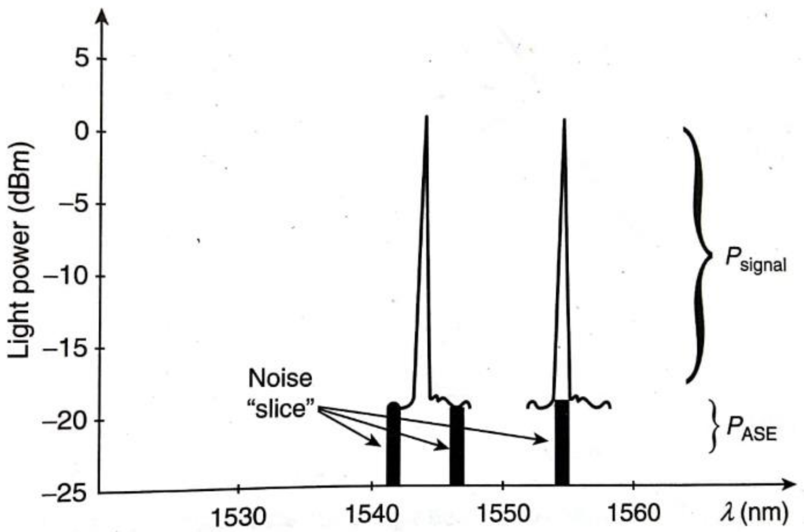


Fig: Noise in EDFA

Noise-noise beating can be easily removed by a narrowband filter. Noise-signal beating, however, cannot be filtered because it is within a signal's bandwidth. The noise figure based on signal-noise beating is $\boldsymbol{F_n}$, which varies from 3.5 to 9 dB for EDFAs.

Spontaneous emission in the amplifier degrades the SNR by adding to the noise during the amplification process. SNR degradation is quantified through the amplifier noise figure NF_{EDFA}:

$$N_{EDFA} = \frac{SNR_{in}}{SNR_{out}}$$

Amplification Factor

$$G = \frac{P_{signal\,out}}{P_{signal\,in}}$$

SNR of input signal

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

$${\sigma_s}^2 = 2q(RP_{signal\,in})B_c$$

Spontaneous emission population inversion factor n_{sp} is given by

$$n_{sp} = \frac{N_2}{N_2 - N_1}$$

Where N1 & N2 are population densities for the exited and ground states of the amplifying medium. The SNR of amplified signal becomes

$$SNR_{out} = \frac{(RP_{signal\,in})^2}{{\sigma_s}^2}$$

And amplifier noise figure is

$$N_{EDFA} = \frac{2\,n_{sp}(G-1)}{G} \approx 2n_{sp}$$

For most amplifiers

$$N_{EDFA} > 3dB\ and\ can\ be\ 6-8dB$$

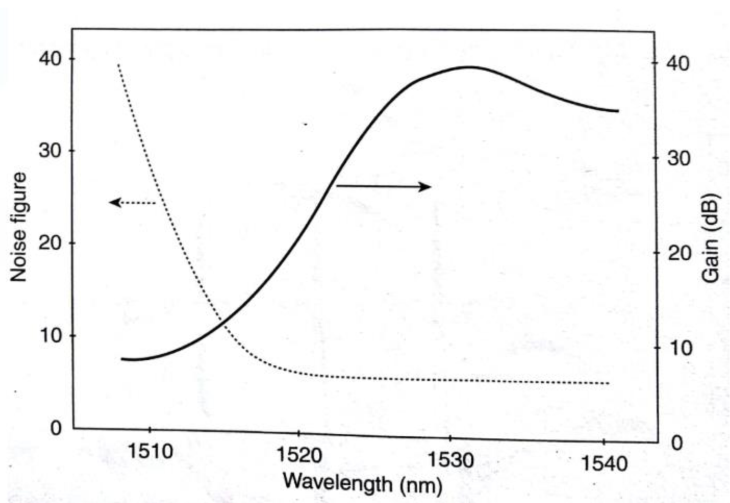


Fig: Characteristic plot of gain & Noise figure for an EDFA pumped ~30mW at 900nm

OPTICAL OSNR

When a number of optical amplifiers are cascaded in a series, ASE noise of each stage gets added, and the signal entering the optical receiver may contain a significant level of ASE noise. In this case, we have to evaluate the optical signal-to-noise ratio (OSNR). This is defined as the ratio of the EDFA optical signal output power Pout to the un-polarized ASE optical noise power PASE Mathematically

$$OSNR(dB) = 10log\frac{P_{out}}{P_{ASE}}$$

OSNR does not depend on factors such as data format, optical filter bandwidth, or pulse shape, but only on average optical signal power Pout and the average optical noise power.

So far we have concentrated on EDFAs operating in the C-band. Several different wavelength bands have been designated for WDM and EDFAs have been designed to operate in these bands.

The wavelength divisions have been designated as

- S-band: l,480-1,520 nm
- C-band: 1,521-l,560 nm
- L-band: l,561-l,620 nm

L-band EDFAs operate on the same principle as C-band EDFAs. The gain spectrum of erbium is much flatter intrinsically in the L-band than in the C-band. Therefore, the design of gain-flattening filter for L-band is easier, but the gain coefficient in the L-band is about three times smaller than in the C-band, so a much longer doped fiber length or a higher erbium doping concentration is required.

5.3.3.2 THULIUM-DOPED FIBER AMPLIFIER (TDFA)

S-band amplifiers use thulium for the active core instead of erbium and are therefore called thulium-doped fiber amplifiers (TDFAs).The transition used for 8band amplification is 3→1 with the central wavelength of the fluorescence being 1460 nm as shown in Fig.

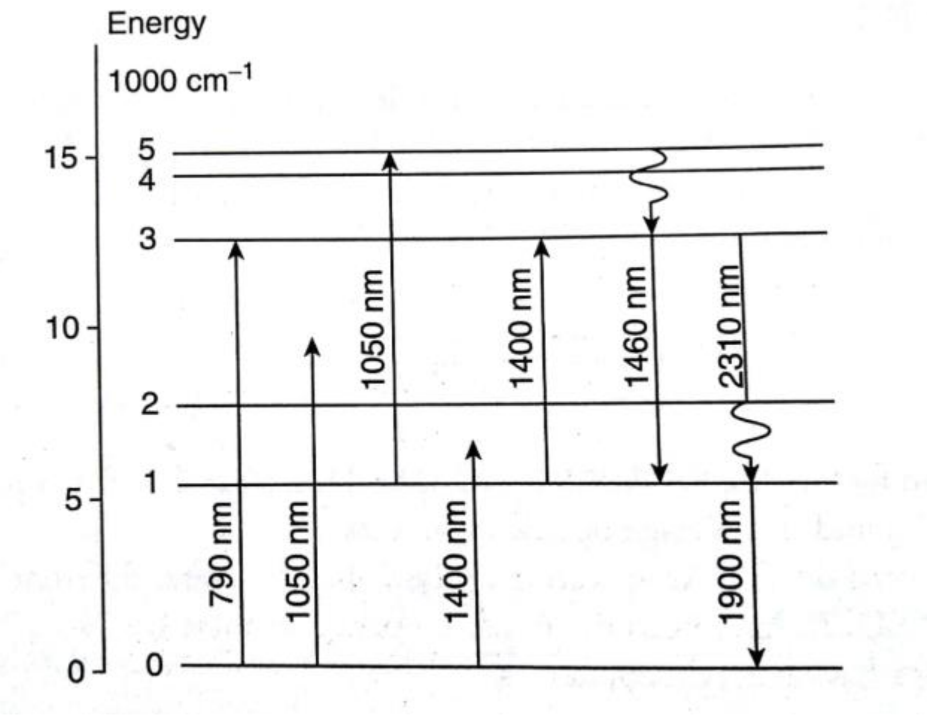


Fig: Energy level diagram for thulium

The lower level of the amplifier transition is nm the ground state of the thulium ion, and the TDFA thus is basically a four-level amplifier. In contrast to the EDFA, an unpumped TDFA shows no signal attenuation. The first pump transition uses 790 nm and excites thulium ions from the ground state to level 3. The next step is a stimulated emission process, which ends up in level 1. At this point the system would terminate, since the lifetime of level 1 in fluoride glasses is about 11 ms, due to the low phonon energy of these glasses. Thus, a second pump transition is needed to depopulate level 1. One possibility IS the excited state absorption (ESA) 1→5 at 1050 nm. Thulium ions in level 5 will undergo a fast non-radiative decay ending in the upper amplifier level 3, so the energy loop is closed. In practice, the large lifetime of level 1 leads to the fact that the second pump is much more important than the first one and the TDFA is even working when the 790 nm pump is omitted, although with lower Power conversion efficiency.

In a pumped TDFA, level 1, due to its large lifetime, plays the role of the ground state, and in fact, in many respects the TDFA behaves as a quasi-three-level amplifier. When compared to the EDFA, the 1050 nm pump in the TDFA corresponds to a 980 nm pump in an EDFA, and the EDFA pumped at 1480 nm corresponds to . a TDFA with its second pump at 1400 nm. In analogy to the EDFA, the TDFA pumped at 1050 nm is best for PT¢~amplif1ers, as it has the lower PCE, but a population 1nversion level of about 100%, resulting 1n a low noise figure, whereas the TDFA pumped at 1400 nm is good for power amplifiers, as it has the higher PCE, but a lower inversion level, thus a higher noise figure.

5.3.4 PERFORMANCE COMPARISON OF OPTICAL AMPLIFIERS

CHARACTERISTIC	EDFA	SOA	RAMAN
GAIN	>40	>30	>25
WAVELENGTH	1530-1560	1280-1650	1280-1650
BANDWIDTH	30-60	60	Pump dependent
PUMP POWER	25 dBm	<400 mA	>30 dBm
NOISE FIGURE	5	8	5
SIZE	Rack module	compact	Bulk module
SWITCHABLE	NO	YES	NO
COST FACTOR	medium	competitive	high

5.3.5 ADVANTAGES AND DISADVANTAGES OF OPTICAL AMPLIFIERS

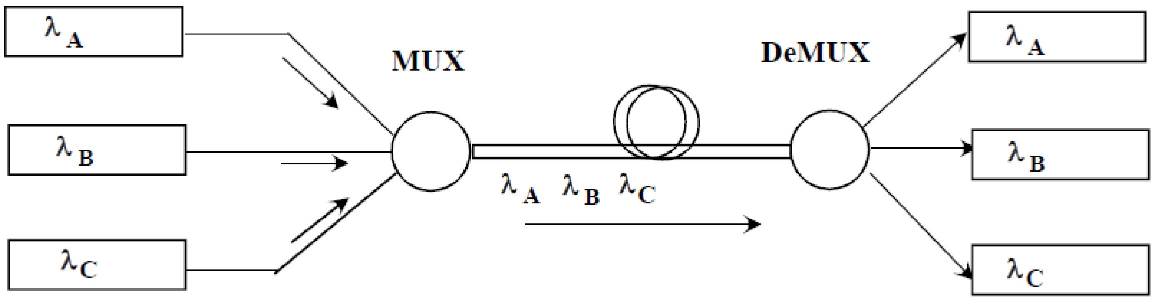
OPTICAL AMPLIFIER	ADVANTAGES	DISADVANTAGES
EDFA	❖ A high power transfer efficiency ❖ Commercially available in C-band & L-band ❖ High gain ❖ Low noise figure ❖ Do not require high speed electronics. ❖ Immunity to cross talk ❖ Suitable for long-haul applications.	❖ Can only work at wavelengths where Er+3 fluoresces ❖ Requires specially doped fiber as gain medium. ❖ Three-level system, so gain medium is opaque at signal wavelengths until pumped ❖ Requires long path length of gain ❖ Gain very wavelength dependent and must be flattened
SOA	❖ Compactness. ❖ Integration potential. ❖ High power output. ❖ 4Broad choice of operating wavelength (400-2000 nm). ❖ Low price with high volume production.	❖ High coupling loss ❖ Polarization dependence ❖ High noise figure (as compared with EDFA) ❖ Polarization dependence ❖ Cross-phase modulation ❖ Four-wave mixing and crosstalk
RAMAN	❖ Variable wavelength ❖ Compatible with SM fiber ❖ Can be used to extend EDFAs. ❖ Can result in a lower average power over a span ❖ Good for lower crosstalk	❖ Multipath interference ❖ Pump noise transfer ❖ Noise figure. ❖ Gain control needed

MODULE VI

WDM & OPTICAL NETWORKS

6.1 WAVELENGTH-DIVISION MULTIPLEXING

Wavelength-division multiplexing (WDM) is conceptually same as the FDM, except that the multiplexing and demultiplexing involves light signals transmitted through fibre-optic channels. The idea is the same: we are combining different frequency signals. However, the difference is that the frequencies are very high. It is designed to utilize the high data rate capability of fibre-optic cable. Very narrow band of light signal from different source are combined to make a wider band of light. At the receiver the signals are separated with the help of a demultiplexer.



WDM STANDARDS

WDM systems are divided into three different wave length patterns, **normal** (WDM), **coarse** (CWDM) and **dense** (DWDM). Normal WDM (sometimes called BWDM) uses the two normal wavelengths 1310 and 1550 on one fiber. Coarse WDM provides up to 16 channels across multiple transmission windows of silica fibers. *Dense wavelength division multiplexing*(DWDM) uses the C-Band (1530 nm-1565 nm) transmission window but with denser channel spacing. Channel plans vary, but a typical DWDM system would use 40 channels at 100 GHz spacing or 80 channels with 50 GHz spacing. Some technologies are capable of 12.5 GHz spacing (sometimes called ultra dense WDM). New amplification options (Raman amplification) enable the extension of the usable wavelengths to the L-band (1565 nm-1625 nm), more or less doubling these numbers.

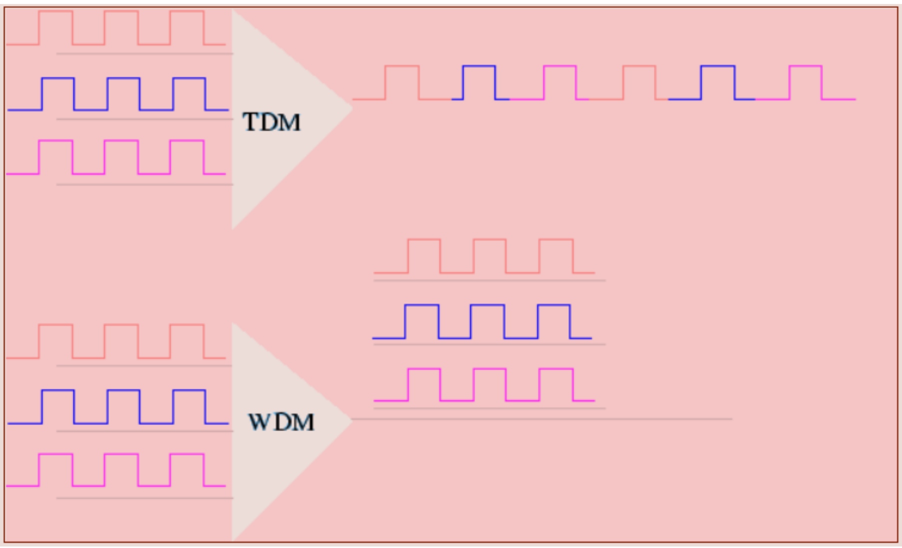
Coarse wavelength division multiplexing (CWDM) in contrast to DWDM uses increased channel spacing to allow less sophisticated and thus cheaper transceiver designs. To provide 16 channels on a single fiber CWDM uses the entire frequency band spanning the second and third transmission window (1310/1550 nm respectively) including both windows (minimum dispersion window and minimum attenuation window) but also the critical area where OH scattering may occur, recommending the use of OH-free silica fibers in case the wavelengths between second and third transmission windows are to be used. Avoiding this region, the channels 47, 49, 51, 53, 55, 57, 59, 61 remain and these are the most commonly used. With OS_2 fibers the water peak problem is overcome, and all possible 18 channels can be used. WDM, DWDM and CWDM are based on the same concept of using multiple wavelengths of light on a single fiber, but differ in the spacing of the wavelengths, number of channels, and the ability to amplify the multiplexed signals in the optical space. EDFA provide an efficient wideband amplification for the C-band, Raman amplification adds a mechanism for amplification in the L-band. For CWDM, wideband optical amplification is not available, limiting the optical spans to several tens of kilometres.

6.2 FEATURES OF WDM:

Bandwidth:

- The fact that one can use different wavelengths over the same channel increases bandwidth capacity enormously. Most WDM systems work in the C-band around 1550 nm. ITU has specified a standard channel separation grid from 191.1 THz to 196.5 THz separated by 100 GHz. In practice, channels separated by 50 GHz are used. (In terms of wavelengths, it corresponds to the range 1526 nm to 1570 nm with a separation of about 0.8 nm. However, in WDM, the channels are equi-spaced in frequency and not in wavelengths.) Older systems which were spaced at 200 GHz are known as WDM whereas systems with denser packing such as give above are called **Dense WDM (DWDM)** . Still older ITU specification, referred to now a days as CWDM (Coarse- WDM) specified a 20 nm spacing in the wavelength range 1270 to 1610 nm.

  The number of channels (also called λs) could be reaching up to 128 so that a single fiber supporting, say OC-48, can give a bandwidth of over 300 Mbit/sec. Modern systems (for instance 40λ at OC-192) can easily pack channels to give a bandwidth of 400 Gbps. A similar calculation for 40λ at OC-768 can reach up to 1.6 Terabits/sec.
- Since WDM carries each signal independently of other signal, each channel has a dedicated bandwidth. Signals arrive at the destination at the same time and not in different time slots as is the case with TDM.



Independent of bit-rates and formats:

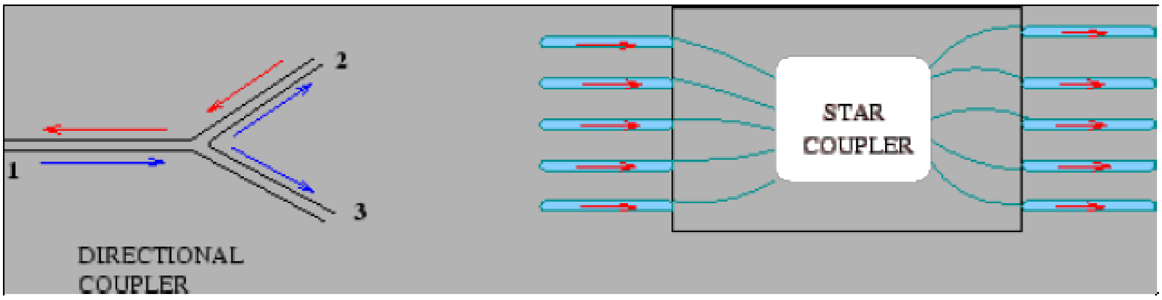
- WDM can support multiple protocols. Each signal can be carried at different bit rates. For instance, one signal can be carried a OC-12 while another at OC-48. Similarly, signals can be carried over different formats like SONET, ATM etc.
- Channel capacity can be increased incrementally by adding more wavelengths. Thus a 10 wavelength OC-12 with a bit rate of 24 Mbps can be upgraded to a 40 wavelength one with a bandwidth of 99.52 Mbps.

6.3 WDM COMPONENTS:

The essential components of a WDM system are primarily those of any network, viz., transmitters, link and receivers. In addition, the system would require other components such as switches, modulators, amplifiers etc. In case of WDM technology, the transmitters are laser sources with stable tunable wavelengths. Before sending the signal through the link, multiplexers mix the wavelengths. Link is low loss optical fiber while at the receiver end there are photo detectors and wavelength demultiplexers

6.3.1 OPTICAL COUPLERS:

Optical couplers are devices which split light to divert them into multiple paths or combine light from multiple paths to channel them into a single path. Light signal propagates differently from electric signal. An electric signal passes through a receiver to the ground. However, a light signal is absorbed by a receiver so that if one puts a series of optical receivers at the output end almost no signal will get past the first receiver. Thus it is necessary to split the beam and put the receivers in a parallel fashion.

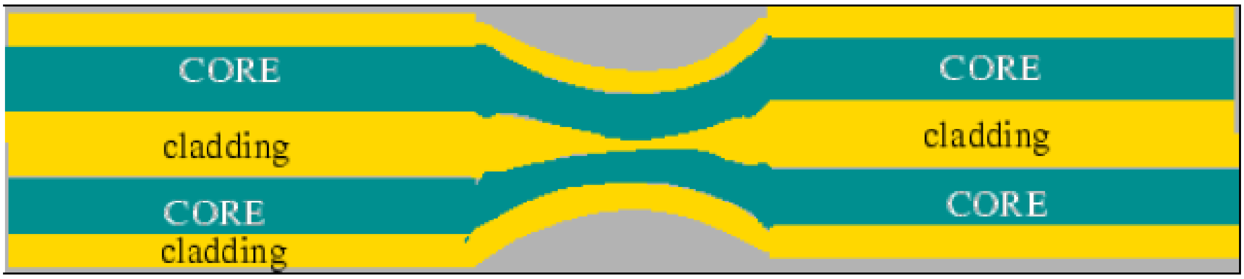


In **Directional couplers** , light energy generally flows in one direction though they are capable of allowing flow in the other direction as well. For instance, in the Y-shaped 1 × 2 coupler shown here, a signal arriving at port 1 would be distributed to port 2 and 3 and would travel from left to right. However, if a signal arrives at port 2 (or 3), it would only go to port 1 because of geometry. Directional couplers can be designed such that a predetermined percentage of optical power is output into a particular port.

Star couplers are passive devices which connect multiple inputs with multiple outputs.

Star couplers can be both directional and non-directional. Couplers may be designed to be wavelength selective which channel different wavelengths in different directions. These are used in making wavelength division multiplexers and demultiplexers.

Couplers are made by fusing and tapering two fibers together so that the cores of the two fibers are close enough so that the evanescent wave from one fiber can be picked by the providing necessary coupling. The property of coupling depends on whether the fibers are multi-mode fibers or single mode fibers.



6.3.2 OPTICAL AMPLIFIERS:

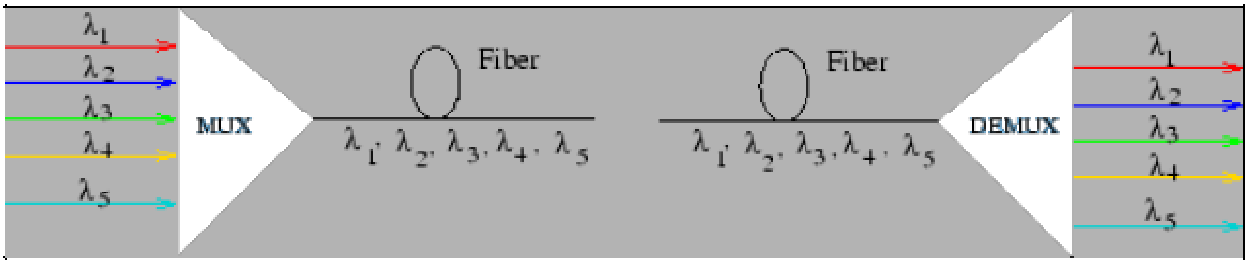
Inline signal amplification is done by placing optical amplifiers along the fiber span. Erbium doped fiber amplifiers (EDFA) are generally used in WDM applications. Key performance parameters of amplifiers are gain, gain-flatness, noise level and power output.
Gains greater than 30 dB over a wide spectral width (100 nm) with low noise are characteristics of EDFAs which are available in both L-band and C-band. Signal gain provided by EDFAs has reasonably flat wavelength response.
However, the flatness can be improved by gain flattening optical filters. Signal can travel over 100 km between amplifiers. If longer haul is required, it will be necessary to regenerate signal. **Regenerators** , in addition to amplifying signals, perform what is known as **3R-operations** , viz., reshaping, retiming and retransmitting.

As the total gain in EDFA is shared between different wavelength channels, the gain per channel decreases. As there are OADMs in the network, this would result in different channels being received with different power at the receiver end. The problem is addressed by equalizing filters which attenuate wavelengths that are strongly amplified.

6.3.3 MULTIPLEXERS (MUX) & DEMULTIPLEXERS (DEMUX)

MULTIPLEXERS (MUX)

At first sight it would seem that multiplexing different wavelengths would be a relatively simple job of simply allowing different wavelength signals to fall on an optical fiber within the latter's angle of acceptance. However, one has to take care to see that the noise associated with each channel is kept to a minimum. Channels must be isolated to ensure that noise at a different wavelength does not interfere with the signal that is being carried



A wavelength multiplexer (MUX) combines incident wavelengths and launches the output to the fiber.

- ***Insertion Loss, Cross Talk and Optical Isolation:***

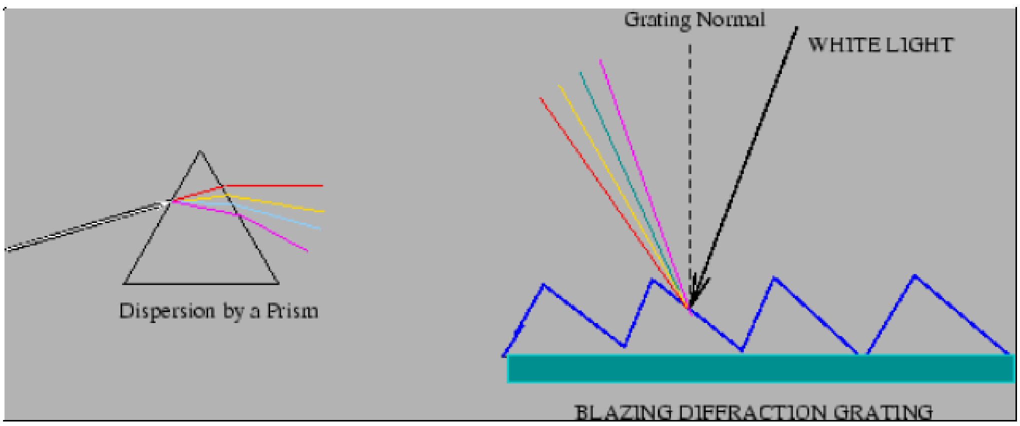
A multiplexer should have low insertion loss and should not allow back scattering of light to any of the input ports. Insertion loss is the attenuation in the signal in travelling from the input port to the output port. It is defined as

$$L = -10\ log\frac{P_{in}}{P_{out}}$$

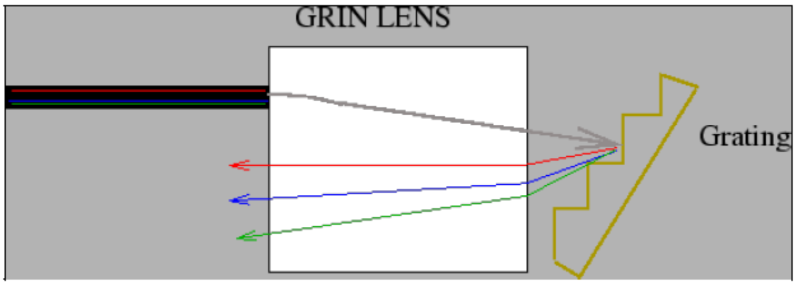
Back reflection can be avoided by use of **optical isolators** , which allow light to propagate only in one direction, similar to a diode in an electronic circuit which allow current in one direction. A typical optical isolator has an insertion loss less than 1 dB and high return loss greater than 40 dB.

DEMULTIPLEXER (DEMUX)

At the receiving end a demultiplexer (DEMUX) reverses the above and separates the signal into the components. Multiplexers are generally based on one of two principles, viz., angular dispersion and optical filtering. Prism and reflection gratings are used for separating wavelengths. The same elements can combine wavelengths on reversing the direction of the beams.



Reflection gratings can also be used to separate wavelengths. By choosing a suitable periodic structure for the grating, it is possible to coincide the directions of constructive interference and specular reflection from the grating for a given order and wavelength. The technique is known as **blazing .**

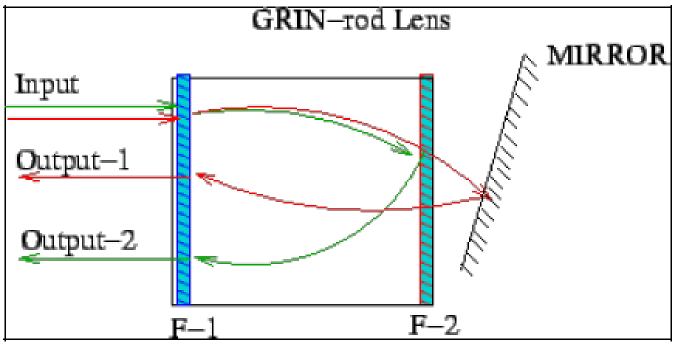


The figure shows a demultiplexer using a blazed reflection grating. Light consisting of a mixture of different wavelengths enters a GRIN lens which collimates the beam to fall on the grating. After reflection, the components are spatially separated and focussed by the lens as outputs to fibers carrying different wavelengths.

- **OPTICAL FILTERS**

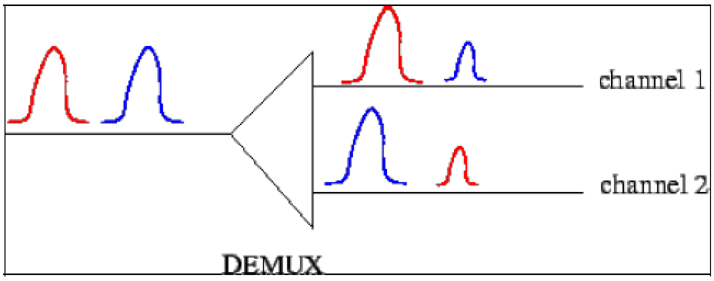
Multiplexers may also be made using **interference filters** . Optical filters can be designed using various techniques, the cheapest being deposition of thin films of varying refractive indices on a substrate. When incident light falls on such a material, it encounters **stacks of boundaries** which produces constructive interference for some wavelengths and destructive interference for some others. As the number of sacks increases, the resolution becomes better and the band of selected wavelengths becomes narrower. The essential difference between filters based on reflection gratings and interference filters is that gratings selectively reflect a narrow range of wavelengths while the interference filters **transmit** a narrow range of wavelengths.

In the figure, a demultiplexer using two optical filters $F_1$and F_2 and a GRIN-lens-mirror assembly is shown. The Filter F_2 is attached at the end of the lens. The input fiber and the output fibers (shown only as light path) are at the focal plane of the lens. Filter F_1 is between the fibers and the lens.



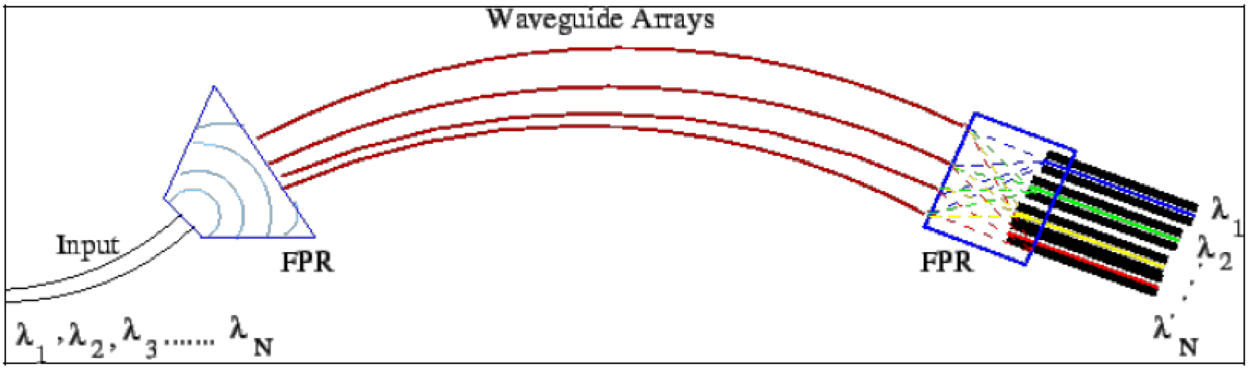
The filter F_1 is a short wavelength pass filter while F_2 is a long wavelength pass filter. Light from the input port becomes parallel at the end of the lens. The shorter wavelength is reflected by F_2 and enters through to the lower output fiber. The longer wavelength enters through F_2 and is reflected by the plane mirror. It is focussed on to the second output port through the filter F1 . The same principle can be used to design a multiplexer.

A demultiplexer should give rise to minimum **cross talk** , i.e., the amount of input power associated with a particular wavelength (say, λ_1) which reaches a channel for a different wavelength (λ_2) should be minimum.



- ***Arrayed Waveguide Grating:***

Arrayed waveguide gratings (AWG) are used for demultiplexing. These are based on diffraction principle. The input consists of several channels carrying different wavelengths.



Light propagating in the input waveguides are coupled to the arrayed waveguides after propagating through a free space region (FPR). The AWG consists of an array of curved waveguides. Each curved waveguide has a length which is

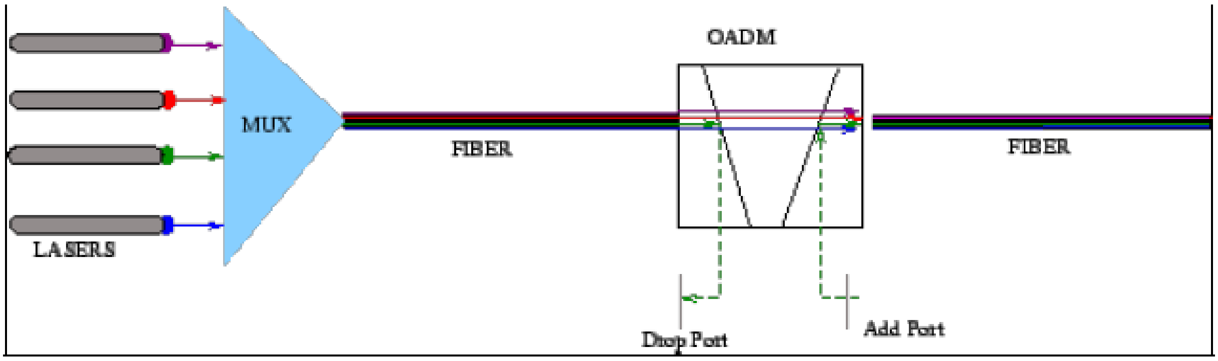
$$\Delta L = \frac{m\lambda_c}{n}$$

more than the array element immediately below it, where $\boldsymbol{\lambda c}$ is the central operating wavelength, $\boldsymbol{n}$ is the effective refractive index and $\boldsymbol{m}$ is an integer. Thus at the central wavelength, the light will focus at the centre of the image plane. Different wavelengths have different phase differences and the focal point for each will be shifted. A second coupler will deliver different wavelengths to different waveguides.

6.3.4 OPTICAL ADD-DROP MULTIPLEXER (OADM)

In its passage from the MUX to DEMUX, the signal passes through one or more **Optical Add-Drop Multiplexer (OADM)**. The function of an OADM is to selectively drop one or more wavelengths by rerouting its data content to another fiber. The OADM may just allow the remaining traffic to pass or add a different data set at a wavelength equal to that of a dropped data. This helps to create a virtual point-to-point circuit.

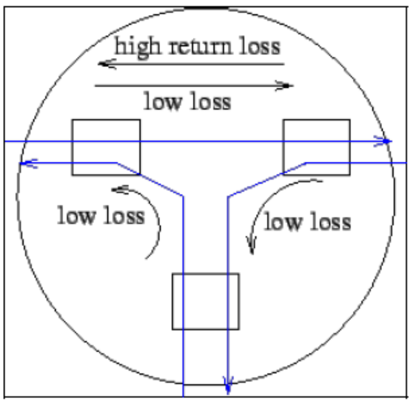
An OADM is generally a device such as a Bragg grating which could be used to selectively reflect a wavelength that is to be dropped while allowing the others to be transmitted. OADMs are passive components of the network. They are manufactured to operate either at fixed wavelengths or at dynamically selectable wavelengths. In case of fixed wavelengths, the wavelengths to be dropped or added are pre-selected.



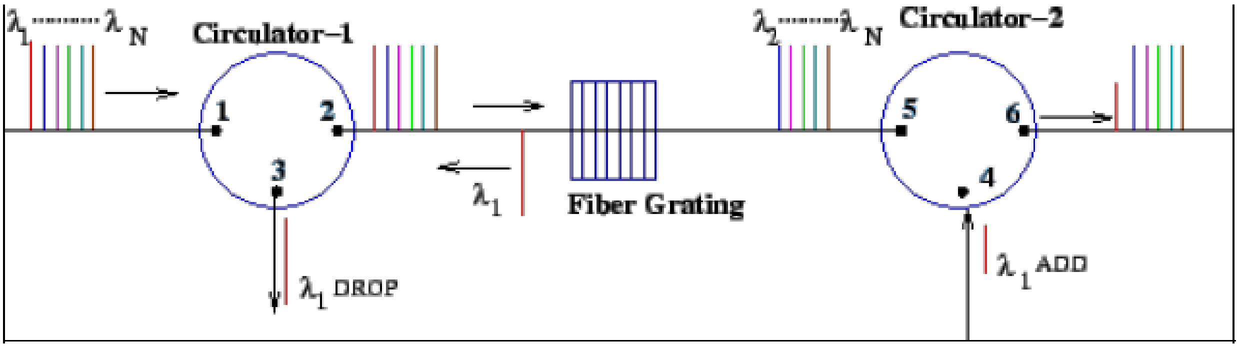
6.3.5 OPTICAL CIRCULATORS

An optical circulator is a 3 or 4 port device which allows flow of light energy in a circular fashion.

For instance in a three port circulator, an input into port 1 appears in port 2 as output with low forward loss and high return loss. Similarly, an input in port 2 goes to port 3 an input into port 3 appears as output in port 1. Circulators are characterised by low insertion loss (<1 dB) and high isolation (>50 dB). Circulators in conjunction with wavelength selective Fiber Bragg Grating (FBG) are used in design of optical add-drop multiplexers.



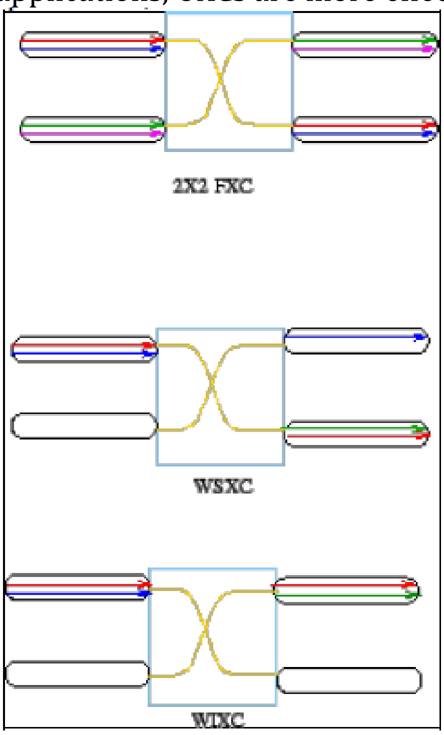
The following figure illustrates the design of an OADM. Several wavelengths from a multiplexer are fed into port 1 of the first optical circulator. The signal passes to port 2 and then on to a fiber grating which selectively reflects , which, in turn, becomes input to port 2.



The signal of wavelength λ_1 then outputs to port 3, where it is dropped. A second signal with wavelength λ_1 arrives at the port 4 of the second circulator (whose ports are numbered 4,5, 6 to avoid confusion). This added signal proceeds to port 5, reflected by Bragg grating and re-enters port 5 as an input. The signal, along with λ_2, λ_3.....is output at port 6.

6.3.6 OPTICAL CROSS CONNECTS (OXC)

Cross connects are essential components of any communication system. Optical cross connects (OXC) are essentially switches which connect any of the input ports to any of the output ports. In the hybrid version of optical switches, switching was done by first converting optical signal to electrical signals, do switching electronically and then reconvert the electrical signals to optical signals. An OXC is an all optical switch which work entirely at photonic level. Because of the high cost of OXCs, hybrid switches are still used today. However, in large bandwidth applications, OXCs are more effective.



Various types of OXCs are made depending on the type of function. **Fiber Cross Connects (FXC)**s are those which connect one fiber channel to another. For wavelength switching **Wavelength Switching Cross Connects (WSXC)** switch wavelength from one port to a port which might be carrying a different wavelength without having to resort to wavelength conversion. WIXCs are switches which provide for wavelength conversion in switching from one fiber to another.

6.3.7 WAVELENGTH CONVERTERS

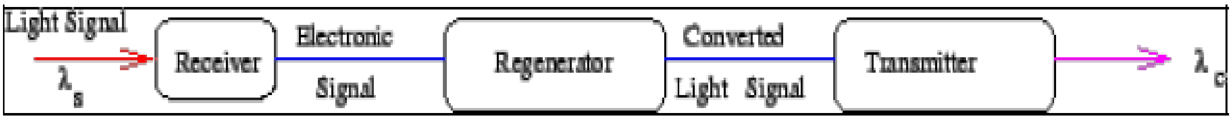
Wavelength converters are devices which changes the wavelength of an input signal. There are several ways in which a wavelength conversion can occur. Usually, wavelength conversion takes place from a shorter wavelength to a longer wavelength. For instance, certain material can absorb radiation and re-radiate at a lower frequency.

In WDM network, frequency converters are used in conjunction with OXCs for better utilization of available wavelengths. The most commonly used techniques of wavelength conversion are

- Electro-optic conversion
- Cross - Gain Modulators (XGM)
- Cross-Phase Modulation (XPM)
- Four-wave mixing

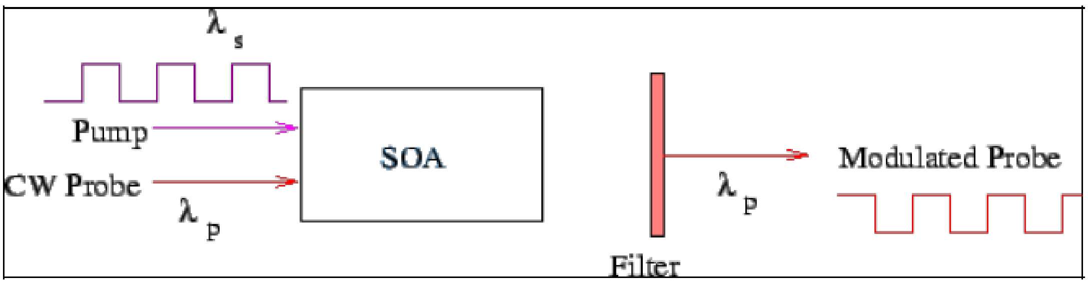
1. **Electro-optic conversion**

In electro-optic conversion an input light signal is converted into an electrical signal, regenerated and re-transmitted at a different wavelength using a tunable laser.



2. **Cross-Gain Modulation (XGM)**

Semiconductor Optical Amplifiers (SOA) are used in WDM systems for switching and wavelength conversion. The active medium in SOAs have homogeneously broadened gain, i.e., change in carrier density in the medium affects all input signals. Thus a strong signal at a wavelength λ_1 will affect a weak signal at a different wavelength.



Consider a strong signal at a wavelength λs and a weak continuous probe at a wavelength λp incident on an SOA. When the signal is in logic state 1, the power is high, carrier depletion occurs and the probe is blocked. However, when the signal goes to logic zero, there is no depletion and the probe signal passes at full power so that probe is in logic 1 state. Thus the probe signal has been modulated same way as the signal, implying that a wavelength conversion of the signal has taken place. It may be noted that the output signal is inverted in the sense that when the signal should have been in logic state 1, the output is in logic state zero and vice versa. This may be easily set right.

3. Cross-Phase Modulation (XPM)

Non-linear properties of some semi conducting material can be used to convert wavelength. As the refractive index of the active medium depends on the carrier density, an incoming signal which depletes carrier density will modulate the refractive index. The change in refractive index, in turn, will phase modulate the continuous wave probe signal. The signal itself is filtered out at the output state, passing the modulated probe signal at a wavelength λp of carrying the same information as the original signal with wavelength λp was carrying.

4. Four Wave Mixing (FWM)

Four wave mixing, which is an undesirable feature in fiber propagation can be exploited to convert wavelength.
When three frequencies $f1, f2$ & $f3(\neq f1, f2)$ are launched into the fiber, it results in a fourth wave of frequency $f = f1 + f2 - f3$. The new wave is known as the *idler* . Four wave mixing causes undesirable effect in optical transmission when the probe wavelength is close to the signal wavelength as the resulting wave has the frequency of the input signal.

6.4 FREE SPACE OPTICS (FSO)

FSO (free space optics) is an optical communication technology in which data is transmitted by propagation of light in free space allowing optical connectivity. There is no requirement of the optical fiber cable. Working of FSO is similar to OFC (optical fiber cable) networks but the only difference is that the optical beams are sent through free air instead of OFC cores that is glass fiber. FSO system consists of an optical transceiver at both ends to provide full duplex (bidirectional) capability. FSO communication is not a new technology. FSO is a LOS (line of sight) technology, where data, voice, and video communication is achieved with maximum 10Gbps of data rate by full duplex (bidirectional) connectivity

CHARACTERISTICS OF AN EFFECTIVE FSO SYSTEM

- FSO systems should have the ability to operate at higher power levels for longer distance.
- For high speed FSO systems, high speed modulation is important.
- An overall system design should have small footprint and low power consumption because of its maintenance.
- FSO system should have the ability to operate over wide temperature range and the performance degradation would be less for outdoor systems.
- Mean time between failures (MTBF) of system should be more than 10 years.

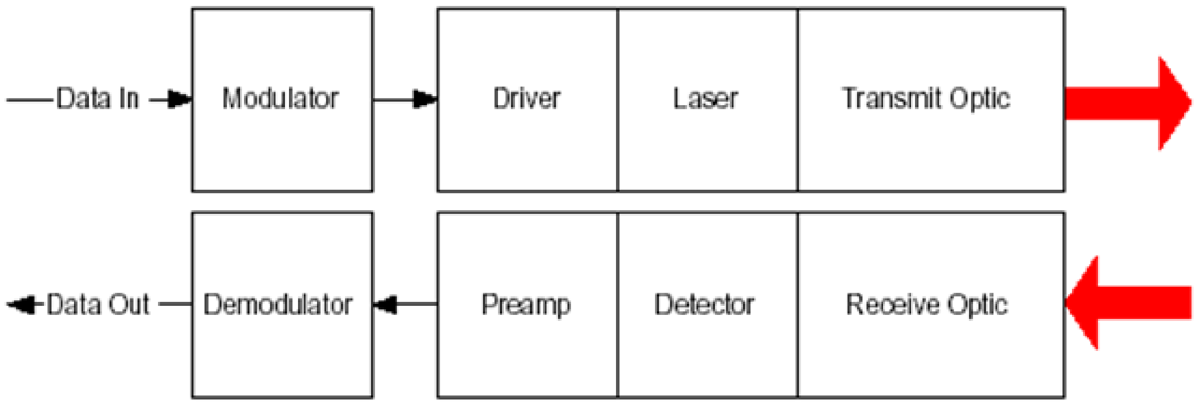
MERITS

- Free space optics is a flexible network that delivers better speed than broadband Installation is very easy and it takes less than 30 minutes to install at normal locations .
- It has very low initial investment .
- It is a straight forward deployment system. There is no need for spectrum license or frequency coordination between users as it is required in radio and microwave systems previously.
- It is a secure system because of line of sight operation and so no security system up gradation is needed.
- High data rate can be obtained which is comparable to the optical fiber cable’s data rate but error rate is very low and the extremely narrow laser beam enables having unlimited number of FSO links which can be installed in a specific area .
- There is immunity to radio frequency interference .
- Electromagnetic and radio-magnetic interference cannot affect the transmission in FSO link .
- FSO offers dense spatial reuse .
- Low power usage per transmitted bit is merit of FSO system.
- There is relatively high bandwidth.
- It has flexible rollouts.

❖ Transmission of optical beam is done in air. Hence, transmission is having speed of light

FREE SPACE OPTICAL TRANSMISSION SYSTEM

A Free Space Optical transmission system is a wireless form of connection designed for the interconnection of two points which have a direct line of sight. The systems operate by taking a standard data or telecommunications signal, converting it into a digital format and transmitting it through free space. The carrier used for the transmission of this signal is Infrared and is generated by either high power LED or laser diode. The basic principles for the transmission of a signal along a fibre are the same as for transmission through free space.



COMPARISON OF FSO WITH DIFFERENT COMMUNICATION SYSTEM.

PARAMETERS	FSO	OPTICAL FIBER	MICROWAVE RADIO	COAXIAL CBLE
Installation	Moderate	Difficult	Difficult	Moderate
Data Rate	Gbps	Independent	Mbps	Mbps
Security	Good	Very good	Poor	Good
Connectivity	P2P, P2MP short & Long reach	P2P, P2MP short & Long reach	P2P short reach	Multidrop short reach
Maintenance	Low	Low	Low	Moderate
Spectrum Licence	Not Required	Required	Required	Required

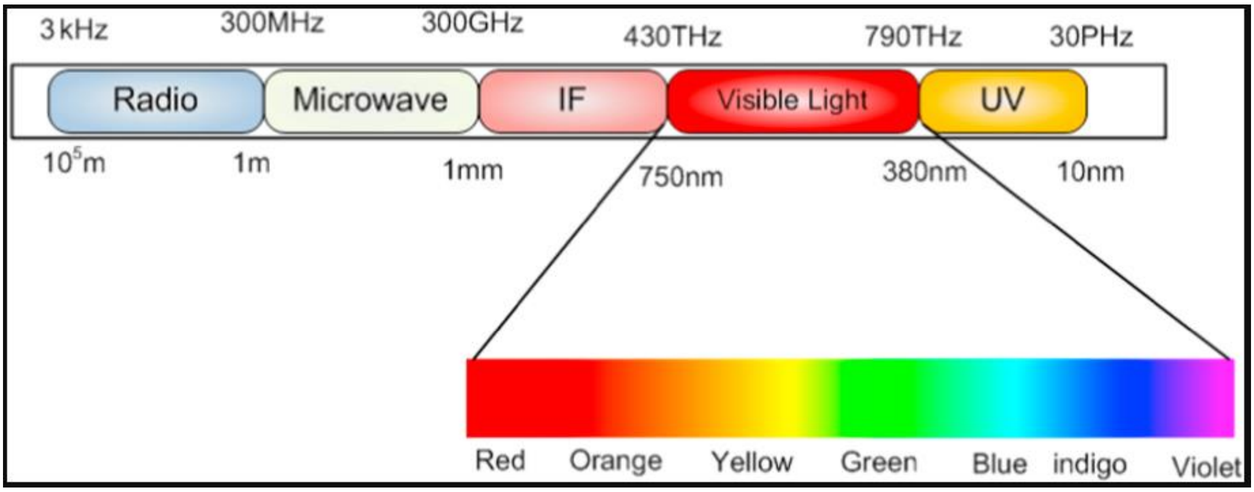
LIMITATIONS

❖ **Physical obstructions**: flying birds, trees, and tall buildings can temporarily block a single beam, when it appears in line of sight (LOS) of transmission of FSO system

- **Scintillation**: there would be temperature variations among different air packets due to the heat rising from the earth and the man-made drives like heating ducts. These temperature variations can cause fluctuations in amplitude of the signal which causes "image dancing" at the FSO receiving end. The effect of scintillation is addressed by Light Pointe's unique multibeam system .
- **Geometric losses**: geometric losses which can be called optical beam attenuation are induced due to the spreading of beam and reduced the power level of signal as it travelled from transmitted end to receiver end .
- **Absorption**: absorption is caused by the water molecules which are suspended in the terrestrial atmosphere. The photons power would be absorbed by these particles. The power density of the optical beam is decreased and the availability of the transmission in a FSO system is directly affected by absorption. Carbon dioxide can also cause the absorption of signal.
- **Atmospheric turbulence**: the atmospheric disturbance happens due to weather and environment structure. It is caused by wind and convection which mixed the air parcels at different temperatures. This causes fluctuations in the density of air and it leads to the change in the air refractive index. The scale size of turbulence cell can create different type of effects given below and which would be dominant:(i)If size of turbulence cell is of larger diameter than optical beam then beam wander would be the dominant effect. Beam wander is explained as the displacement of the optical beam spot rapidly.(ii)If size of turbulence cell is of smaller diameter than optical beam then the intensity fluctuation or scintillation of the optical beam is a dominant one. Turbulence can lead to degradation of the optical beam of transmission. Change in the refractive index causes refraction of beam at different angle and spreading of optical beam takes place .
- **Atmospheric attenuation**: atmospheric attenuation is the resultant of fog and haze normally. It also depends upon dust and rain. It is supposed that atmospheric attenuation is wavelength dependent but this is not true. Haze is wavelength dependent. Attenuation at 1550nm is less than other wavelengths in haze weather condition . Attenuation in fog weather condition is wavelength independent.
- **Scattering**: scattering phenomena happen when the optical beam and scatterer collide. It is wavelength dependent phenomenon where energy of optical beam is not changed. But only directional redistribution of optical energy happens which leads to the reduction in the intensity of beam for longer distance. Atmospheric attenuation is divided into three types
    - Rayleigh scattering which is known as molecule scattering.
    - Mie scattering which is known as aerosol scattering.
    - Nonselective scattering which is known as geometric scattering.

6.5 VISIBLE LIGHT COMMUNICATION (VLC)

Visible Light Communication (VLC) systems employ visible light for communication that occupy the spectrum from 380 nm to 750 nm corresponding to a frequency spectrum of 430 THz to 790 THz .



The low bandwidth problem in RF communication is resolved in VLC because of the availability of the large bandwidth as illustrated in above figure. The VLC receiver only receives signals if they reside in the same room as the transmitter, therefore the receivers outside the room of the VLC source will not be able to receive the signals and thus, it has the immunity to security issues that occurs in the RF communication systems. As a visible light source can be used both for illumination and communication, therefore, it saves the extra power that is required in RF communication. Keeping in view the above advantages, VLC is one of the promising candidates because of its features of non-licensed channels, high bandwidth and low power consumption.

To function, VLC uses visible light between 780 to 380 nm which are visible to the human eye. Every form of data can be broken down into single units of ones and zeroes that can be deciphered as low or high signals. In VLC, this is achieved by fast turning of light on and off (also called on-off keying, OOK). However, this form of data transmission is dependent on how fast the light can go on and off. To achieve great results, LED lighting is well suited for the task as it has a short rise and fall time thus faster switching. Due to this, LED lighting is used in all wireless forms of VLC.

To function, VLC requires a receiver (photodetector), a transmitter (LED's) and a channel of communication. In addition, the circuit features a photodiode, transimpedance amplifiers, auto gain controllers, high pass filters and in some cases analog-digital converters. From the source of the signal, an enhanced photodiode is fitted so as to convert light into a current. At the source and recipient of the instructions, a digital unit is fitted so as to encode and decode the instructions relayed accordingly. So as to increase the speed and the gain of the photodiode, a transimpedance amplifier is used to make the process faster. Additionally, an automatic gain control is featured thus boosting speeds for messages between the sender and the receiver.

Once the message is relayed, the photodiode on the other end breaks the current into a voltage that can be interpreted by the computer as a unit of ones and zeros hence achieving a targeted result. So as to prevent disturbance from surrounding light sources, a high pass filter is used in the model. However, this is a passive set of both the transimpedance amplifier and the auto gain controllers are both gainers and no more gain was required. With this, the set is completed and thus messages are delivered instantly without external disturbances

APPLICATIONS OF VLC

- **Smart lighting:**

With the infusion of technology with real estate development, smart homes have become a trendy topic. With VLC in housing, one will be able to connect to fast speeds of data transmission in the house and also have a cheaper source of bright light. With appliance of VLC in a building, one will not only cut on the cost of wires but also save the electricity costs

- **Infrastructure and transportation:**

Among the fields that highly apply visible light communication, the transport sector is on top of the list. Ranging from traffic signs, street lamps, and car LED's VLC proves to be a great addition. Not only because the minimal wiring is required but also because the systems get to operate efficiently with minimal chances of damage. In vehicle indicators, VLC is used to send signals to the LED lights thus achieving communication between vehicles. The messages indicated via this medium include breaking warning, direction indicators, and hazard lighting. This, in turn, prevents road accidents and carnages.

- **Security purposes:**

Unlike other media transmission of data, chances of messages being relayed via VLC getting intercepted are equally low. This given that one across the wall cannot access the messages getting delivered on the other side of the wall. This, in turn, reduces the ability of messages leaking as the messages will be accessed by people within a given floor space. Additionally, this method is way faster than other methods present and thus few instances of delay of messages.

- **Mobile connectivity:**

By directing a visible light to another device, a high-speed medium of data transmission is created. This medium is way faster than Bluetooth and equivalent transmission methods hence ability to transfer large data packets within a small duration of time.

- **Healthcare sector:**

In hospitals, several machines will benefit from VLC as they will get less interference from radio waves from other machines. This will reduce interruption from other devices using radio waves hence easier operation.

Li-fi- unlike Wi-Fi where a radiofrequency is used, Li-Fi solely depends on the light so as to operate. With this, data is relayed faster and costs on wiring are saved.

- **Aviation:**

Since radiofrequency is warned against by several flights in passenger compartments, VLC would be a great replacement. This provided that LED lighting already exists in aircraft. Usage of VLC will reduce the overall weight of the plane and cut on wiring costs. Additionally, passengers will enjoy fast data connections hence easy communication inflight.

6.5.1 LiFi technology

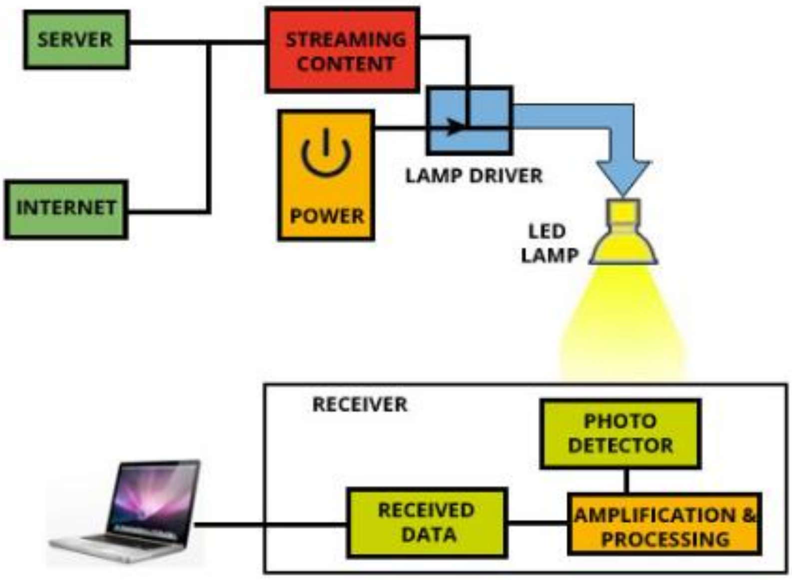
Li-Fi is a wireless technology which transmits high-speed data using visible light communication (Li-Fi is the abbreviated form for Light Fidelity).

Working

It is a form of communication that is supposed to use the light that is being emitted by the Light Emitting Diodes (LEDs) as a medium to provide high speed communication. This is a variant of Visible Light Communication (VLC) which uses visible light in the electromagnetic spectrum. The LEDs are switched on and off which indicates data transfer within nanoseconds without the human eye gets noticed.

White LED lights are used to implement this technology which is present at the downlink transmitter. By applying a constant current these LED lights can be used for illumination. And depending upon the variations of current, the light output undergoes variation at high speeds. This is the setup basically used in Li-Fi. When the LED is ON it transmits 1 and in case, it is OFF, then 0 is transmitted. Due to the faster switching speeds of LEDs, the chances of transmitting data is very high. The circuitry for data transmission through light essentially requires LED lights and a controller, which can code data into the LEDs followed by flickering of LED light depending upon the data to be transmitted.

A setup that has been implemented to showcase the Light-Fidelity technology is given below.



Here the data that is originated from server and internet modulates the LED lamp light intensity which is normally imperceptible to the human eye. As LEDs are semiconductor devices, the modulated current and the output is detected by a photo-detector. The photo-detector device converts light energy back to electrical energy. This is then converted into data streams and further transmitted to mobiles, laptops etc. High Speed Communication is possible with this technology with ease. Researches have achieved a transmission rate of 10GBps data rate. Thus LED bulbs can light up a room as well as carry out data transmission without any harmful side effects.

FEATURES OF LIGHT-FIDELITY

Radio spectrum is becoming endangered depending upon the increasing demand. The issues regarding the radio spectrum is capacity, efficiency, safety and security which is actually the main features under Li-Fi technology.

- **Capacity**

The bandwidth of visible spectrum is 10,000 more than the radio frequency spectrum and is absolutely untouched and free to use. The data density of this technology is 100 times better than Wi-Fi as light is less prone to interference or spreading out when compared RF waves.

High intensity light output, greater bandwidths and low interference provides high speed data rates.

- **Efficiency**

The components requirement for this technology is very less when compared to RF technology and thus it is a low cost technology. The data transmission via LED light requires less power making it energy efficient. Li-Fi working is very much environmental friendly when compared to RF technology that is actually not propagated in water.

- **Safety**

There is no question of health or safety concerns related to this technology. Radio frequencies generally interfere with other electronic circuitry which makes it non-hazardous to the environment

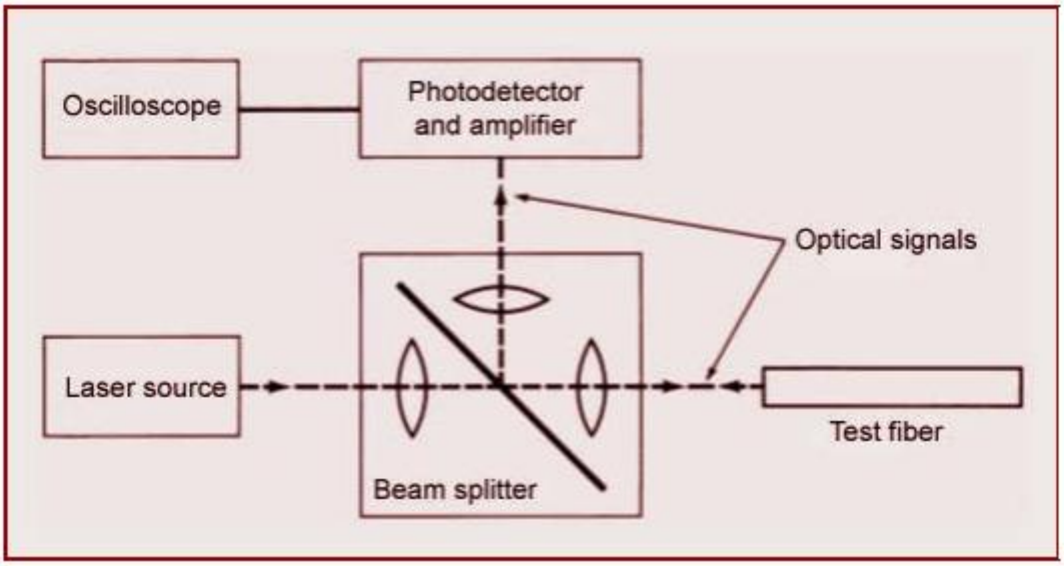
- **Security**

Li-Fi signals are less interpreted as the signals are confined within an illumination area that is a closed network and does not travel through the walls. Sometimes user can see the data transfer so make the transmission under control.

Comparison between Wi-Fi and Li-Fi

PARAMETERS	WI-FI	LI-FI
Reliability	Medium	Medium
Security	Medium	High
Range	Medium	low
Speed	High	High
Data Density	Low	High
Power Available	High	Low
Device-Device Connectivity	High	High
Obstacle Interference	Low	High
Environmental Impact	Low	Medium

6.6 OPTICAL TIME DOMAIN REFLECTOMETER (OTDR).

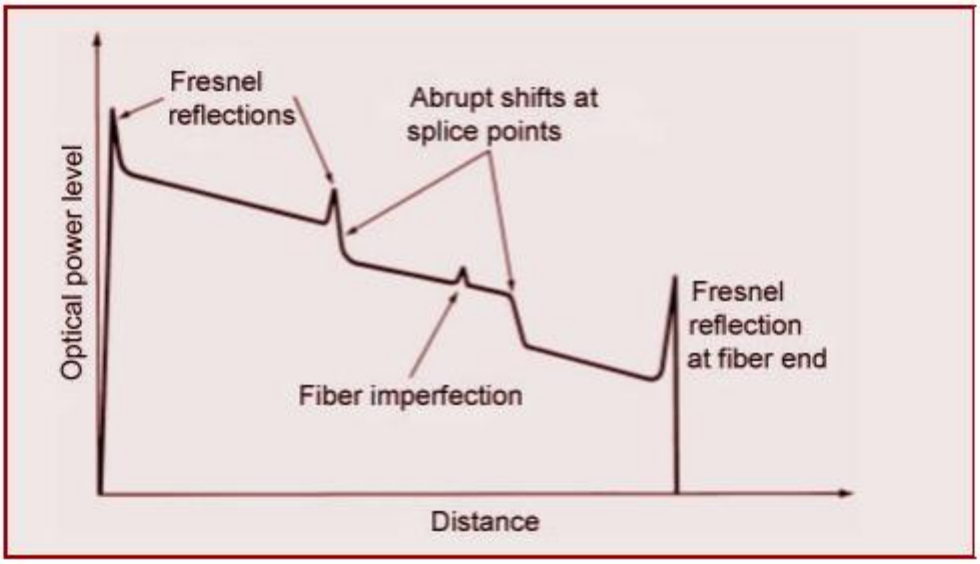


The OTDR is essentially an optical radar. The laser source launches a narrow pulse of light inside the optical fiber and measures its reflection. The optical pulse when travels inside the fiber, gets Rayleigh scattred. The backward scattered light is collected by the photo-detector and displayed as a function of time. Now the intensity of the Rayleigh scattered light depends upon

- Intensity of the light propagating at that location
- The variation in the refractive index at that location.

For a continuous fiber, the refractive index perturbation is same all along the fiber. The optical intensity however decreases along the fiber due to loss. The intensity of the back scattered light also then decreases in the same proportion. The back scattered travels along the fiber and gets further attenuated. The intensity of the back scattered light then is proportional to twice the loss of the fiber. From the delay of the back scattered we can find the location on the fiber. In addition to the Rayleigh back scattering, there could be local disturbance in the refractive index, like due to a splice or connector or a lossy bend. There will be stronger echo from these locations due to Fresnel reflections.

A typical back scatter intensity variation as a function of time is shown in Fig.



The slope of the line on the OTDR display gives twice the attenuation /Km of the fiber. Since the Rayleigh scattering is very week in the optical fiber, the back scattered light intensity is very small to be detected in the presence of electrical noise. Multiple pulses are therefore transmitted and the received signal is integrated to improve the signal to noise ratio of the OTDR trace. The separation between the pulses has to be more than the round trip delay on the fiber. If the maximum fiber length for which the OTDR is to be used is $\boldsymbol{L_{max}}$ and its effective index is $\boldsymbol{n_{eff}}$.

$$\boldsymbol{The\ Minimum\ seperation\ of\ pulses\ should\ be\ \leq \frac{L_{max}n_{eff}}{C}}$$

where C is the velocity of light in vacuum. The maximum pulse repetition frequency therefore is $Max\ PRF = \frac{C}{L_{max}n_{eff}}$

6.6.1 FAULT DETECTION USING OTDR

The OTDR can also be used to monitor the status of the optical fiber while in operation. It can detect faults like tempering of the fiber as well as breakage in the fiber. The accuracy with which the faults can be located depends upon the width of the optical pulse. The minimum separation needed between two identical faults to be identified as the two faults is called the **resolution of the OTDR**. The resolution depends upon the laser pulse width as well as the dispersion on the fiber.

If the laser pulse width is τ_i, the pulse width of the received back scattered light will be

$$\tau = \sqrt{{\tau_i}^2 + (DL\sigma_\lambda)^2}$$

where D is the dispersion on the fiber, σ_λ is the spectral width of the laser and L is the distance on the fiber

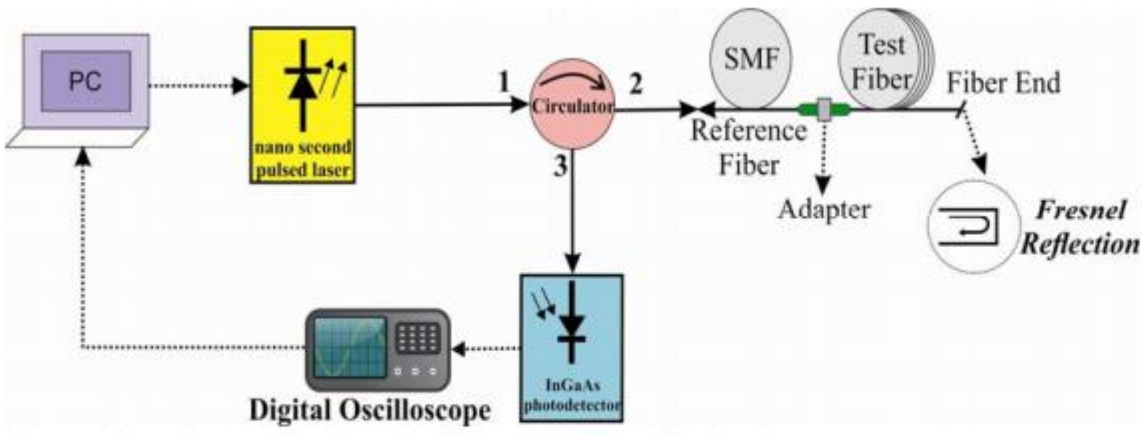
The spatial resolution of the OTDR is

$$Resolution = \frac{C/n_{eff}}{\tau}$$

For short distance, the dispersion does not play much role and the resolution is independent of the distance. However, for longer lengths, the resolution worsens as a function of distance.

6.6.2 LENGTH MEASUREMENT

The basic idea of this technique is to determine the length of the fiber optic cable by measuring differential time between two reflected pulses from the reference fiber and the test fiber ends.



A nanosecond optical pulse is generated by a pulsed laser source with a pulse width of about 50 ns and a repetition rate of 10 kHz, at 1,550 nm and then it is injected into the first port of the optical circulator. The second port of the optical circulator is spliced with the reference fiber. The reference and the test fibers are terminated with FC/PC connectors which cause sufficiently strong Fresnel reflections to be able to measure the length of the test fiber. The test fiber is connected to the reference fiber output with an FC/PC adapter. The length information of the test fiber is extracted from the differential time delay for the Fresnel reflected pulses in both ends by a photodetector with 5 GHz bandwidth connected at the third port of the optical circulator. The reflected pulses are measured in the real-time using a 2 GS/s digital oscilloscope and processed with a computer.

It is accepted that the speed of light is 299,792.458 km/s in the vacuum . But, the light travels slower in optical fiber than vacuum because of optical fiber has a refractive index of n >1. It is well known that the parameter of refractive index n only defines the refractive index of a core or a cladding layer in a fiber. The value of the effective group index of refraction n_{eff} is a weighted average for all the indices of the refraction, encountered by the light as it travels within the fiber. Therefore, it represents an actual behaviour for the light travelling in a fiber. So, the parameter of neff is more useful than the classical refractive index n in the latency applications. The value of neff in standard single mode fiber, LEAF (large effective area fiber), NZ-DSF (non-zero dispersion shifted fiber) are 1.4682, 1.4681 and 1.4691 for 1,550 nm, respectively.

The speed of light in a single mode fiber at 1,550 nm wavelength can be calculated

$$c_{fiber} = \frac{c}{n_{eff}}$$

The length of a test fiber (L) can be obtained by measuring the time delay of the reflected signals (Δt), from the reference and the test fiber ends.

$$2L = C_{fiber} \times \Delta t$$

Here, the constant 2 means that the light travels two times in the test fiber because of the reflection at the fiber end.

6.6.3 MEASUREMENT OF REFRACTIVE INDEX PROFILE

The OTDR is used to measure the effective refractive index and numerical aperture of the fiber cable. The OTDR is essentially a one-dimensional, closed circuit optical RADAR, requiring the use of one end of a fiber to make measurements. These measurements which are attenuation at breaks, connectors and other fiber imperfection points are obtained from input parameters, namely pulse width and refractive index. The input parameter which is refractive index and fiber length are displaced on the OTDR with each measurement. Due to the relationship of refractive index and length ,the cable length displayed by the OTDR is accurate if and only if the refractive index input of OTDR is accurate. This relationship will be used to measure the refractive index.

After measuring the travel time of light pulse, OTDR calculates distance according to equation

$$D = \frac{C \times t}{2N}$$

Where

D= distance to a defect or end of fiber

t= Round trip travel time between launch pulse and returned pulse

C= Speed of light in vacuum

N= Average refractive index (Group index) of the optical fiber core.

If for some unknown reason the effective refractive index of optical fiber with in cable did not match the core refractive index specified in data sheet, the OTDR measured distance to break could be quite inaccurate. Assuming this to be the case , one can derive an equation for calculating the effective refractive index.

$$Nc = \frac{N_f \times D_2}{D_1}$$

Where

Nc = The correct "effective refractive index" to be used with a specific cable under test, whose physically measured length is D1

N_f = the index of refraction set into an OTDR, which then indicates an optical fiber length D_2

D_1 = the physically measured cable length

D_2 = the OTDR measured optical fiber length, when set with refractive index of N_f

Therefore the physically measured cable length D_1 is known ,the effective refractive index can be calculated using above equation.

OPTOELECRONIC DEVICES

Optoelectronic Devices - the electronic technology in which optical radiation is emitted, modified, or converted (as in electrical-to-optical or optical-to-electrical).

Related technologies:

- Photonics - science and technology concerned with the behavior of photons
- Electronics - science and technology concerned with the behavior of electrons

Types of devices that are based on semiconductor junction electronics include:

- Photodiodes (PDs) – optical radiation is converted to an electrical signal
- Light-Emitting Diodes (LEDs) – electrical energy is converted to an optical signal
- Laser Diodes (LDs) – electrical energy is converted to optical energy in laser form

Application Examples:

- Fiber optic communications
- Image processing
- Optical sensing

Other Definitions:

- Photon - a quantum of electromagnetic energy with no mass, no charge, and energy hc/λ.
- Light - electromagnetic radiation in the ultraviolet, visible, and infrared bands or optical range
- Electromagnetic (EM) Spectrum - radiation of all frequencies or wavelengths including electrical power transmission, radio frequencies, optical frequencies, and high-energy rays. Wavelength λ (in vacuum) or frequency f are related by $\lambda f = c$ where c is the speed of light in vacuum.
- Radiation - energy emitted or propagated as waves and energy quanta.
- Radiometry – the measurement of radiant EM energy at specific wavelength ranges.

ELECTROMAGNETIC ENERGY

The propagation of electromagnetic energy may be characterized by the vacuum wavelength λ, frequency $f = \omega/2\pi$, or quantum energy E_p. These waves travel with a phase velocity of v_P. Material influences can be described by the index of refraction or refractive index n for light propagation.

The wavelength and frequency are related as

$\lambda f = c$ where c is the speed of light in vacuum.

The quantum energy is

$E_p = hf = hc/\lambda$ where h is Planck's constant.

The phase velcity is

$v_p = c/n$ where n is the refractive index (n is unitless and is equal to or greater than 1).

Divisions of the electromagnetic spectrum include the following.

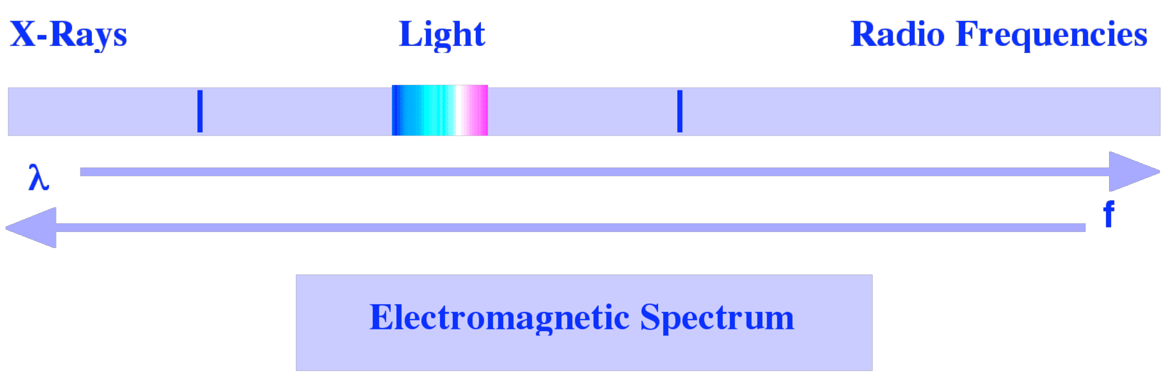
Radio Frequency (RF) - electromagnetic radiation band with frequencies between about 10 kHz and 300,000 Mhz.

Shortwave Spectrum - EM band with wavelengths between about 200 meters and 20 meters; includes the middle bands of radio frequencies.

Microwave Spectrum - EM band with wavelengths between about 1 meters and 1 millimeters; includes the upper bands of radio frequencies.

Light - electromagnetic radiation in the ultraviolet, visible, and infrared bands or optical range with wavelengths between about 1 nm and 10^5 nm.

X-rays - electromagnetic radiation with wavelengths between about 10 nm and 0.01 nm; usually described as high-energy photons.



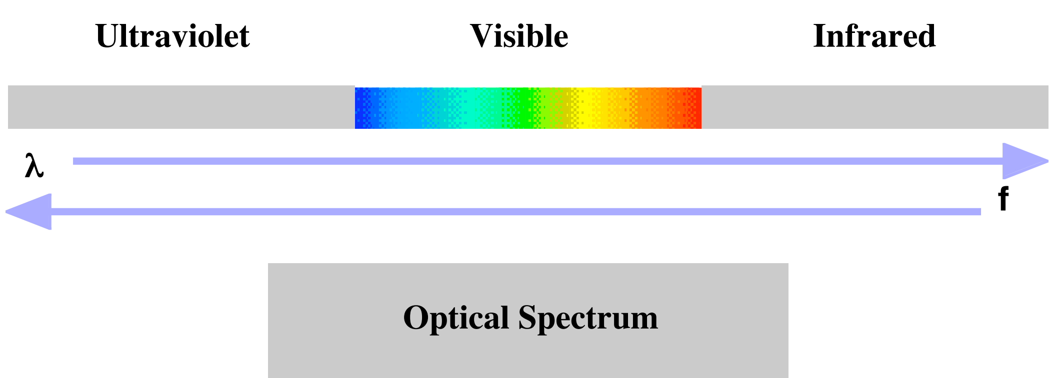
OPTICS: THE NATURE OF LIGHT

Light refers to radiation in the ultraviolet, visible, and infrared portions of the electromagnetic spectrum. The wavelength λ is associated with color in the visible portion of the spectrum. The effective wavelength inside a material, as well as the phase velocity of light, is then decreased by the refractive index. The effective wavelength and phase velocity are then λ /n and c / n.

Preferred designation for wavelength: vacuum wavelength rather than frequency f or energy.
Preferred designation for semiconductor applications: photon energy E_P

Optical Spectrum: Optical wavelengths extend beyond what the eye can detect and include wavelengths between about 1 nm and 10^5 nm which interact with materials in similar ways. For instance, the physical mechanisms behind many optical sources are electronic and molecular transition and the methods of beam control often depend on reflection and refraction from interfaces. Light is subdivided into the ultraviolet, visible, and infrared bands. There are not precise wavelength divisions between bands.

Light Bands	Lower Wavelength Limit	Upper Wavelength Limit
Infrared (IR)	about 700 nm	about 10^5 nm
Visible	about 450 nm	about 700 nm
Ultraviolet (UV)	about 1 nm	about 450 nm



LIGHT ANALYSIS

Wave-Photon Duality: Light is unusual in that it readily displays both wave-like and quantum behavior. Many of the properties of light can be adequately described by waves. Notable exceptions include some cases of emission and absorption. In particular, photoelectric emission led to the concept of photons which was part of the development of the quantum mechanics. Also, the operation of laser diodes and photodiodes can only be explained using a quantum description of semiconductor and light. The quantum energy $E_p = hf = hc/\lambda$ where h is Planck's constant A comparison of the parameters and representations are given.

Wavelengths	Frequency	Quantum Energy
10^5 nm	2.998×10^{12} Hz	1.240×10^{-02} eV
700 nm	4.283×10^{14} Hz	1.771 eV
450 nm	6.662×10^{14} Hz	2.755 eV
1 nm	2.998×10^{17} Hz	1.240×10^3 eV

Analysis of Optical Phenomena

Ray Optics - a geometric representation of the behavior of light (also called geometrical optics) which corresponds to the limiting case of $\lambda \to 0$.

Electromagnetic (EM) Optics - or physical optics, an electromagnetic representation of the behavior of light using Maxwell's equations (limiting case as photon number approaches ∞).

Quantum Optics - the most general representation of the behavior of light in terms of photons, i.e. radiant energy packets, using quantum mechanics.

Interaction with Semiconductors

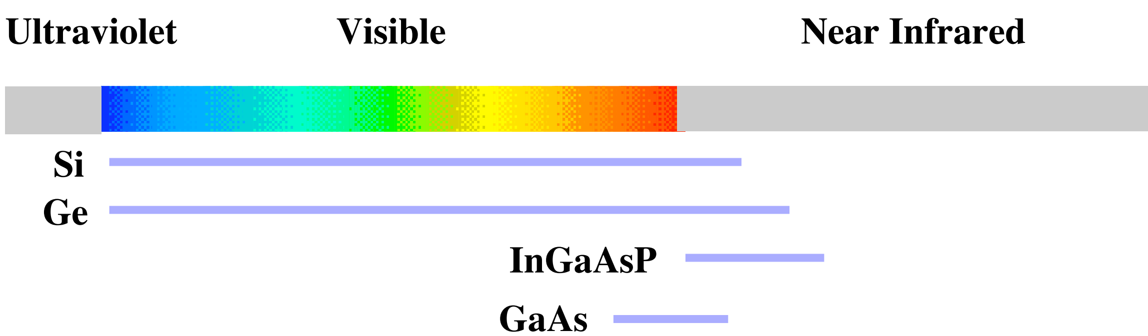
Absorption - loss due to energy conversion as light passes through a material. Photon can be absorbed by electron causing an upward band- to-band transition.

Emission - conversion of energy into light. Photons can be emitted as electrons undergo a downward band-to-band transition.

SEMICONDUCTOR OPTICAL DEVICES

Photodetectors:

Semiconductor structures - Incident photons are converted by semiconductor structures into usable electrons. Solar cells convert light to electrical power. Common devices for imaging and information detection are CCDs (charge coupled devices), photodiodes, and avalanche photodiodes. The design of semiconductor photodetectors depends on the wavelength sensitivity of the materials. For instance, silicon and germanium are sensitive across the visible spectrum and near infrared spectrum. The compound semiconductors InGaAsP and GaAs are sensitive in the upper visible and near infrared. The peak quantum efficiency (electronic conductors generated per incident photon) of about 900 nm in silicon is near its upper cut-off wavelength of 1100 nm. Detectors made of materials such as InGaAsP are optimized for important optical fiber wavelengths of 1300 nm and 1550 nm.



Light Sensitivity of Common Semiconductors

Semiconductor Sources:

Light Emitting Diodes and Laser Diodes - Light is emitted due to quantum transitions in gases, liquids, or solids. Injection electrolumninescence is the mechanism for light emission in semiconductor diodes. Carriers make a downward transition from the conduction band to the valence band and emit light. Laser sources are characterized by high coherence and directionality over an extremely narrow spectrum.

LIGHT ABSORPTION

Attenuation: A media in which light is propagating may be lossy. For a given wavelength, the irradiance will decrease at a rate proportional to the irradiance magnitude. The resulting loss may be represented by an attenuation constant α_L in units of inverse meter (1/m). The attenuation constant is positive for a lossy media, zero for a lossless media, and negative for a media with gain.

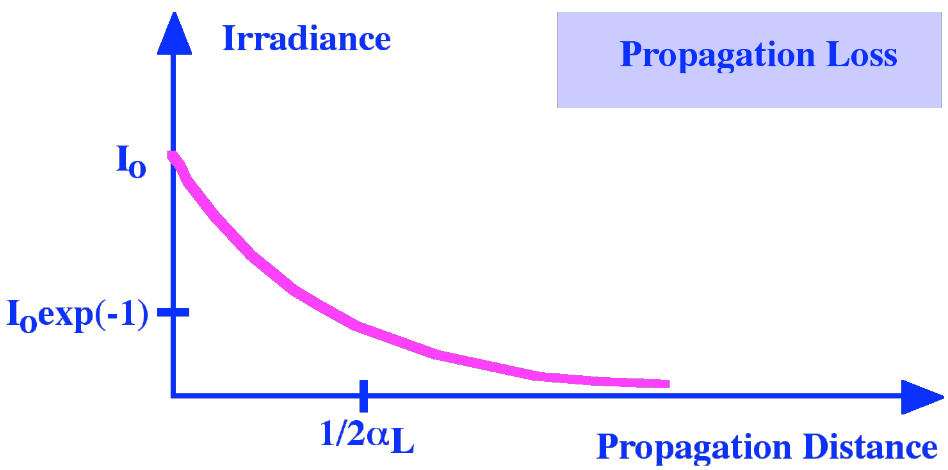
For one-dimension, the defining differential equation for the irradiance (irradiance I with units of W/m^2) amplitude is

$$dI/dx = -\alpha_L I.$$

The solution is

$$I = I_o \exp(-\alpha_L x)$$

Where I_o is the value of I at the position (x=0).



This loss does not include reflection loss at interfaces.

Care must be taken to distinguish between the exponential loss constant for irradiance and that for fields. The attenuation constant α_L as defined here refers to irradiance. The corresponding exponential loss constant for fields is $\alpha_L/2$. Some texts, especially in the semiconductor field, will define the absorption coefficient (α_L) for irradiance with units of inverse meters (m^{-1}) or inverse centimeters (cm^{-1}) while optics or fields text will use define an equivalent quantity for field attenuation, i.e. equivalent to $\alpha_L/2$. Note that the terminology and symbol notation are sometimes used interchangeably in the literature.

PN PHOTODIODES

Photodiode – an optoelectronic device that is based on a semiconductor junction which absorbs light and converts the light input to a current.

- Incident photons are absorbed through upward bandgap transitions
- Photon-induced carriers contribute to the drift current if absorbed within or at the edge of the transition region W.

Photodiode current

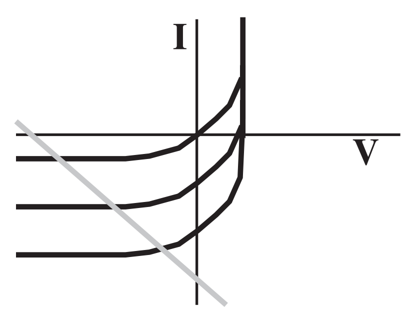
$$I = I_0 [\exp(qV/kT) - 1] - I_{Light}$$

Photon-generated current

$$I_{Light} = \eta q P\lambda/hc$$

where
η = efficiency = carriers generated per incident photon
q = charge per carrier
P = optical power absorbed (J/s)
hc/λ = energy per incident photon (J/photon)
note: $P\lambda/hc$ = incident photons per second

Photoconductive mode – the current-voltage behavior for reverse bias (negative V) depends on the incident light.



Reverse bias with V << 0, the current is magnitude is proportional to the optical power with a small offset.

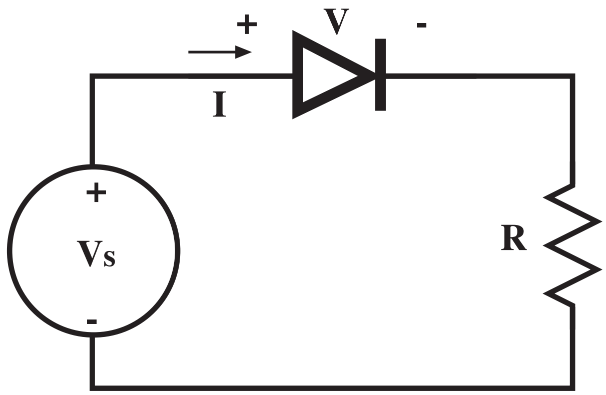
$$I = I_0 [\exp(qV/kT) - 1] - I_{Light}$$
$$I \sim -I_0 - I_{Light}$$

To maximize the efficiency η

- Primary absorption in transition region
- Large transition region for large absorption percentage
- Little recombination in transition region (carriers lost to drift current)
  (Note that photo-generated carriers must exit transition region before recombination. Need to have a small recombination lifetime, a small W, and/or a large electric field in W.)

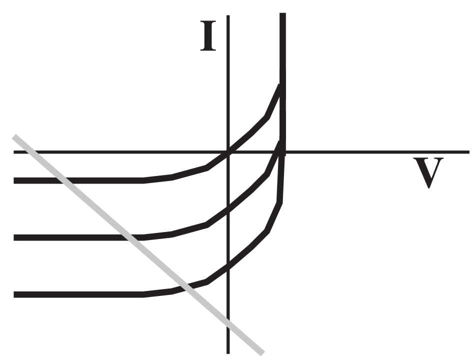
PHOTODIODE BIASING CIRCUIT

The circuit operation of a diode is illustrated in the following figure. Consider a photodiode with a reverse saturation current of $-I_0$.



The current is shared by all of the circuit elements. KVL gives the load-line (LL) equation:

$$V = V_S - IR$$



The nonlinear photodiode equation for reverse bias is

$$I = I_0 [\exp(qV/kT) - 1] - I_{Light}$$
$$I \sim -I_0 - I_{Light}$$

The load-line equation and the nonlinear diode equation must be satisfied for the operating point simultaneously. The solution depends on the term I_{Light}.

- Reverse Bias (Negative V_S): If the operating V and I are away from the knee of the diode curve, the diode current is approximately
  $$I = -I_0 - I_{Light}$$
  and the voltage can be found by substituting I into the LL.
  $$V = V_S - (-I_0 - I_{Light})R$$

Note that the intercepts of the load-line equation are:

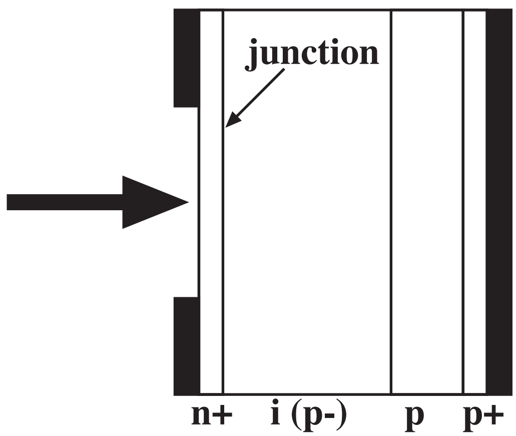
$$I = 0 \text{ for } V = V_S \quad \text{and} \quad V = 0 \text{ for } I = V_S/R$$

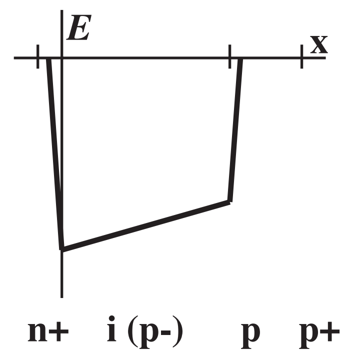
PHOTODIODE TYPES – PIN STRUCTURE

PIN or pin Photodiode

- Structure: "i" intrinsic region (commonly p- or n-) between regions with "p" and "n" doping.
- Efficiency: $\eta < 1$

Example Structure





Structural Design and Function

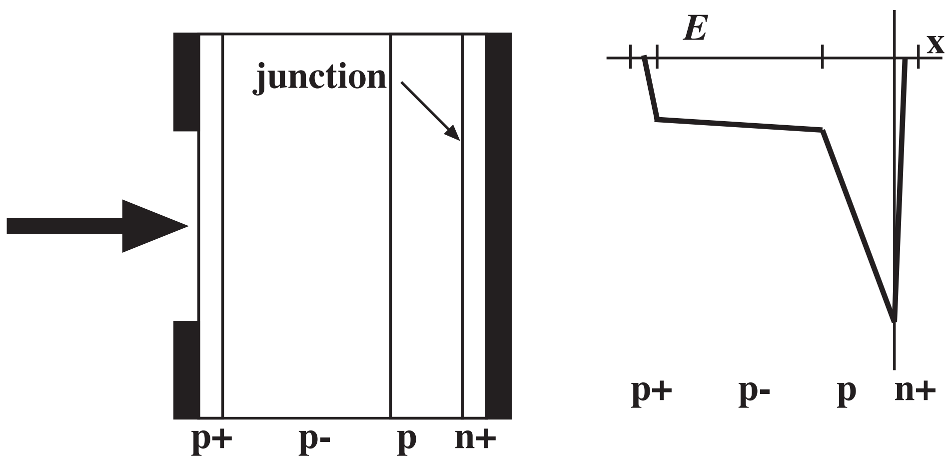
Thin n+ region to allow light to reach the transition region
n+ region provide electrons as the primary carrier (faster than holes)
Transition region width matched to absorption needs (from α_L)
Transition region width primarily i-region for voltage insensitivity
Large electric field throughout transition region

PHOTODIODE TYPES – AVALANCHE STRUCTURE

Avalanche Photodiode (APD)

- Structure: "p-"region for absorption and "p" region for avalanche multiplication between regions with "p+" and "n+" doping.
- Efficiency: $\eta > 1$ (one photon gives many carriers by avalanche gain)

Example Structure



Design

Thin p+ region to allow light to reach the transition region
n+ region provide electrons as the primary carrier (faster than holes)
p- transition region width matched to absorption needs (from α_L)
Separate p multiplication region with large electric field

LIGHT EMITTING DIODES

Emission: A process that converts energy into light.

Injection Electroluminescence

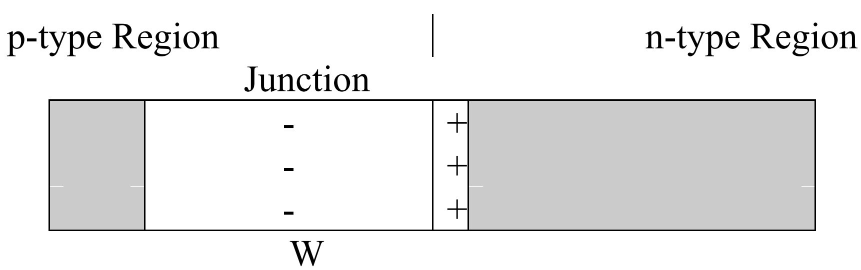
- A "direct-bandgap" semiconductor such as GaAs (Si and GE are indirect semiconductors and do not emit light)
- Injected carriers recombine with a light-emitting transition.
- The transition can be spontaneous or stimulated and occurs near the edges of the depletion region in a diode structure.

Light Emitting diode (LED): an optoelectronic device that emits non-coherent optical radiation at a photon energy close to bandgap of the junction.

- Structure: Typically a p+n or n+p diode such that the main transitions occur on the n-side or p-side respectively of the depletion region.
- Operation: Forward-bias effect producing spontaneous emission.

Example Band Structure for n+p diode (Forward Bias)

Structure



The current is primarily electron flow and the main recombination region is the edge of the depletion region on the p-side.
The optical output increases with forward-bias diode current.

An important issue is the re-absorption of emitted photons. Heterostructures (the use of semiconductors with different bandgaps) are often used such that the photons are emitted in a small bandgap semiconductor and exit the diode through a larger bandgap semiconductor.

LASER DIODES

LASER or Laser: light amplification by stimulated emission radiation. A process that emits optical radiation which is coherent, highly directional, and nearly monochromatic. The spectral purity of laser light is a key property, i.e. the output for a laser has an extremely small spectrum (wavelength spread).

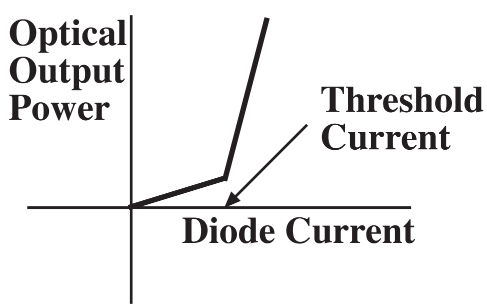
Lasing Operation

- Active material – A material in which energy is converted into light
- Pumping Mechanism – A mechanism to excite ions, electrons, or molecules so that a light-emitting transition is produced.
- Resonant Cavity – A structure to produce optical feedback, i.e. light is amplified through stimulated emission verses spontaneous emission.

Laser diode (LD): an optoelectronic device that is based on a semiconductor junction which emits optical laser radiation at a photon energy close to bandgap of the junction.

- Active Material – Direct-bandgap Semiconductors
- Pumping Mechanism – Diode Junction Structure (Injection Electroluminescence). Heterostructures are common.
- Resonant Cavity – A Waveguide Structure combined with End-face Mirrors

Typical Output Characteristic (Forward Bias)



The Threshold current is the diode current needed to produce stimulated emission, i.e. it is the onset of lasing.
A laser diode is highly efficient in that it converts a high fraction of the electrical energy into useful optical output.

EXAMPLES