Optical *Communication*

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COURSE OUTLINE

INTRODUCTION

- ❖Historical Development
- ❖Electromagnetic Spectrum
- ❖Optical Power Basics
- ❖Need of Optical Fiber Communications
- ❖Light Wave System Components
- ❖Optical Fibers as a Communication Channel
- ❖Advantages of Optical Fiber Cables
- ❖Disadvantages of Optical Fiber Cables
- ❖Applications

COURSE OUTLINE

BASICS OF OPTICAL FIBERS

- ❖Review of Optical Ray Theory
- ❖Light Propagation in Optical Fibers
- ❖Classification of Optical Fibers
- ❖Propagation Modes
- ❖Dispersion in Optical Fibers
- ❖Types of Dispersions
- ❖Attenuation in Optical Fibers
- ❖Transmission Losses in Optical Fiber Cable
- ❖Comparison of Optical Fibers

COURSE OUTLINE

OPTICAL SOURCES AND TRANSMITTERS

- ❖Requirements for an Optical Source
- ❖Light Emitting Diodes (LEDs)
- ❖Laser Diodes
- ❖Optical Transmitter Block Diagram

OPTICAL RECEIVERS

- ❖Requirements for a Photodetector
- ❖Semiconductor Photodetectors
- ❖Optical Receiver Block Diagram
- ❖Receiver Noise
- ❖Receiver Sensitivity

COURSE OUTLINE

WDM CONCEPTS AND COMPONENTS

- Principle of Wavelength Division Multiplexing
- WDM System Configurations
- WDM MUX/DEMUX
- Wavelength Converters
- Wavelength Routers
- WDM Transmitters
- WDM Receivers
- System Performance Issues

COURSE OUTLINE

OPTICAL WIRELESS COMMUNICATION (OWC)

- ❖A brief History of OWC
- ❖OWC/Radio Comparison
- ❖Link Configuration
- ❖Safety and Regulation
- ❖OWC Challenges
- ❖Line of Sight Propagation Model
- ❖Non-Light of Sight Propagation Model

REFERENCES

- T. L. Singal, "**Optical Fiber Communications Principles and Applications**", Cambridge University Press.
- Govind P. Agrawal, "**FIBER-OPTIC COMMUNICATION SYSTEMS**", A JOHN WILEY & SONS, INC., PUBLICATION.
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INTRODUCTION

After studying this Introduction, you should be able to

- get a historical overview of optical fibers and optical fiber communications;
- give reasons for the use of optical fiber in preference to wire cable and suggest suitable applications for fiber–optics;
- describe essential elements of optical fiber communications link;
- know advantages and disadvantages of optical fibers

INTRODUCTION

- Light wave at higher frequency range of electromagnetic spectrum (3×10^{11}–3×10^{16} Hz).

- It is used for transmission of information through fibers as transmitting medium in optical fiber communications.

- It can offer a large bandwidth (more than 50 THz) for data transmission.

HISTORICAL DEVELOPMENT

- Optical fiber communication has been developed over the last two centuries.
- The first optical communication system, known as the '*optical telegraph*', was invented in the 1790s by French engineer Claude Chappe.
- The invention of the laser greatly accelerated research efforts in fiber–optic communications.

HISTORICAL DEVELOPMENT

- In 1970, Maurer, Keck, and Schultz developed single-mode fibers, with attenuation less than 2 dB/km at the operating wavelength of 633 nm.

- In the early 1980s, the first long-distance transatlantic backbone networks were developed for telecommunication purpose using single-mode fiber as communication medium and optical sources at 1300 nm wavelength.

- Optical fiber communication has only been practical since about 1970, when glass fiber was finally made with low enough loss to be useful.

ADVANCES IN OPTICAL FIBER COMMUNICATION

- In general, Optical Fibers were proposed to attain high data rate transmissions.

- The main challenge to provide higher data rate in optical fiber communication is managing the dispersion.

- For any optical fiber system increase in the bit rate will increase the dispersion effect on the system leading to pulse broadening, causing incorrect reception of data at the receiver.

Advances in Optical Fiber Communication

- A new generation optical fiber system operating at 1550 nm wavelength region using single-mode fibers having fiber loss of about 0.2–0.3 dB/km.

- Low-loss single-mode fibers enable larger repeater spacings.

- Using Dense Wavelength Division Multiplexing (DWDM) technology, multiple optical signals generated by different sources.

Generation of Light Wave Systems

Generation	*Wavelength (μm)*	*Fiber Type*	*Bit Rate*	*Fiber Losses (dB/km)*	*Repeater Spacings*
1st (1970s)	0.85	Multimode (graded core)	2–45 Mbps	≥ 1	≈ 10 km
2nd (Early 80s)	1.3	Multimode (graded core)	45–90 Mbps	0.5–1.0	≈ 40 km
3rd (Late 80s)	1.55	Single mode	≥1.7 Gbps	≈0.3	≈ 60–70 km
4th (Early 90s)	1.45–1.62 (Typical 1.55)	Single mode (dispersion-shifted)	2.4 Gbps	≈ 0.2	≈ 80 km
5th (In 2000s)	1.50–1.57 (Typical 1.55)	Single mode (dispersion-shifted/soliton) + Fiber Amplifier	≥2.4 Gbps	0.1–0.2	≥ 100 km

ELECTROMAGNETIC SPECTRUM

- In a *wireline medium*, electromagnetic signals propagate along a metallic cable in the form of voltage (or current) waveforms.

- In a *wireless medium* through free space, electromagnetic signals propagate in the form of radio waves, usually termed as electromagnetic waves.

- In an *optical fiber medium*, the information signals propagate as electromagnetic light waves.

ELECTROMAGNETIC SPECTRUM

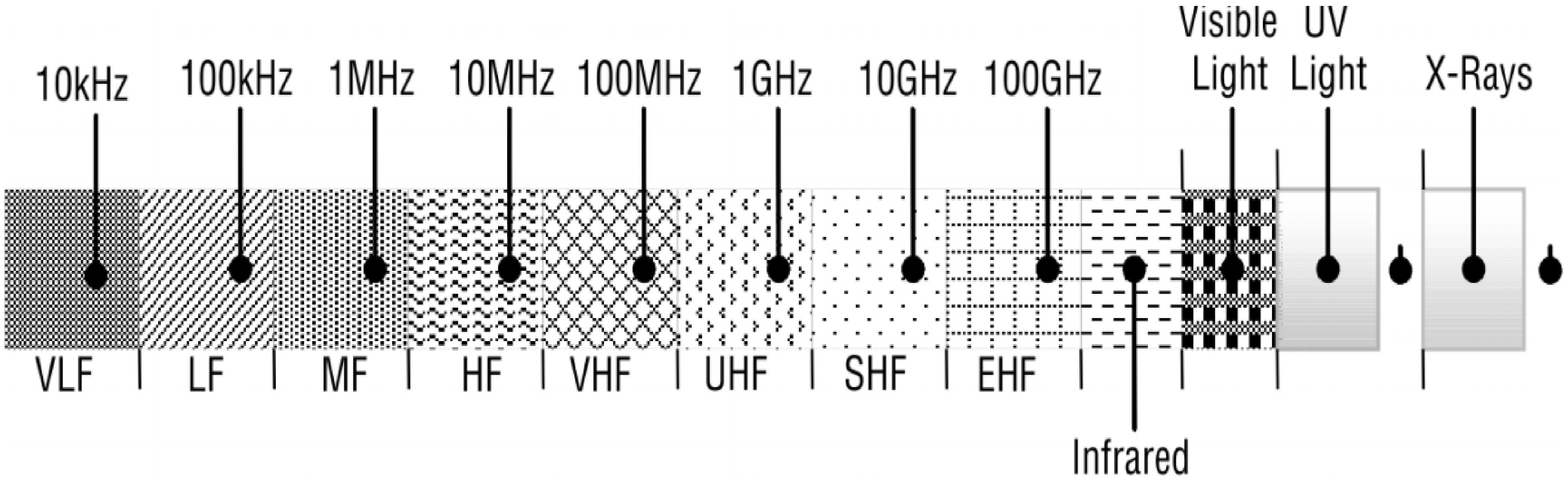


Fig. 1 The electromagnetic frequency spectrum.

Light Frequency Spectrum

- The light frequency spectrum can be divided into three general frequency bands:

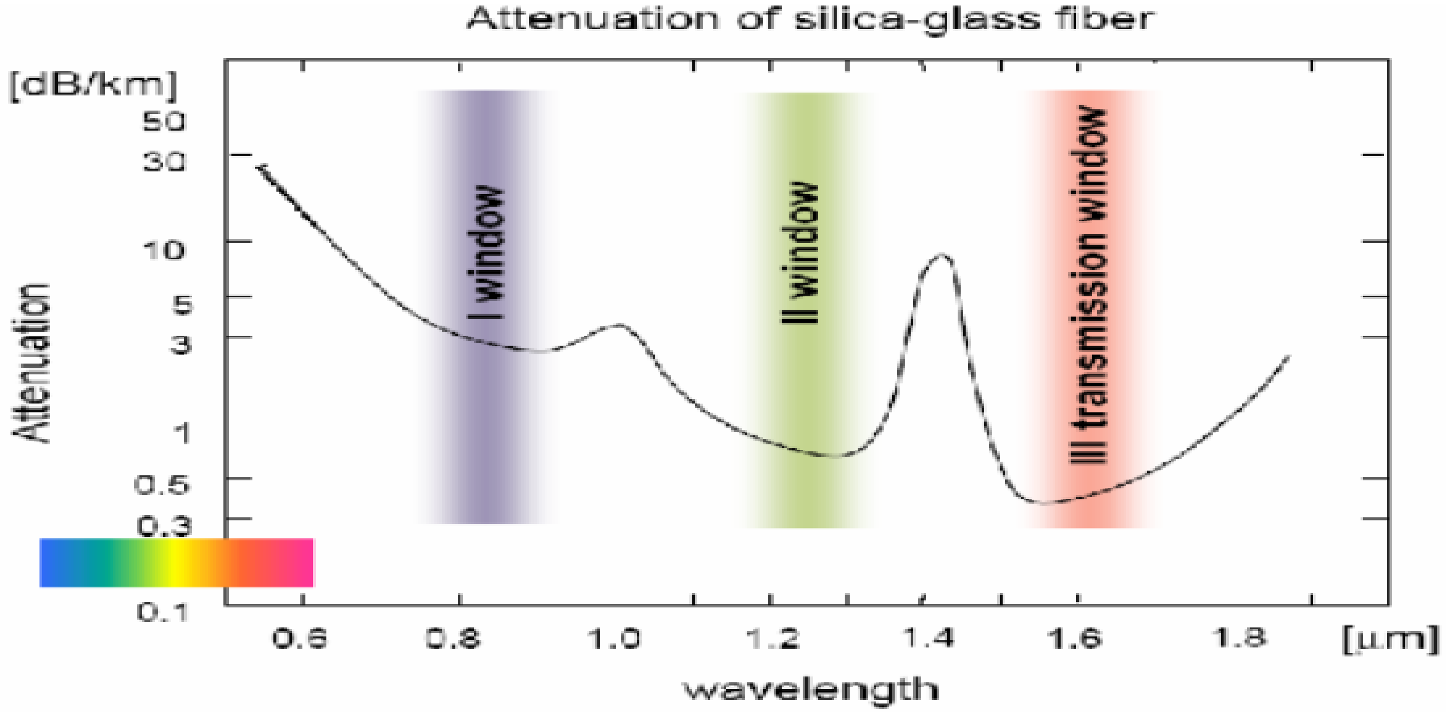
1. **Infrared (IR).** Infrared is the band of light frequencies which is quite high and cannot be seen by the human eye. Typical useful wavelengths range between 770 nm and 1600 nm. In the infrared spectrum, there are three regions (850 nm, 1300 nm, and 1550 nm) in which silica glass fibers are relatively efficient. Optical fiber systems generally operate in the infrared band.

Light Frequency Spectrum

2. *Visible.* It is the band of light frequencies (typically 390–770 nm wavelength range) which is visible to the human eye. Silica glass fibers are not very good transmitters of light in the visible spectrum. They attenuate the light waves to such an extent that only short optical transmission links are useful.

3. *Ultraviolet (UV).* It is the band of light frequencies which cannot be seen by the human eye. Typical wavelengths range between 10 nm and 390 nm. The fiber losses in the ultraviolet spectrum are even greater. This band is used in medical applications.

Light Frequency Spectrum



Fiber Optic Transmission Windows

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

Relationship Between Frequency and Wavelength

- The wavelength ($\boldsymbol{\lambda}$ in meter) is defined as the length occupied by one cycle of an electromagnetic wave in space. It is directly proportional to the velocity of propagation of light in free space ($c = 3 \times 10^8$ m/s) and inversely proportional to the frequency (f in Hz) of the electromagnetic wave.

$$\boldsymbol{\lambda} = \frac{c}{f}$$

Relationship Between Frequency and Wavelength

- **Example 1:** Determine the wavelength (in nm and Angstrom) for radio frequency of 100 MHz, cellular phone frequency of 1 GHz, and light wave frequency of 10^15 Hz.

- **Example 2:** Determine the light wave frequency for the following wavelengths: a) 953 nm, b)828 nm, c) 800 nm and d) 869 nm.

RELATIONSHIP BETWEEN FREQUENCY AND WAVELENGTH

- The velocity of electromagnetic waves differs in medium other than that in free space.
- Its value depends on the material and on the geometry of any waveguide structure such as optical fiber that may be present.
- The wavelength of a light beam (**λ** in meters) can be expressed as:

$$\boldsymbol{\lambda} = \frac{v}{f}$$

RELATIONSHIP BETWEEN FREQUENCY AND WAVELENGTH

- where, v = velocity of light beam in a guided medium (m/s) f = frequency of the light beam (Hz).

- ***Note:*** The frequency (or wavelength) of the optical signal is determined by the optical source. It does not change when the light beam (optical signal) travels from one type of material to another type of material. Instead, the velocity difference causes a corresponding change in wavelength so that the frequency remains the same.

OPTICAL POWER BASICS

- The optical power measures the rate at which electromagnetic waves transfer light energy.

- It is expressed in joules per second, or watts.

- Optical power is generally stated in decibels relative to a defined power level, such as 1 mW (dBm) or 1 μW (dBμ).

$$dB_m = 10log\frac{P}{1mW}, dB_{\mu} = 10log\frac{P}{1\mu W}$$

OPTICAL POWER BASICS

- It is important to take care while adding or subtracting different power levels and gains/losses (expressed in decibels) in a communication system.
- For example, the transmitted power level, *Pt* (dBm), the system loss, *L* (dB) , and received power level, *Pr* (dBm) are related by:

$$Pr\ (dBm) = Pt\ (dBm) – L(dB)$$

OPTICAL POWER BASICS

- **Example 3:** An optical source radiates 2 mW power. Compute the power level (in mW) at the input of optical receiver if the system losses accumulate to 23 dB.

- **Example 4:** A system has 23 dB of power loss. Compute its transmission power efficiency.

- **Example 5:** Prove that 0 dBm = 30 dBμ.

LIGHT WAVE SYSTEM COMPONENTS

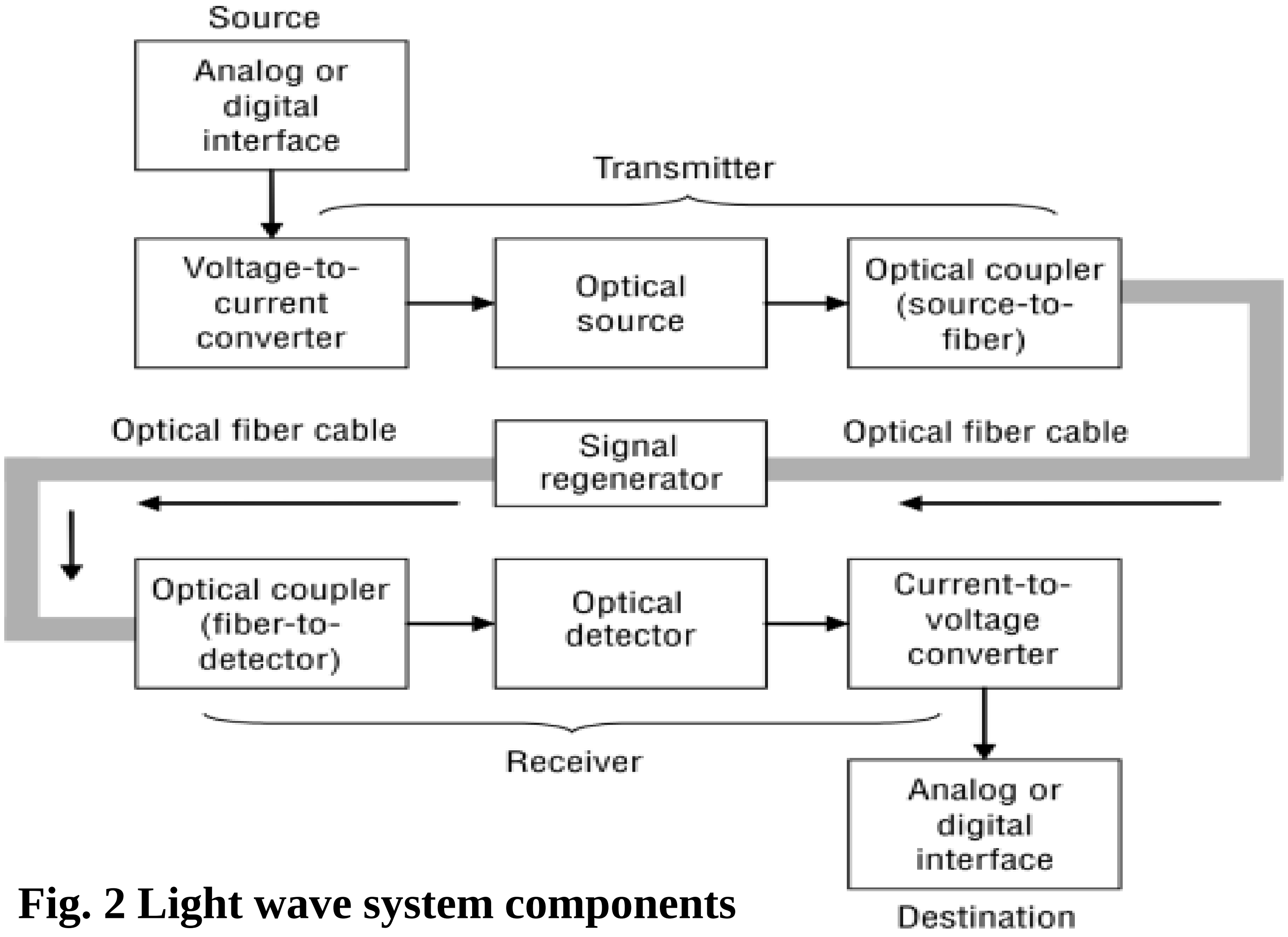


Fig. 2 Light wave system components

LIGHT WAVE SYSTEM COMPONENTS

1. *Information Source.* The source information such as voice or image/video.
2. *Voltage-to-current converter.* The amount of light emitted by the light source is generally proportional to the amount of its drive current. Thus, the voltage-to-current converter is necessary to convert an input signal voltage to a current that is used to drive the light source
3. *Optical source.* The optical source is either a light-emitting diode (LED) or a laser diode (LD), which generates an electromagnetic wave in the infrared region of the optical spectrum.

LIGHT WAVE SYSTEM COMPONENTS

4. *Optical couplers.* The function of source-to-fiber coupler is to collect the light signals from the optical source and send it efficiently to the optical fiber cable. Similarly, the fiber-to-detector coupler is used at the other end of the fiber cable to direct the received light signals onto the photodetector.
5. *Optical fiber cable.* It is the guided transmission medium, which is either an ultrapure glass or a plastic cable.
6. *Optical signal regenerators.* Optical regenerators (amplifiers) are used at appropriate distances from the transmitter along the length of the fiber cables which help to restore the strength and shape of transmitted signal.

LIGHT WAVE SYSTEM COMPONENTS

7. *Optical detector.* The optical detector is generally a *p–i–n* (*p*-type-intrinsic-*n*-type) diode, an avalanche photodiode (APD), or a phototransistor.
8. *Current-to-voltage converter.* It transforms variations in photodetector current to corresponding variations in voltage. It produces an output voltage which is proportional to the original source information.
9. *Destination output*. Finally, the received information is presented in a form similar to that of input information source.

PARTS OF OPTICAL FIBER CABLE

- An optical fiber is essentially a waveguide for light, usually in infrared spectrum.

- It consists of a core and a cladding that surrounds the core. Both are made of transparent material, either glass or plastic, but the main difference is in their index of refraction.

- The material used in cladding has lower refractive index than that used in the fiber core.

PARTS OF OPTICAL FIBER CABLE

- The fiber portion in an optical fiber cable is generally considered to include both the fiber core and its cladding.

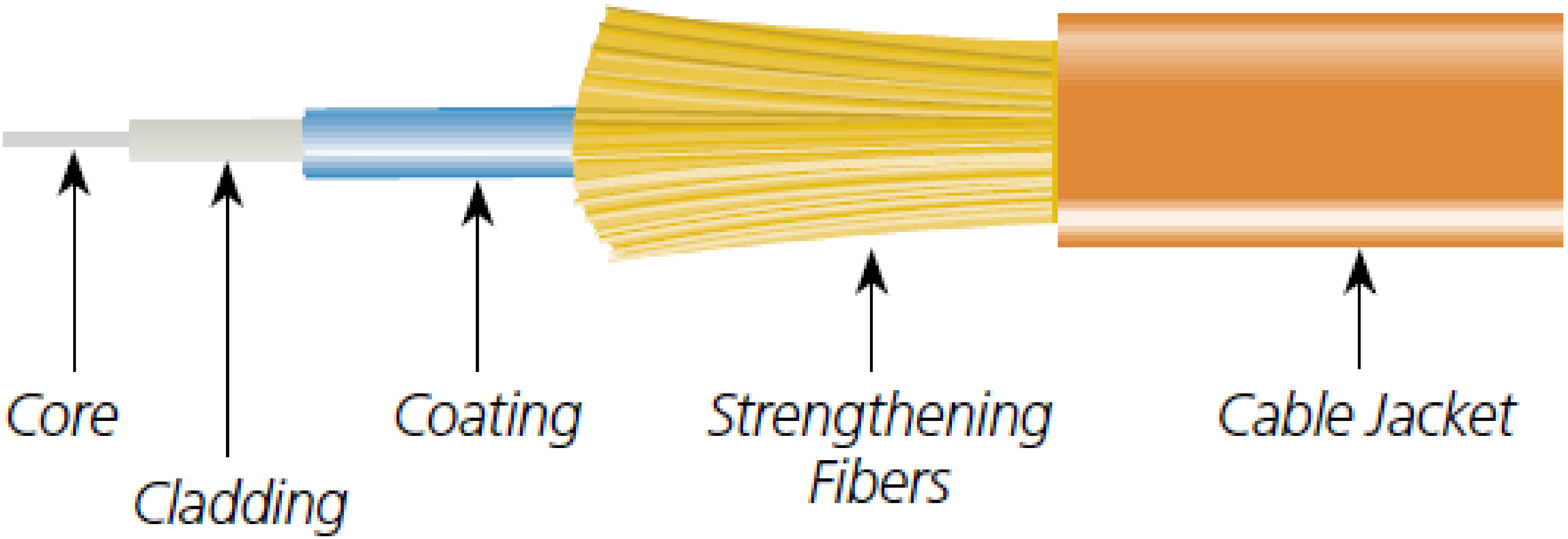


Fig. 3: Parts of optical fiber cable

PARTS OF OPTICAL FIBER CABLE

- **Core:** A fiber optic's center is made of glass, and this tube carries the cable's light signals.

- **Cladding Layer:** Also constructed of glass, this it is used to keep the light in the core.

- **Cable Buffer:** Also called the buffer coating, it is used to protect the core and cladding from foreign material.

- **Cable Jacket:** The fiber optic's cable exterior is typically made of tough, durable polyurethane. Its job is to protect the overall integrity of the fiber optic cable.

ADVANTAGES OF OPTICAL FIBER CABLES

- *Larger bandwidth and greater information capacity .*
- *Lower transmission loss .*
- *Security .*
- *Immunity to static noise.*
- *Immunity to environmental variations.*
- *Reliability.*
- *Easier to install and maintain.*

DISADVANTAGES OF OPTICAL FIBER CABLES

- Lower tensile strength.
- Susceptible to bending losses.
- Interfacing with electronic devices.
- Need of specialized tools.
- Reaction by chemicals.

APPLICATIONS

- Optical fiber cable has wide bandwidth and is widely used in backbone networks.

- A hybrid CATV network is creating by using a combination of RF coaxial cable and optical fiber cable by some cable TV companies.

- The small size and large information-carrying capacity of optical fibers make them viable alternatives to traditional twisted-pair copper cables as trunk lines in modern telecommunication networks

APPLICATIONS

- Optical fiber cables are also used in several types of local area networks (LANs).

- Optical fiber video transmission successfully competes with coaxial cable for surveillance and remote monitoring systems due to its EMI rejection and low susceptibility to lightning damage.

- Fiber sensors have been used to measure temperature, pressure, and liquid levels.

HWs

1) The output power of an optical transmitter is 5 mW. What will be the input power at the optical receiver if the total system loss is 20 dB?

2) What is the difference (in watts) between -60 dBm and 60 dBm?

3) Two fiber cables are connected together, each having loss of 4-dB and the splice used between them has 2-dB loss. If the optical power at the input is 2 mW, compute the optical power output of combined fiber cables.

4) An optical receiver requires an input power of 1 nW. How much optical power must be transmitted by the source if the total system losses add up to 50 dB?

BASICS OF OPTICAL FIBERS

PRINCIPLE OF OPERATION OF OPTICAL FIBER

- The light can be considered as electromagnetic wave (Wave Theory).

- The light can be considered as ray or beam (Geometric Optics).

- The light can be considered as band of photons (Quantum Theory).

OPTICAL RAY THEORY

- An optical fiber communications system is one that uses light (optical signal) as the carrier of analog or digital information signal.

- The optical energy in a light wave follows narrow paths, called light rays or beams.

- Ray theory is known as geometric optics.

VELOCITY OF PROPAGATION

- All light frequencies are not propagated with the same velocity.

- Since materials are denser (possess higher refractive index) than free space, electromagnetic waves travel slower in materials than in free space.

- When the velocity of an electromagnetic wave is reduced as it travels from one medium to another medium of denser material, the light ray refracts (i.e., bends or changes direction) ***toward*** the normal.
- When an electromagnetic wave travels from a denser material into a lighter one, it gets refracted ***away*** from the normal.

VELOCITY OF PROPAGATION

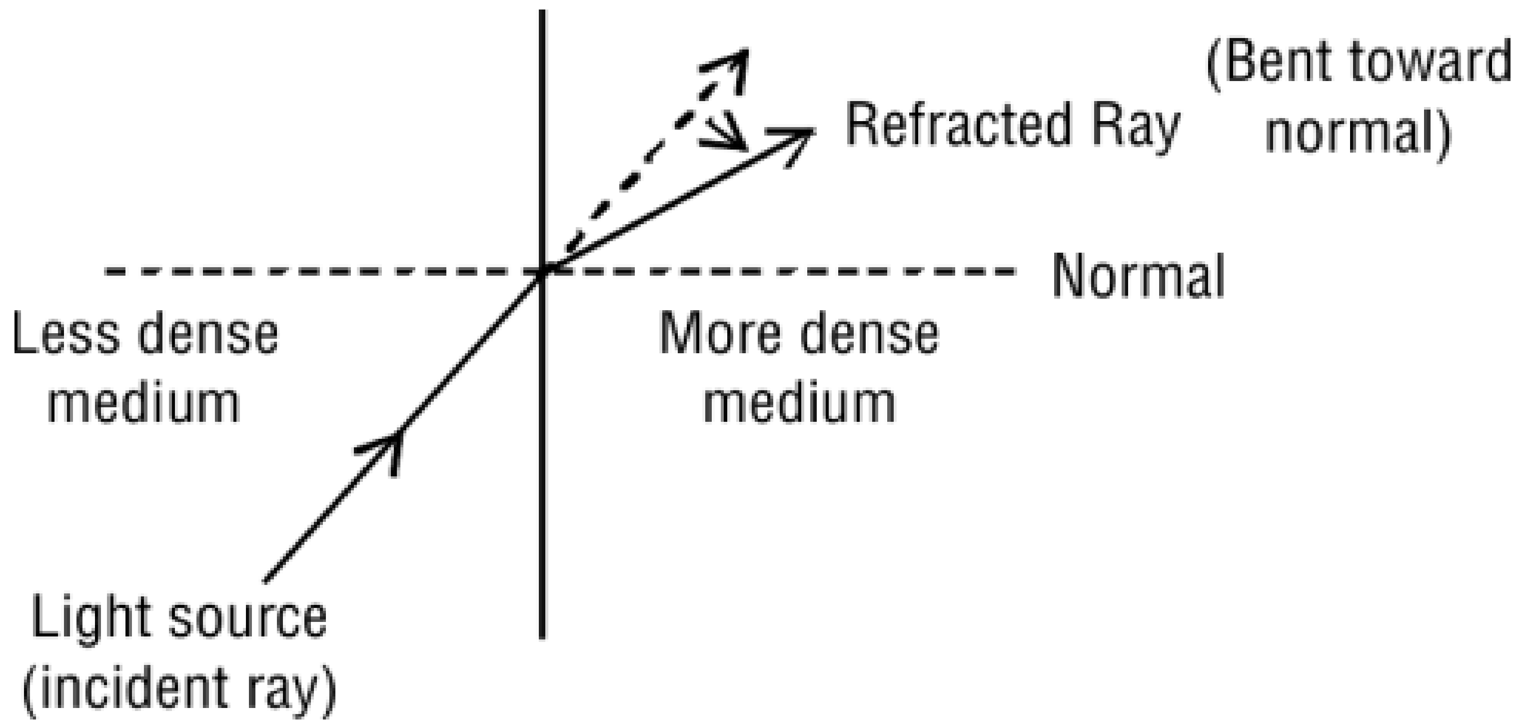


Fig. 1: Refraction of Light

REFRACTIVE INDEX

- Refractive Index (n) is the ratio of the velocity of propagation of a light ray in free space to that of in a specified material.

$$n = \frac{c}{v}$$

- Refractive index is dimensionless.

- The refractive index of any material varies with a number of parameters including wavelength and temperature.

REFRACTIVE INDEX

Example 1: Let the wavelength of light in free-space is 900 nm. Calculate the wavelength of the light that propagates in glass material having a refractive index of 1.5.

SNELL'S LAW

- Snell's law explains how a light ray reacts when it meets the intersection of two types of transparent media of uniform but different indices of refraction.

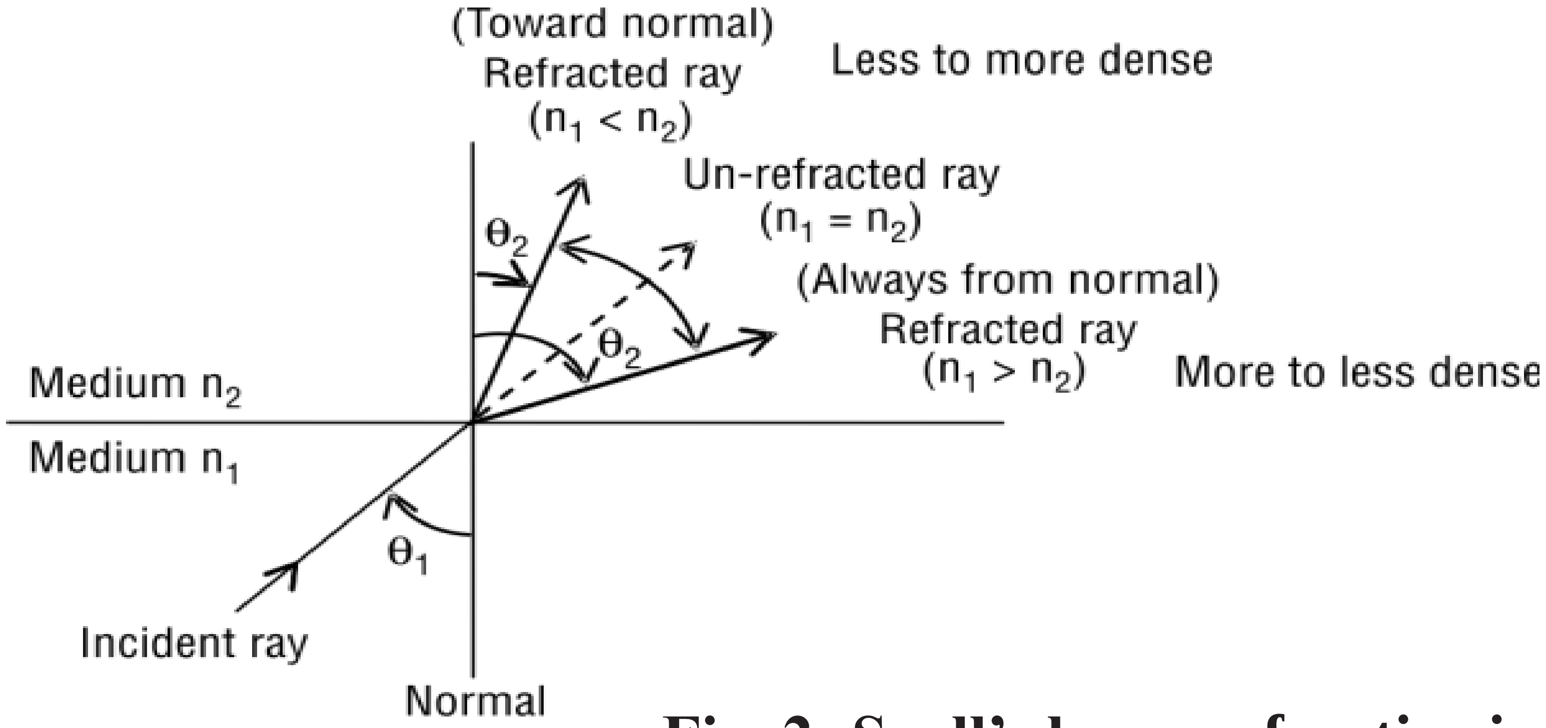


Fig. 2: Snell's law – refractive index model.

SNELL'S LAW

- *Angle of Incidence ($\theta 1$):* It is defined as the angle at which the light ray strikes the intersection of two different materials with respect to the normal in the first medium.
- *Angle of Refraction ($\theta 2$):* It is defined as the angle formed between the refracted light ray and the normal in the second medium.
- *Normal:* The normal is a straight line drawn perpendicular to the intersection of two different mediums at the point where the incident ray strikes it.

SNELL'S LAW

- Mathematically, according to the Snell's law,

$$n_1 \sin(\vartheta_1) = n_2 \sin(\vartheta_2)$$

- **Example 2:** A light ray is refracted as it travels from a denser (n_1 = 1.5) into a less dense (n_2 = 1.36) media. If the angle of incidence made by the ray at the point of intersection of two materials is 30°, then determine the angle of refraction.

CRITICAL ANGLE

- *Definition of critical angle:* It is the minimum possible angle of incidence at which if a light ray is incident at the intersection of two different mediums, then it gets refracted with an angle of refraction exactly equal to 90°.

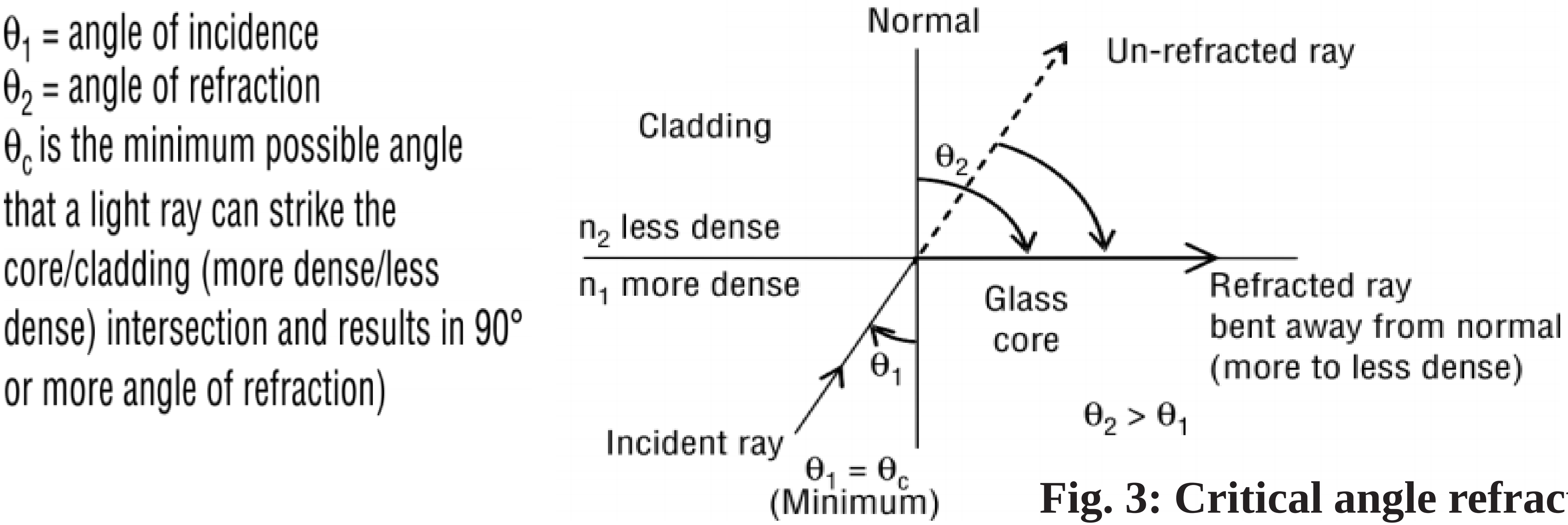


Fig. 3: Critical angle refraction

CRITICAL ANGLE

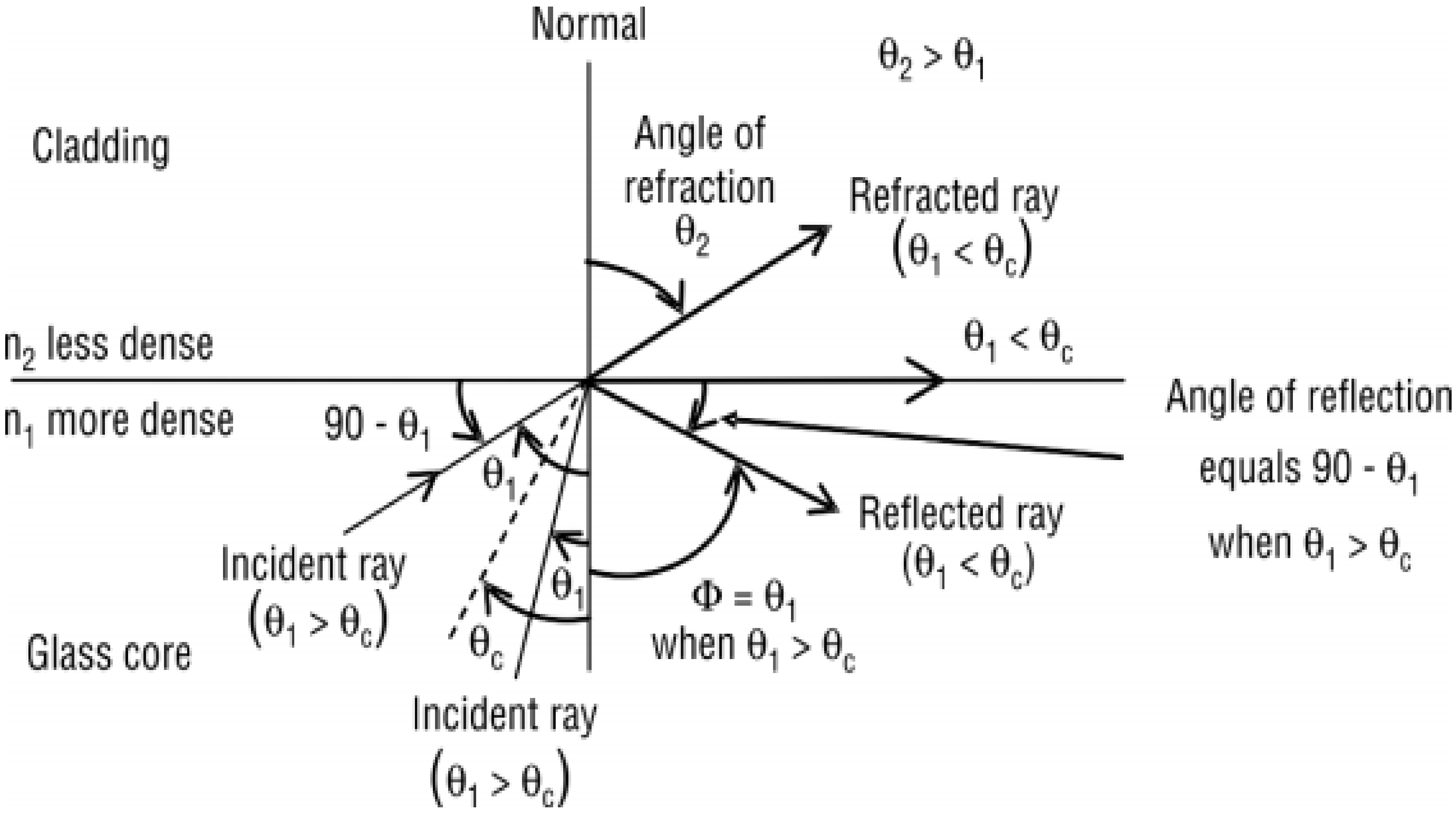


Fig. 4: Angle of refraction and reflection

CRITICAL ANGLE

- **Example 3:** A typical optical fiber cable has specification of refractive index of 1.6 and 1.4 for the core and the cladding, respectively. Determine the following:

1) The critical angle.
2) ϑ_2 for $\vartheta_1 = 30^o$
3) ϑ_2 for $\vartheta_1 = 75^o$

TOTAL INTERNAL REFLECTION

- When a ray (or beam) of light travels from a medium with a higher refractive index (such as fiber core) to another medium with a lower refractive index (such as fiber cladding) and it happens to strike (incident) the core–cladding intersection at more than the known critical angle of incidence (at which the angle of refraction is 90°), then total light will be reflected back to the medium of incidence (i.e., the fiber core). This particular phenomenon is known as Total Internal Reflection

TOTAL INTERNAL REFLECTION

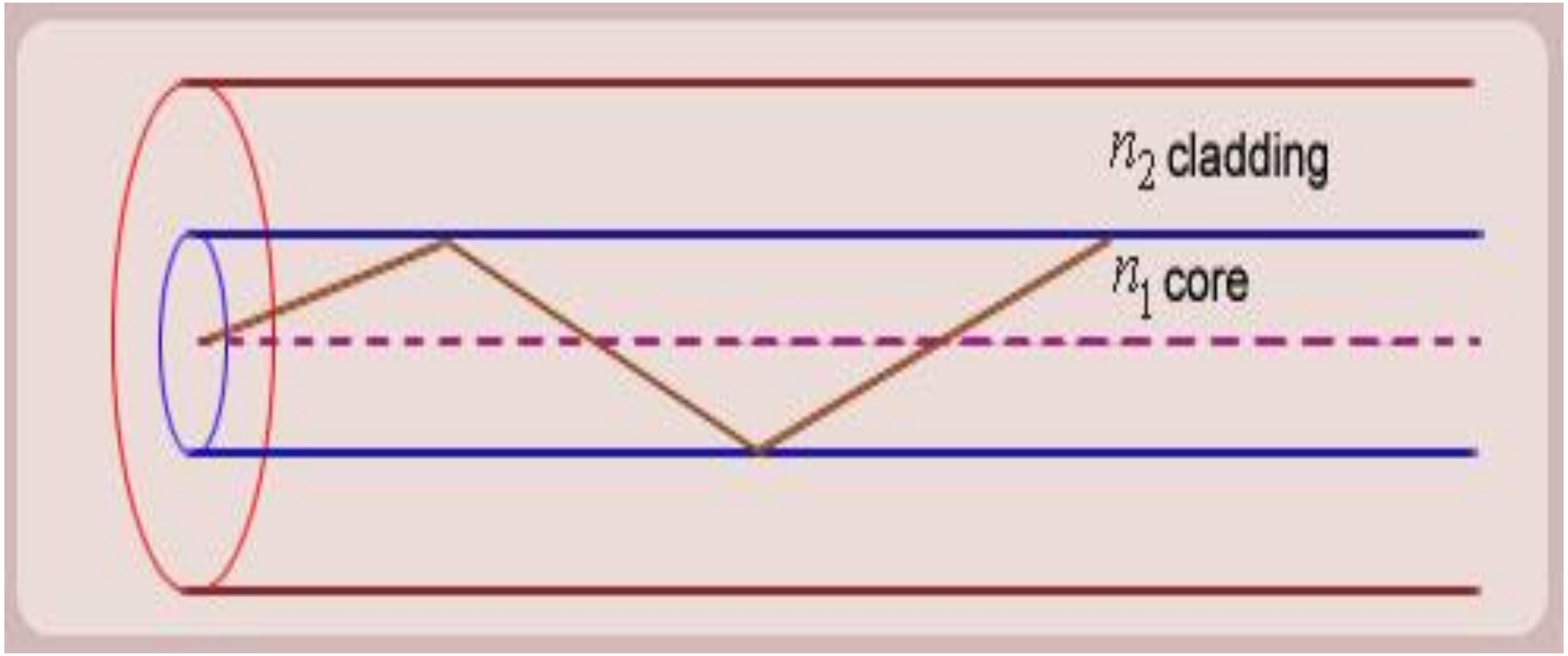


Fig. 5: Concept of total internal reflection

TOTAL INTERNAL REFLECTION

- When angles of incidence greater than the critical incidence angle, then all the light gets reflected back into the fiber core with high efficiency.

- **Example 4:** Consider a light ray traveling from a denser (*n1 = 1.5*) material into a less dense (*n2 = 1.47*) material. Show that the desired criterion of total internal reflection phenomenon is completely satisfied.

ACCEPTANCE ANGLE

- It is defined as the maximum (not minimum) external angle of incidence at which the external light rays must strike the air/glass (fiber core) intersection and enters the fiber core and propagate within it.

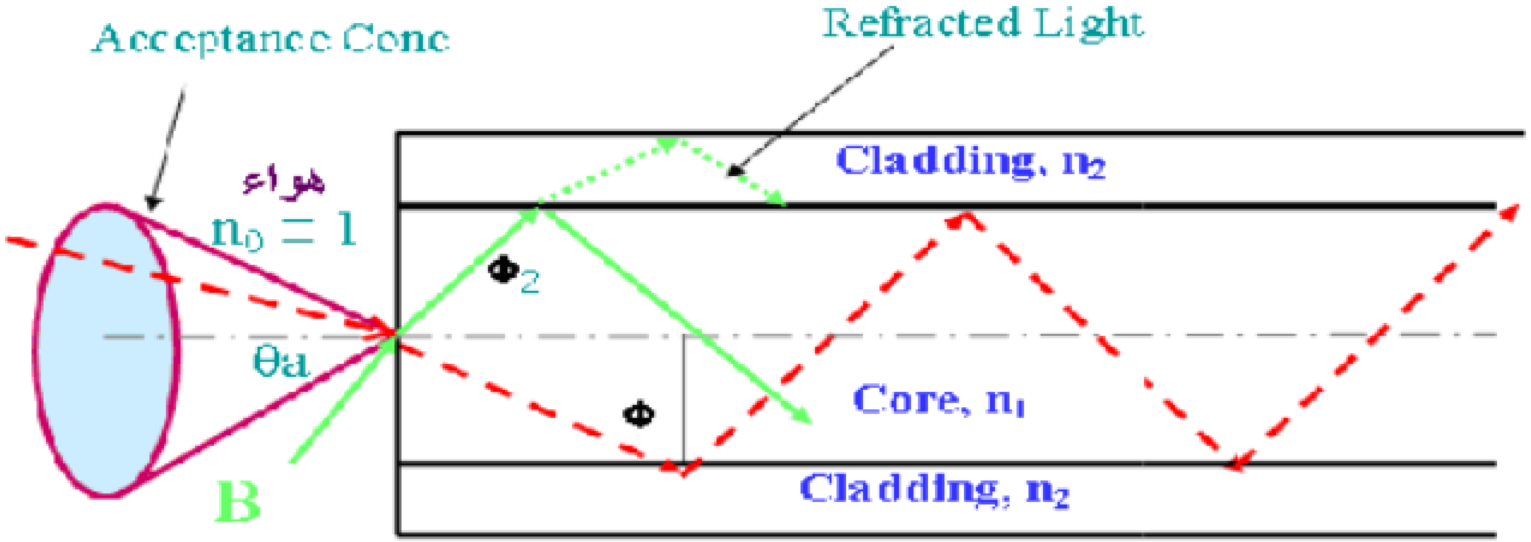


Fig 6: Acceptance angle discerption.

ACCEPTANCE ANGLE

$$\vartheta_i = \vartheta_a = sin^{-1}\left(\sqrt{n_1^2 - n_2^2}\right)$$

Note: The acceptance angle is the maximum value of incidence angle made by a light ray that enters the interface of open air and fiber core (of glass material) that will not ensure total internal reflection. In case it exceeds the acceptance angle, then the light ray is likely to enter the cladding material, resulting in signal loss, because then it will not travel within the fiber core at all.

NUMERICAL APERTURE

- Numerical aperture (NA) is the figure of merit which is used to describe the capability of an optical fiber to gather the light efficiently.

- This parameter is closely associated with the acceptance angle. In fact, the value of numerical aperture can be used to measure the magnitude of the acceptance angle.

NUMERICAL APERTURE

$$NA = \sin(\vartheta_a) = \sqrt{n_1^2 - n_2^2}$$

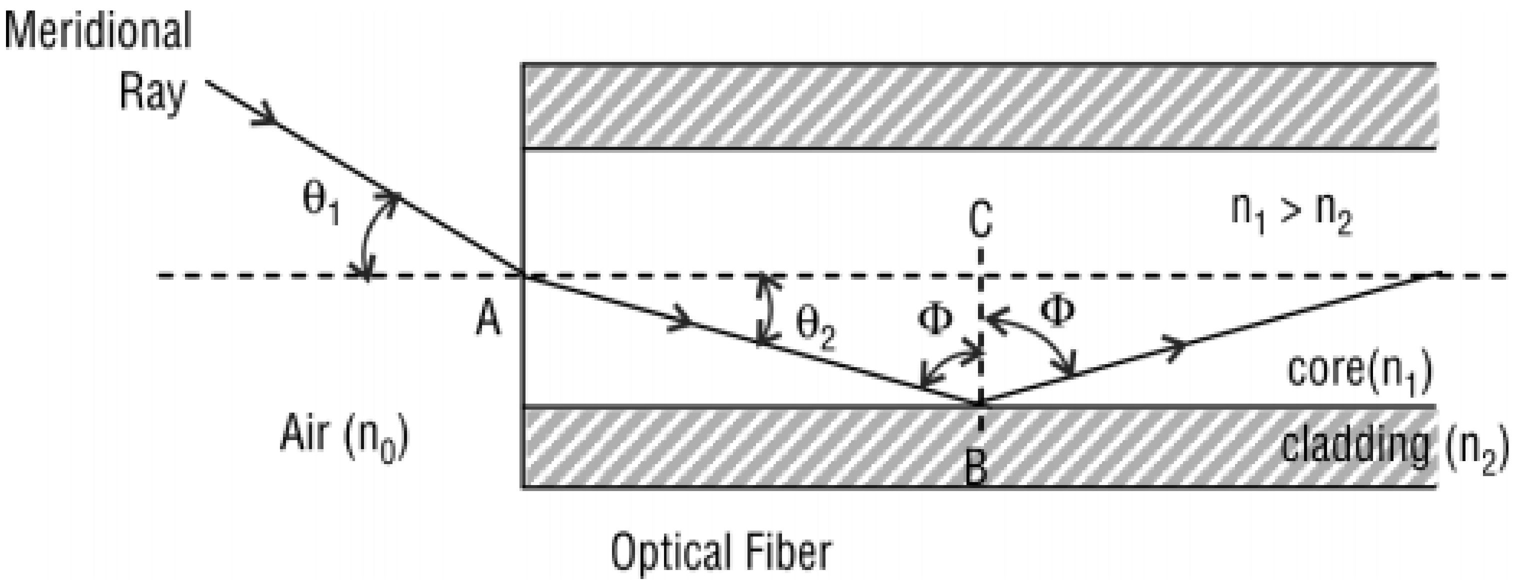


Fig. 7: Total internal reflection in optical fiber

NUMERICAL APERTURE

- Numerical aperture can also be related with the relative difference or fractional change in the refractive index of the fiber core and the cladding of the optical fiber cable. Let us define another term known as **relative refractive index difference**, Δ (not italic) as:

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

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

NUMERICAL APERTURE

- **Example 5:** An optical fiber cable has values of refractive index of 1.46 for the fiber core. If the fractional change in the index of refraction of the optical fiber is specified as 0.01, then find its numerical aperture.

- **Example 6:** An optical fiber cable has specified refractive index values of 1.6 and 1.4 for the fiber core and cladding, respectively. Determine the numerical aperture and the total width of the acceptance cone.

HW

1) In a given optical fiber, the relative refractive difference between the core and cladding is 0.9 % and a solid acceptance angle in air is 0.15 radians. Determine the velocity of light in the fiber core, assuming the fiber has a core diameter such that ray theory can be applied for analysis.

2) A step-index fiber has a refractive index of 1.46 for the cladding and numerical aperture of 0.17. Determine the followings:
(a) the acceptance angle of the fiber when it is placed in water (refractive index of 1.33). (b) the critical angle at the core-cladding interface.

3) The refractive index of the fiber core is specified as 1.46 for a typical optical fiber cable. If the fractional change in the index of refraction of the fiber is specified as 0.01, then show that the fiber would accept light that is incident over a cone with semi-angle (acceptance angle) of about *11.5°*.

CLASSIFICATION OF OPTICAL FIBERS

- There are various ways to classify optical fibers.

1) Based on the refractive index profiles of the fiber core, there can be two types of optical fibers, namely,
   - Step-index optical fiber.
   - Graded-index optical fiber.
2) Based on the number of modes (rays or light wave patterns) propagated within the optical fiber, there can be two types of optical fibers. These are
   - Single-mode optical fiber
   - Multi-mode optical fiber
3) Based on the improvement in propagation properties, there can be three different types of optical fibers, such as
   - Polarization-maintaining optical fiber
   - Dispersion-shifted optical fiber
   - Dispersion-flattened optical fiber

Step-Index (SI) Optical Fiber

- A step-index optical fiber cable has a central core having a uniform index of refraction (i.e., constant density throughout the core).

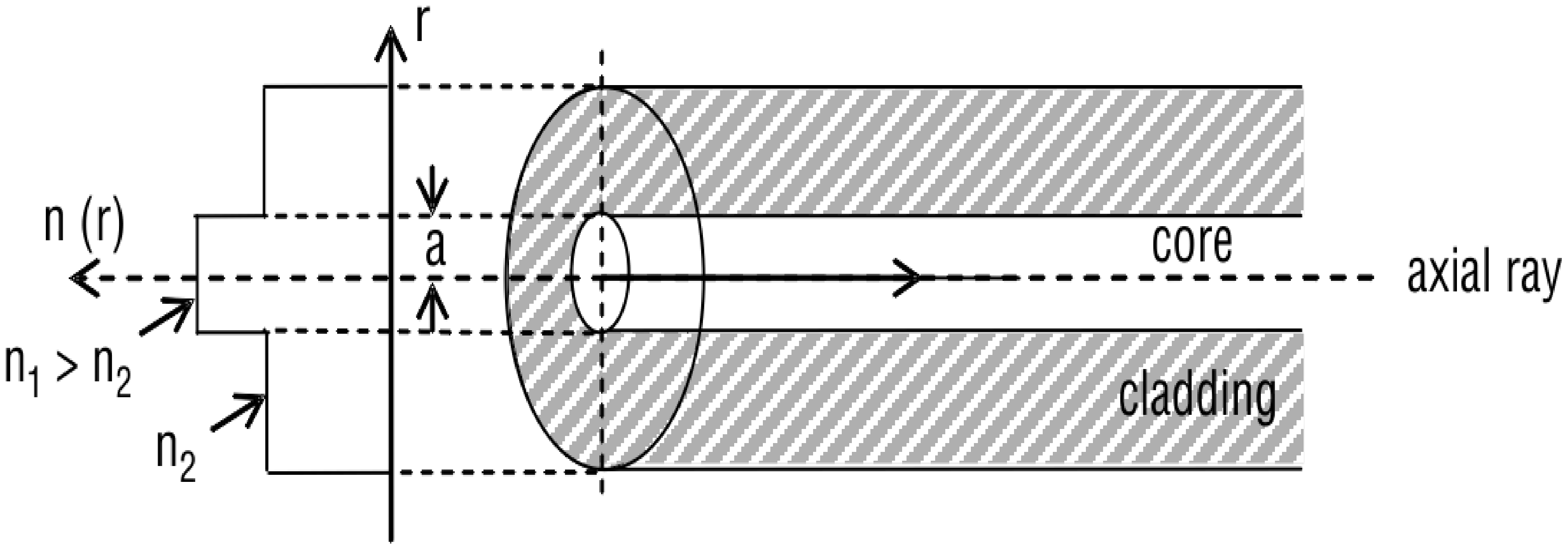


Fig. 8: Index profile of step-index fiber

Graded-Index (GI) Optical Fiber

- It has a central core with a non-uniform index of refraction.
- This simply means that the refractive index of the fiber core is maximum in the middle and then it gradually decreases towards its outer edge up to core–cladding interface.

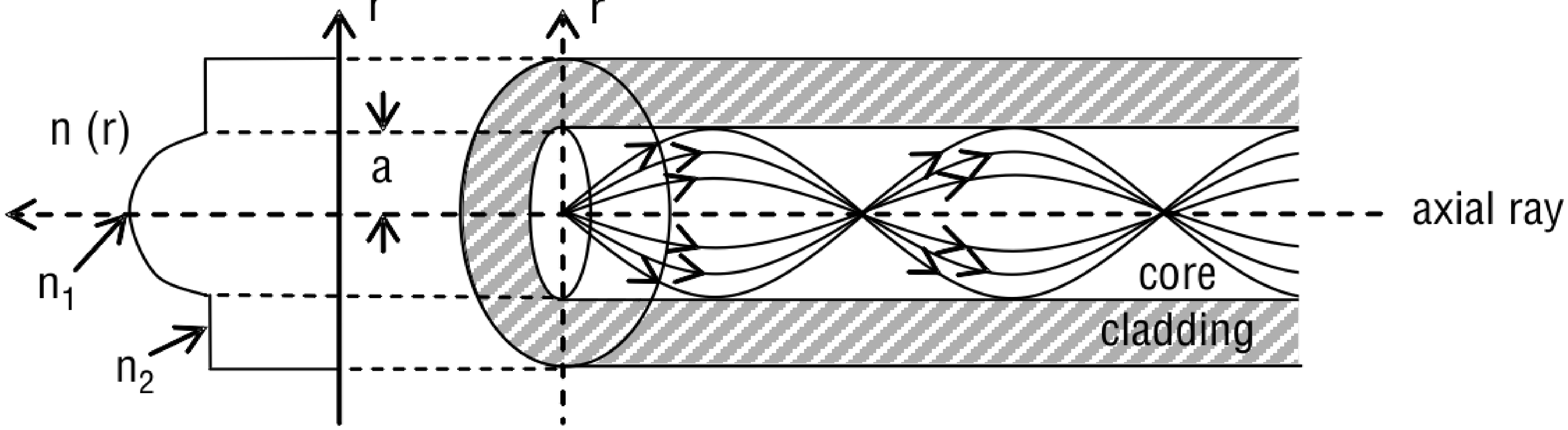


Fig. 9: Index profile of a graded-index fiber

Graded-Index (GI) Optical Fiber

- Mathematically, the index profile can be expressed as:

$$n(r) = \begin{cases} n_1\left(1-(2\Delta)\left(\frac{r}{a}\right)^{\alpha}\right)^{1/2}, r < a \ core \\ n_2, r > a \ cladding \end{cases}$$

- α known as the index profile parameter of the fiber core which specifies the characteristic refractive index profile. It is a dimensionless quantity.

α=1 for triangular profile of graded-index fiber
α=2 for parabolic profile of graded-index fiber
α=∞ for a step-index fiber (n(r) = n1)

Graded-Index (GI) Optical Fiber

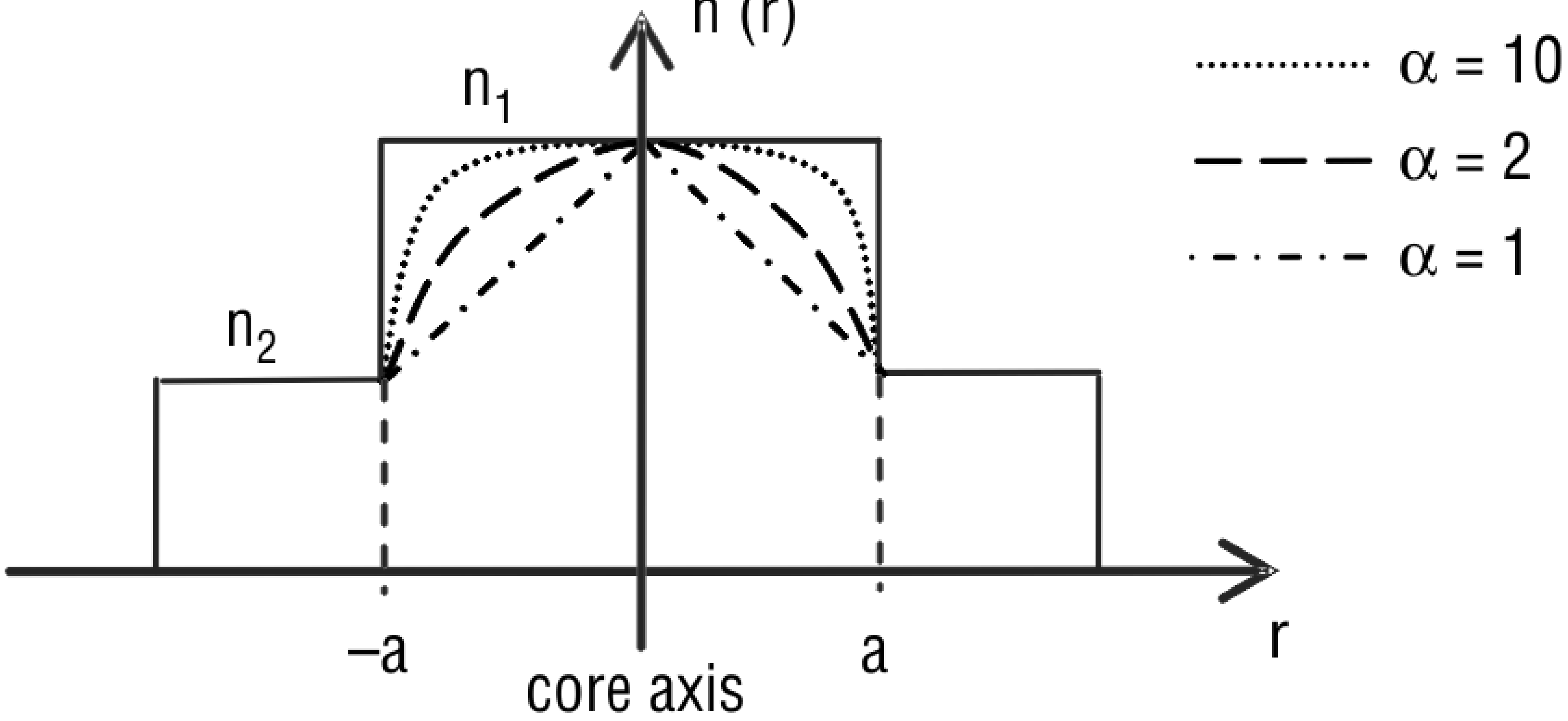


Fig. 10 Refractive index profile *(a)* of graded-index fiber

Graded-Index (GI) Optical Fiber

- It is worth mentioning here that graded-index profile optical fiber produces the best results for multimedia optical propagation.

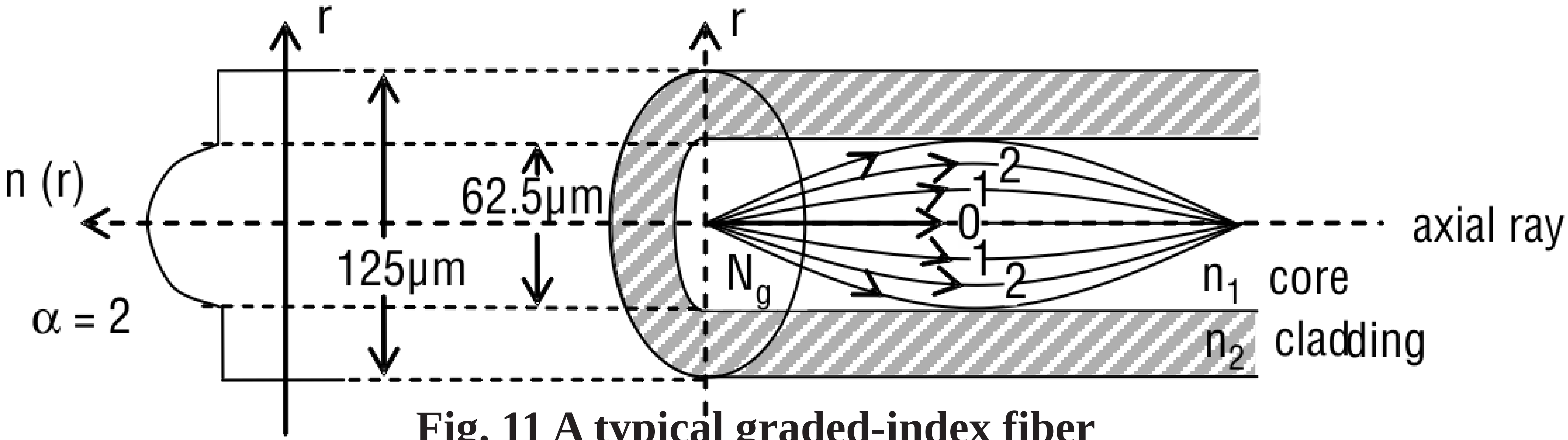


Fig. 11 A typical graded-index fiber

Graded-Index (GI) Optical Fiber

- The numerical aperture for graded-index fibers is a function of the radial distance from the axis of the fiber, expressed as:

$$NA(r) = \begin{cases} \sqrt{n^2(r) - n_2^2} & ; \quad r \le a \\ 0 & ; r > a \end{cases}$$

HW1) Find NA(0), *NA(0)* represents the value of numerical aperture at fiber axis

HW2) draw NA with r.

Propagation Modes

- In fiber–optics terminology, the word `mode' simply means `path', the path that is traversed by the propagation of light within the fiber.

- Modes are distinguished by their propagating angles (incidence or reflected)

- The smaller the propagating angle the lower will be the order of the propagating mode.

Propagation Modes

- An optical fiber can be considered as a waveguide.

- If the diameter of a fiber is sufficiently narrow, then it may support only one mode of propagation of light.

- If the diameter of a fiber is relatively large, light entering at different angles will excite different modes of propagation of light.

Propagation Modes

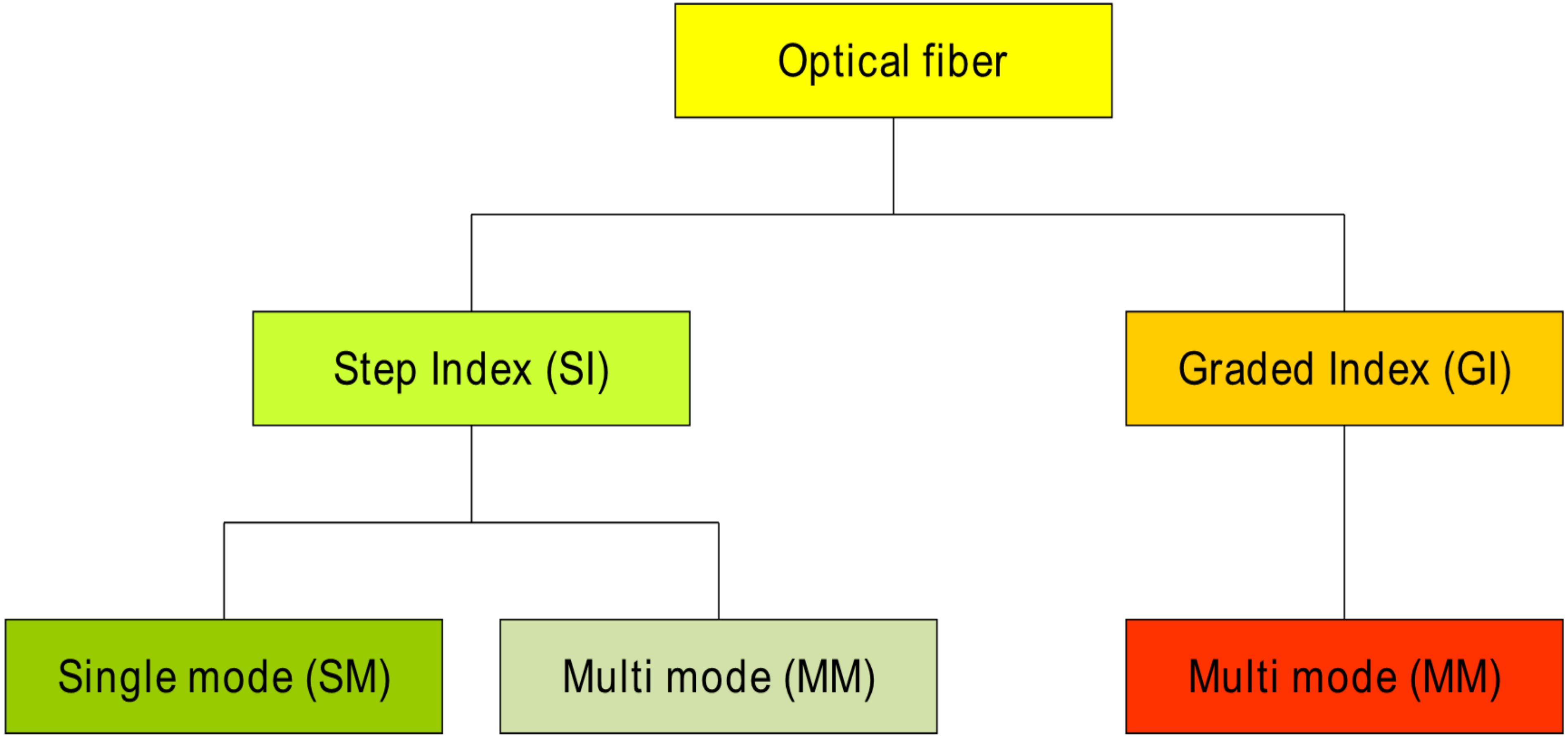


Fig. 12: Types of Optical fibres.

Single Mode Propagation

- As the name suggests, if there is only one possible path for light rays to travel through an optical fiber cable, it is called single mode propagation.

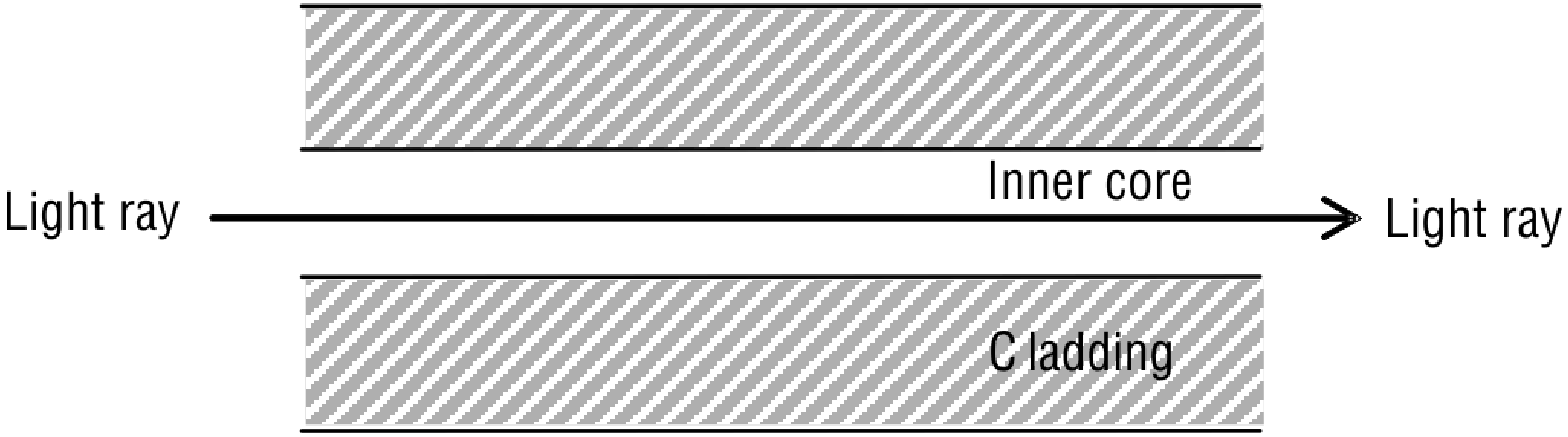


Fig. 13: Single mode propagation

Single Mode Propagation

- It requires a highly focused optical source that emits light beam with a very narrow beam width.
- the single-mode optical fiber cable itself is manufactured having considerably lower index of refraction and much smaller diameter as compared to that of multimode optical fiber cable.
- The lower refractive index results in a critical angle of incidence that is approximately equal to 90° so as to make the propagation of light rays almost horizontal to the central axis of the fiber core.

Single Mode Propagation

- The maximum allowable diameter for a single mode fiber is given as:

$$d_{max} = \frac{0.766\lambda}{NA}$$

d_{max} is the maximum diameter of the core

- **Example 7:** A single-mode fiber cable has specified value 0.15 for numerical aperture. What is the maximum core diameter it could have for use with infrared light with a wavelength of 850 nm?

Single Mode Propagation

- **Example 8:** In the crudest form of a single-mode step-index optical fiber, the cladding may be just external air. In this case, the index of refraction of the glass core (*n1*) is approximately 1.5, and that of the air cladding (*n2*) is 1. With the help of suitable geometrical representation, determine (a) critical angle; (b) acceptance angle.

Multimode Propagation

- If there is more than one path for light rays to travel through an optical fiber cable, it is called multimode propagation.

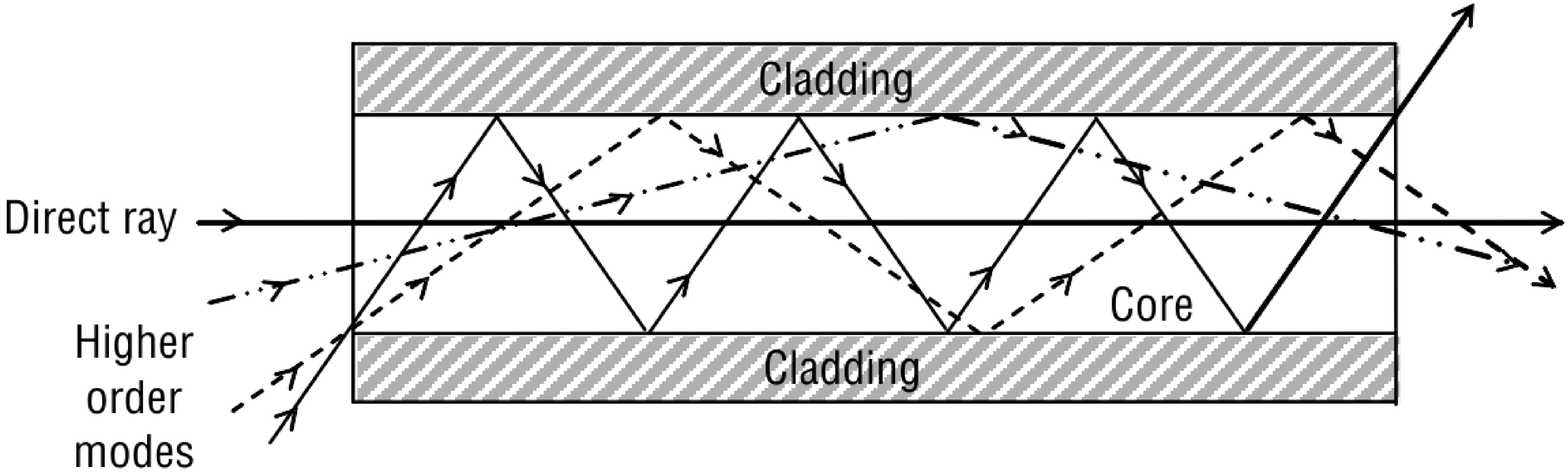


Fig. 14: Multimode propagation

Multimode Propagation

- In terms of propagation of light through fiber, modes can be categorized in the following three types:

1) ***Guided mode*****:** which experiences total internal reflection.
2. ***Radiation mode*****:** which experiences total refraction in the cladding and propagate outside the fiber core.
3. ***Leaky mode*****:** in which some light rays are partially reflected within the fiber core and some are partially refracted toward the cladding.

Multimode Step-index Fiber

- Multimode step-index fiber has a larger core diameter (typically of the order of 50 μm or more) than that of single-mode step-index fiber.

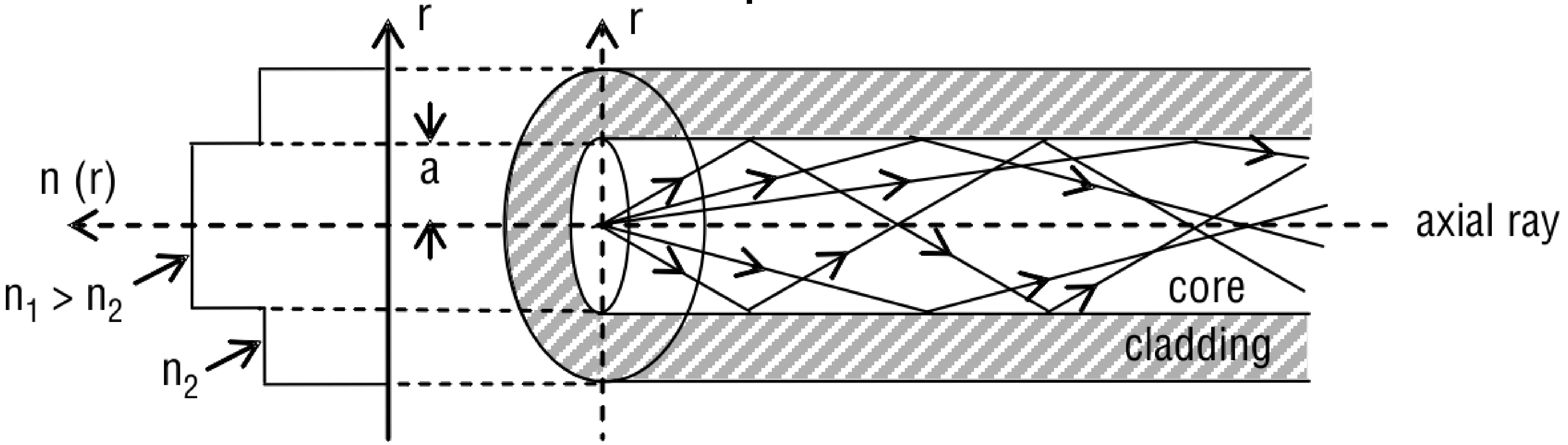


Fig. 15: Core index profile in multimode step-index fiber

V-Parameter

- This parameter is called the normalized frequency parameter *V*, or simply the *V*-number, or *V*-parameter.

- It depends on the core radius, operating wavelength, and refractive index of core and cladding.

$$\mathrm{V} = \frac{2\pi a}{\lambda}\sqrt{n_1^2 - n_2^2} = \frac{\pi d}{\lambda} NA$$

V-Parameter

- **Example 9:** A light of wavelength 850 nm is transmitted through a commercial step-index fiber whose numerical aperture is specified as 0.17 and core diameter as 100 μm. Determine the normalized frequency parameter V.

Number of Modes

- The number of modes, guided by a multi-mode fiber, depends on the following parameters:

- the radius of the fiber core
- the operating wavelength of the light rays
- the index of refraction of the fiber core and the cladding
- the optical characteristic of the fiber cable
- the geometrical characteristic of the fiber cable

Number of Modes

- For a step-index fiber, the number of modes (Ms) can be expressed as:

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

- For a graded-index fiber, the number of modes (Mg) can be expressed as:

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

Number of Modes

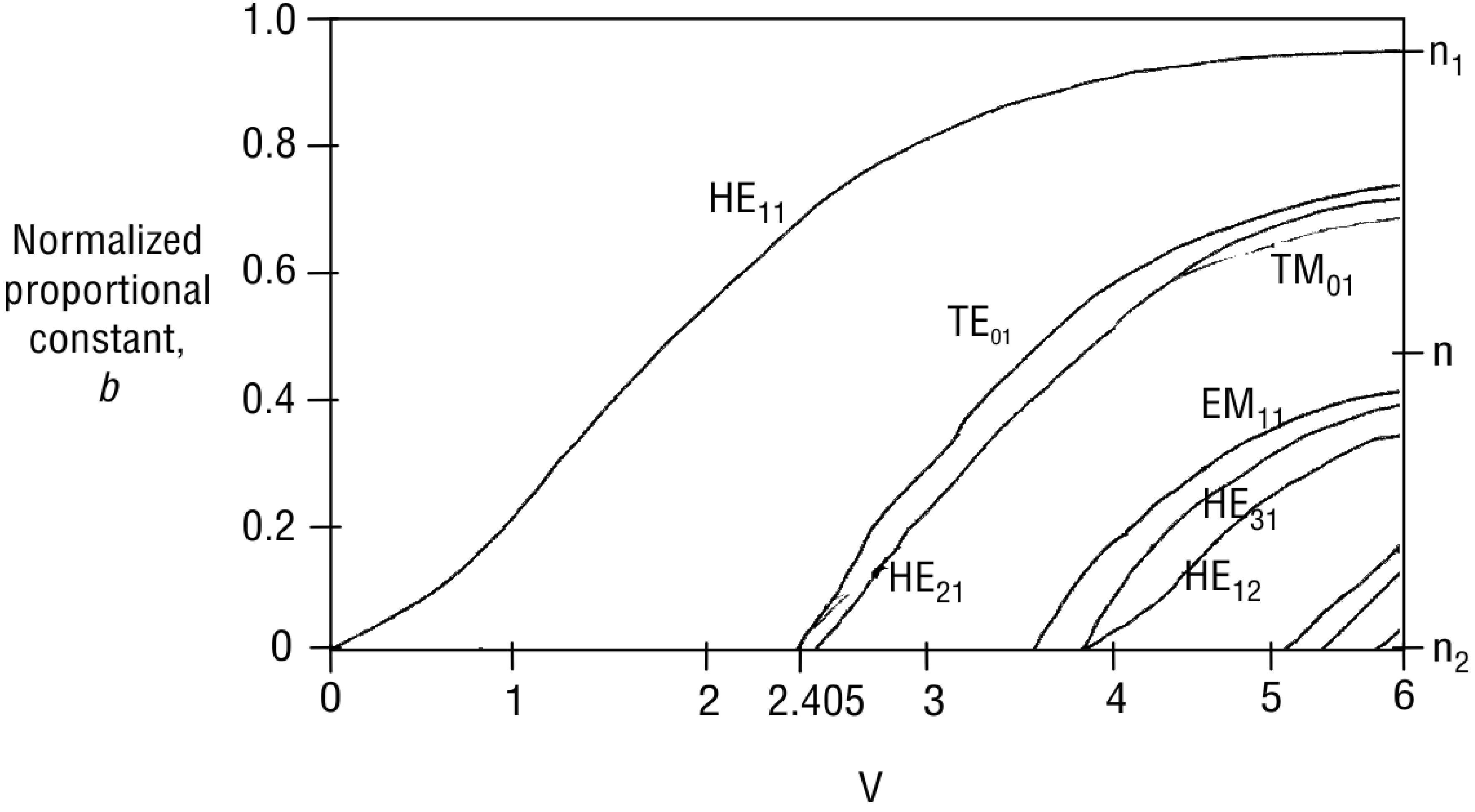


Fig. 16: Normalized frequency versus normalized propagation constant

Number of Modes

- **Example 10:** A multimode step-index fiber cable has the following specifications: the fiber core diameter = 50 μm, the index of refraction of a fiber core = 1.6 and the index of refraction of cladding = 1.584. If the wavelength of light propagating through it is 1300 nm, determine the approximately number of propagating modes.
- **Example 11:** The core refractive index and a relative refractive index difference of a multimode step-index fiber are specified as 1.5 and 2%, respectively. At operating wavelength of 1300 nm, the approximate number of propagating modes is 1000. Determine the diameter of the fiber core.

HW

1. For an optical fiber cable with indices of refraction as 1.46 and 1.41 for the core and cladding, respectively, calculate the maximum diameter which the fiber core could have so as to operate for single-mode propagation at a given wavelength of 1.5 μm.
2. A single-mode fiber is required to be designed having $n1$ = 1.505 and $n2$ = 1.502 as refractive index of core and cladding, respectively. If it is to be operated at wavelength of 1300 nm, then find the dimension of the fiber core (a).
3. A light of wavelength 0.85 μm is transmitted through a multimode step-index fiber whose core diameter and numerical aperture are specified as 100 μm and 0.17, respectively. Compute the approximate number of guided propagating modes in this fiber.
4. A graded-index fiber has a well-defined parabolic index profile. It has the following specifications: Fiber core diameter = 75 μm, Fiber core refractive index = 1.45, Relative refractive index difference = 2% and Number of guided modes supported = 700.
   (a) Determine the normalized frequency parameter V.
   (b) Compute the wavelength of light travelling through the given fiber.
   (c) Calculate the maximum diameter of the fiber core so that the fiber can function in the single-mode configuration.

DISPERSION IN OPTICAL FIBERS

- Dispersion, also known as pulse spreading, means spreading out of an optical pulse of light energy in time as it propagates down a fiber.

- Dispersion occurs because of the difference in the propagation time taken by the light rays that traverse different propagation paths within the fiber.

- If the pulse spreading is sufficiently severe, one pulse may interfere with another.

Dispersion in a single-mode step-index fiber

- There is only a single transmission path that all rays must follow as they propagate through the fiber length.

- Virtually no intermodal dispersion.

- A light pulse, although propagating as a fundamental mode, has a number of spectral components, and the group velocity of the fundamental mode varies with frequency, that results in broadening of the transmitted optical pulse.

- This phenomenon is known as intramodal, or group velocity dispersion (GVD).

Dispersion in a multimode step-index fiber

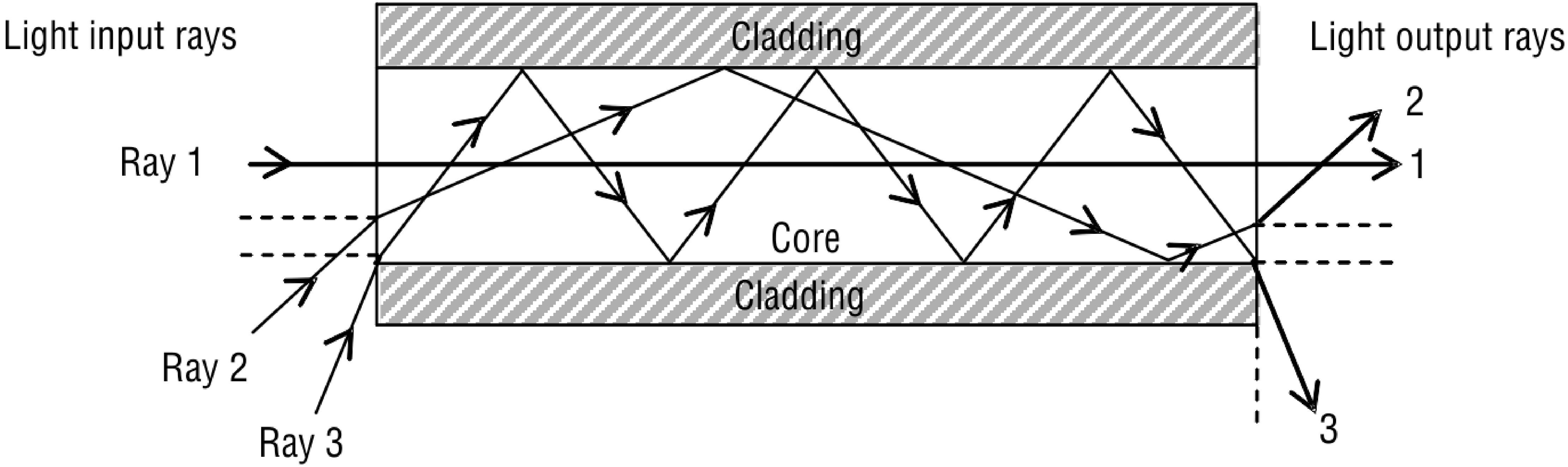


Fig. 17: Propagation of light down a multimode step-index fiber

Dispersion in a multimode step-index fiber

- The lowest-order propagation mode (i.e., light ray 1) travels in a path parallel to the central axis of the optical fiber.

- The middle-order propagation mode (i.e., light ray 2) bounces several times at the interface before traveling the length of the fiber.

- The highest-order propagation mode (i.e., light ray 3) makes many trips back and forth across the fiber as it propagates the entire length. It is quite evident that light ray 3 travels a considerably longer distance than ray 1 over the length of the cable.

Dispersion in a multimode graded-index fiber

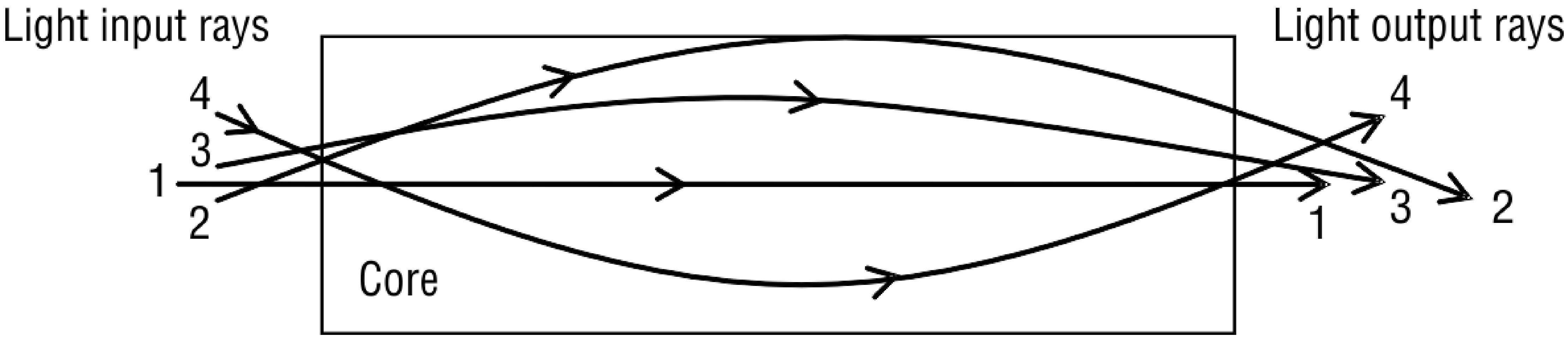


Fig. 18: Light propagation down a multimode graded-index fiber

Dispersion in a multimode graded-index fiber

- Three rays are shown traveling in three different modes.

- Although the three rays travel different paths, they all take almost identical amount of time for propagating through the length of the optical fiber.

- This is due to the reason that the index of refraction decreases with radial distance from the center axis of the fiber core toward the cladding. We know that the velocity at which a ray travels is inversely proportional to the refractive index. So, the rays 2 and 3 travel farther away from the center of the cable, they propagate faster and reach the end almost at the same time as ray 1.

Bandwidth × Length Product

- For multimode propagation, dispersion is often expressed as a bandwidth-length product (B × L).

- Bandwidth-length product indicates what signal frequencies can be propagated through a given distance of fiber cable.

- Mathematically, (B × L) is expressed as the product of distance and bandwidth (sometimes called linewidth). Bandwidth-length products are often expressed in MHz-km units.

Bandwidth × Length Product

- **Example 12:** Determine the transmission bandwidth of a 300-meter optical fiber cable having specified Bandwidth Length Product (BLP) of 600 MHz-km.

- **Example 13:** An optical fiber cable has a specified bandwidth-length product of 500 MHz-km. If it is required to obtain a transmission bandwidth of 85 MHz for a particular mode of propagation, determine the maximum distance that can be used between repeaters.

Bandwidth × Length Product

Typical values of bandwidth-length product

S. No.	*Fiber Type*	*Bandwidth × Length Value (Typical)*
1.	Step-index	20 MHz-km
2.	Graded-index	1 GHz-km
3.	Single mode	100 GHz-km

HW: For fiber optic, is it better to get BLP with low value or large value and why?

TYPES OF DISPERSIONS

- ***Chromatic or Intramodal Dispersion:*** This type of dispersion results from the finite spectral linewidth of the optical source. Propagation delay differences between the different spectral components of the transmitted light signal causes broadening of each transmitted mode and hence collectively known as intramodal dispersion.
- ***Intermodal Dispersion or Mode Dispersion:*** The main reason for intermodal dispersion is that the difference in propagation delay between various propagation modes within a multimode fiber (hence, it is not applicable for single mode fiber).
- ***Polarization Mode Dispersion:*** Due to variations in the fiber core diameter in a practical single mode fiber, two orthogonal, linearly polarized modes are supported that are degenerate. The variations in the fiber core diameter may be due to the presence of non-uniform stress, bends, stress, etc. along the length of the fiber.

Intramodal Dispersion

- A light source such as LED emits light which contains several wavelengths in a beam.

- We know that the velocity of light in any medium or material through which it propagates is expressed as: $v = \frac{c}{n} = \frac{c}{n(\lambda)}$.

- This clearly shows that 'Light of different wavelengths travels along the length of the optical fiber cable at different velocities.

Intramodal Dispersion

- Chromatic dispersion is expressed directly in units of time rather than bandwidth.

- The chromatic dispersion is then the duration of the output pulse when an infinitesimally short pulse of light is applied to the input.

- The linewidth of the optical source is very important in determining the chromatic dispersion for single-mode fiber.

Intramodal Dispersion

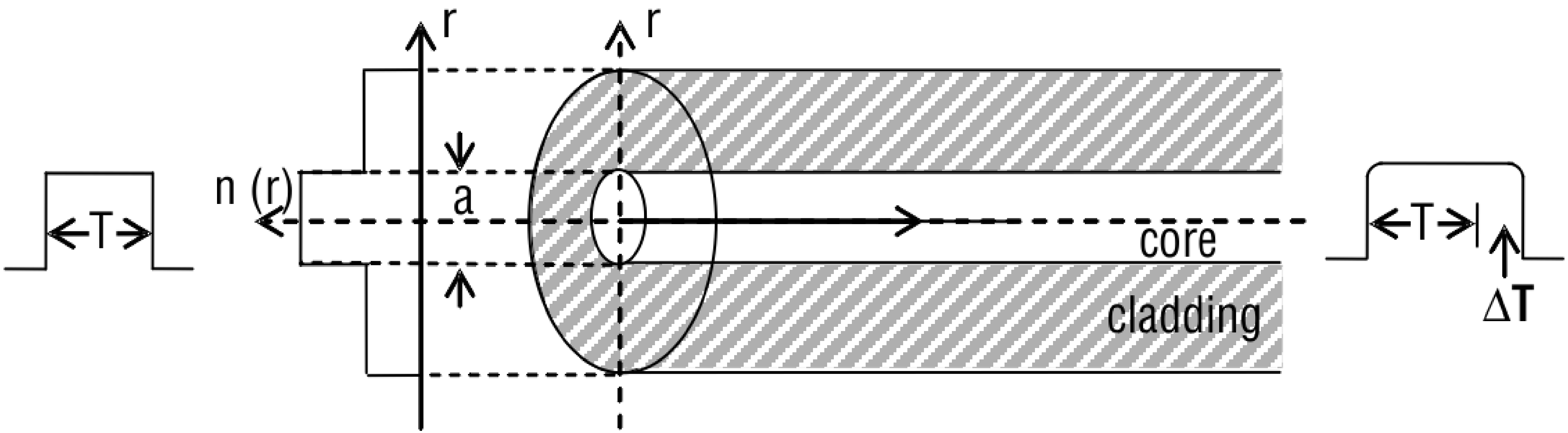


Fig. 19: Broadening of transmitted light pulse – single-mode fiber

Intramodal Dispersion

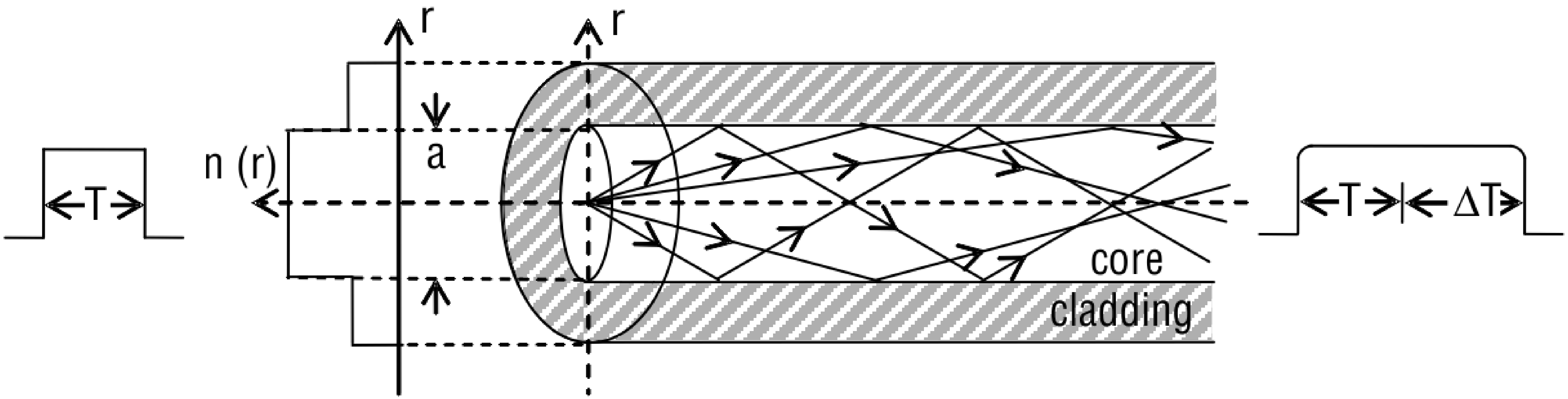


Fig. 20: Broadening of transmitted light pulse – multimode fiber

Intramodal Dispersion

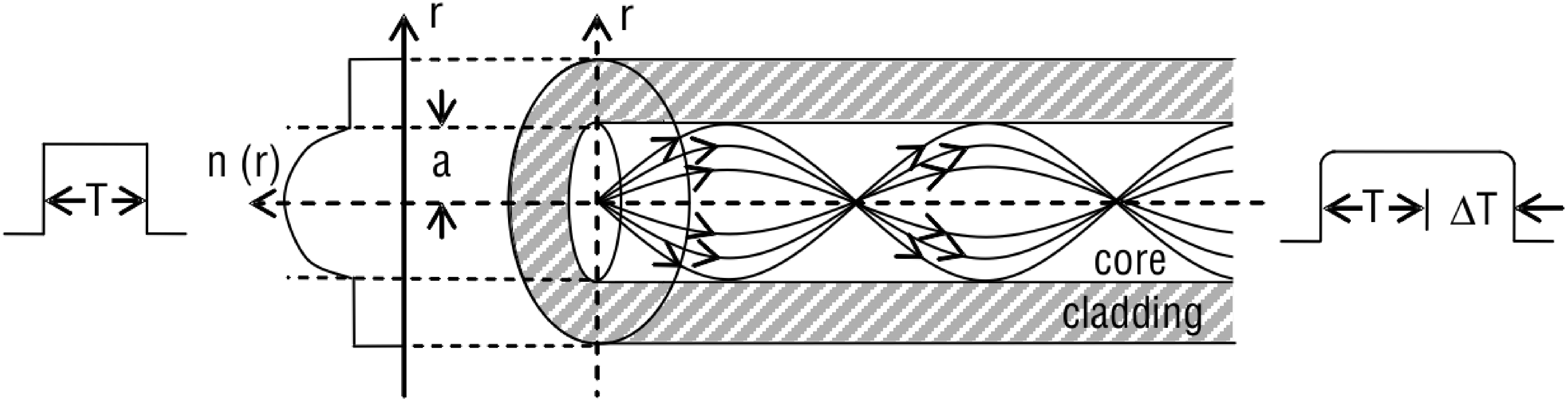


Fig. 21: Broadening of transmitted light pulse – graded-index fiber

Intramodal Dispersion

- Chromatic dispersion is proportional to source linewidth as well as to the length of the optical fiber.
- In a single-mode fiber, the *chromatic dispersion parameter* is given in picoseconds per nanometer of source linewidth for each unit of kilometer of the length of the fiber (abbreviated as ps/(nm–km).
- The expression for chromatic dispersion can be written as Δ (italic):

$$\Delta t_c = D_c L(\Delta\lambda)$$

Intramodal Dispersion

- The chromatic dispersion parameter D*c* is zero at the specific wavelength, known as the *zero-dispersion wavelength*, λ_{ZD}.

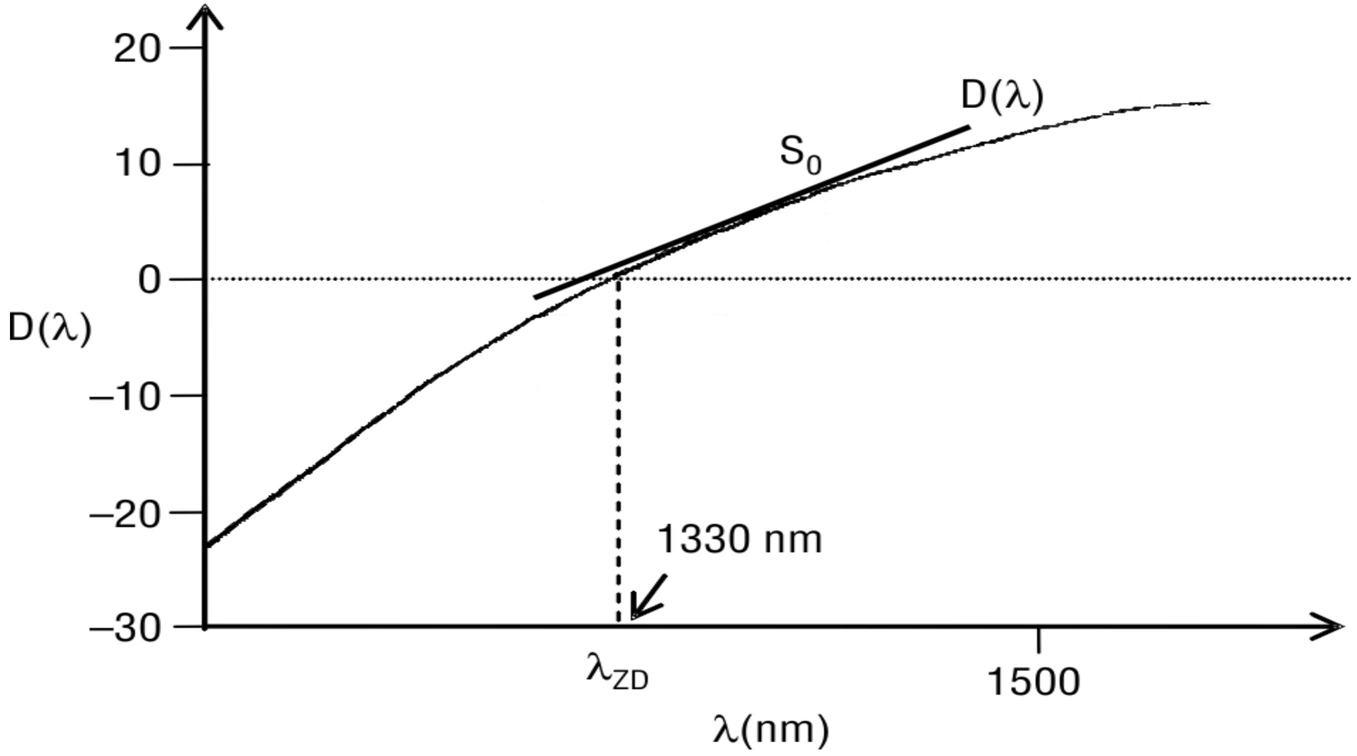


Fig. 22: Chromatic dispersion parameter versus wavelength

Intramodal Dispersion

- **Example 14:** A typical single-mode fiber has specified chromatic dispersion parameter of 9.5 ps/(nm–km) and zero dispersion at a wavelength of 1310 nm. Determine the total chromatic dispersion of 50 km of this fiber when it is used with an optical source having a linewidth of 2 nanometers at an operating wavelength of 1.5 µm.

Effect of Chromatic Dispersion

- Assume that a square wave signal corresponding to NRZ data with alternating 1s and 0s is applied to the fiber.

- When the dispersion is large enough that a pulse merges into the next bit period, inter-symbol interference (ISI) takes place.

- This limits the fiber's capacity for most applications.

- This ISI takes place when the dispersion is one-half the period of the square wave.

Effect of Chromatic Dispersion

- The dispersion can be said to be equal to one-half of the period of an optical pulse at the maximum transmission bandwidth of the optical fiber.

$$\Delta t_c = \frac{T_{min}}{2} = \frac{1}{2f_{max}} = \frac{1}{2B_{max}}$$

T_{min} is the period of a signal at the maximum frequency transmitted by the fiber.

B_{max} is the maximum bandwidth of the fiber.

Material Dispersion

- Material dispersion can be considered as the spreading of the transmitted optical pulse through the optical fiber due to dispersive properties of the fiber core material.

- It mainly occurs as a result of the variation of the refractive index of the fiber core material with respect to the operating wavelength of the light propagating through the fiber.

- If the spectral width (also called the linewidth) of an optical source is quite large, then the broadening of the transmitted optical pulse due to this effect may be significant.

Material Dispersion

- The broadening of the optical pulse due to material dispersion parameter in case of a single-mode fiber is expressed as:

$$\Delta t_m = D_m L(\Delta\lambda)$$

Δt_m: is he broadening of the optical pulse due to material dispersion.

D_m: is the material dispersion parameter (ps/nm-km).

L: is the length of the fiber.

Material Dispersion

Example 15: Let the spectral width of the optical source is specified as 30 nm. Calculate the total amount of pulse broadening due to material dispersion in the following cases: (a) For an optical fiber of 80-km length when the optical source emits at 850-nm wavelength. The material dispersion parameter 850 nm is specified as -105.5 ps/(nm–km).

(b) For an optical fiber of 80-km length when the optical source emits at 1300-nm wavelength. The material dispersion parameter at 1300 nm is specified as -2.8 ps/(nm–km).

Intermodal Dispersion

- From the basics of digital optical transmission, we represent a logic 1 with the presence of an optical pulse, and a logic 0 with the absence of an optical pulse (i.e., no optical pulse).

- When these optical pulses are coupled into an optical fiber, then each optical pulse is divided into a number of small optical pulses, each one is carried by an individual mode of propagation.

- At the output of the fiber, individual optical pulses may recombine due to overlapping

Intermodal Dispersion in Step-index Fiber

- Fig. 23 depicts a typical phenomenon of pulse broadening created by four different modes of an incident light beam propagating through the optical fiber.

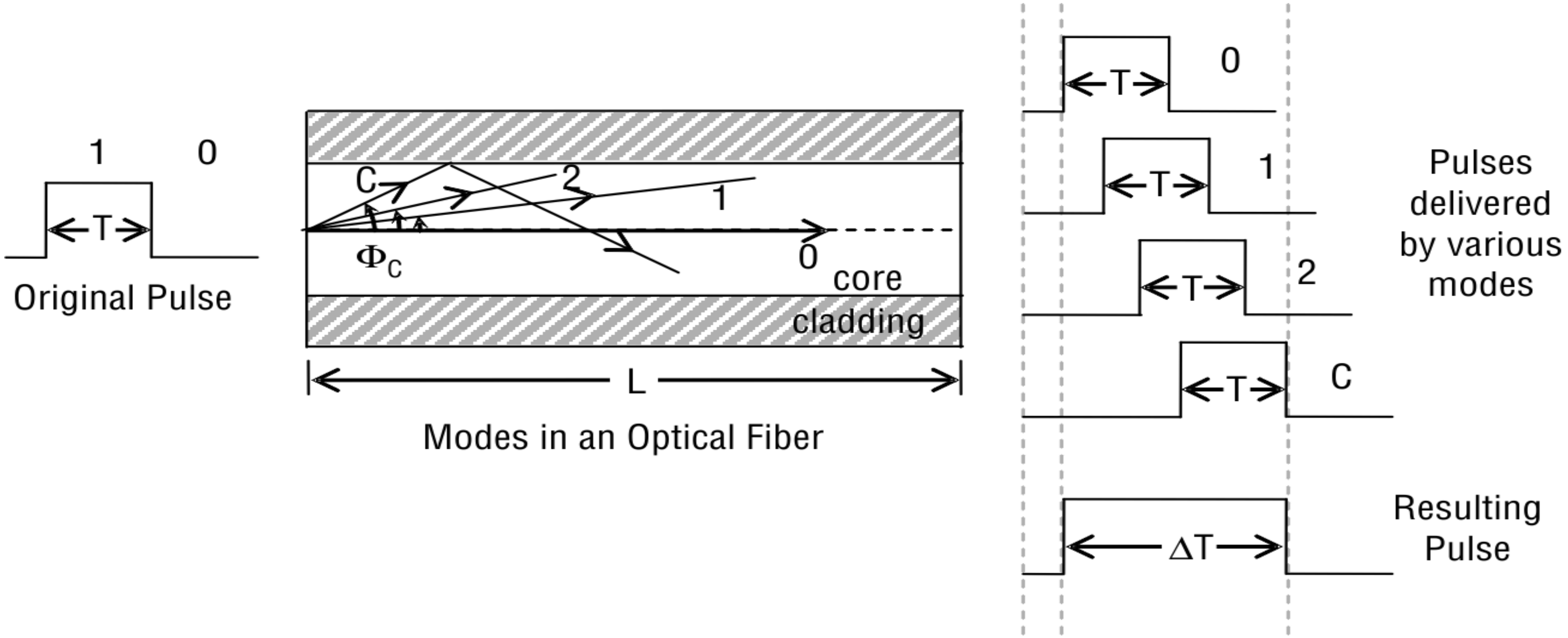


Fig. 23: Effect of intermodal dispersion

Intermodal Dispersion in Step-index Fiber

- The difference in time delay between the axial ray (the fastest mode propagation) and the extreme meridional ray (the input optical ray incident at critical angle) depends on their respective path lengths travelled within the multimode step-index fiber.

$$\Delta t_{SI} = \frac{Ln_1}{n_2}\left(\frac{n_1 - n_2}{c}\right)$$

Δt_{SI}: is the pulse broadening intermodal dispersion in step-index fiber

Intermodal Dispersion in Step-index Fiber

- **Example 15:** A step-index multimode fiber has the following specifications:
  - Fiber core diameter = 100μm
  - Core refractive index = 1.5
  - Cladding refractive index = 1.48.

  Calculate the pulse broadening per unit length of the above-mentioned optical fiber cable due to multipath dispersion.
- **Example 16:** A step-index multimode fiber has specified core refractive index = 1.486 and numerical aperture = 0.2. Assuming modal dispersion, calculate the maximum transmission bit rate (bps) for 1 km fiber length.

Intermodal Dispersion in Graded-index Fiber

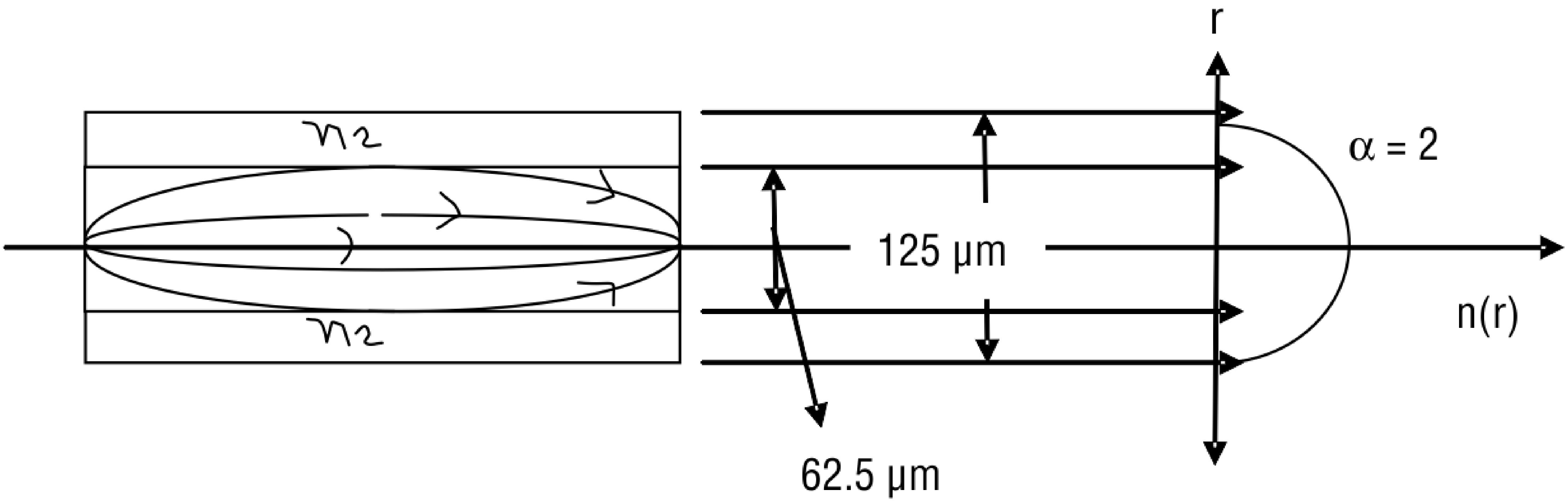


Fig. 24: Light propagation in a graded-index fiber

Intermodal Dispersion in Graded-index Fiber

$$\Delta t_{GI} = \frac{L n_1 \Delta^{\mathbf{2}}}{8c} = \frac{L NA^4}{32 c n_1^3} \text{ Proof it}$$

Note: If the refractive index profile of a graded-index fiber is chosen in such a way so that the time taken for the axial light ray and the most oblique light ray is nearly same, then the multipath dispersion will be zero. In practice, a parabolic profile (a = 2) reduces this type of dispersion considerably

Intermodal Dispersion in Graded-index Fiber

- **Example 17:** A typical fiber has core refractive index = 1.50, and relative refractive index difference = 2%. Show that the graded-index profile fiber exhibits much less modal dispersion as compared to that of step index fiber for a given fiber length of 5 km.

- **Example 18:** An optical source having line width of 40 nm excites a 2-km long multimode fiber cable which has the following specifications:

• Modal dispersion = 1 ns/km

• Dispersion parameter due to chromatic dispersion = 100 ps/(nm–km). Find the total system dispersion and the achievable transmission data rate.

HW

1) A light pulse is launched into source end of a 30-km long optical fiber with specified total dispersion value 20 ns/km. What will be the pulse width at the other end of the fiber?
2) A fiber has core refractive index = 1.50 and numerical aperture = 0.3. Show that the graded-index profile fiber exhibit less amount of modal dispersion as compared to that exhibited by step-index profile fiber for a total fiber length of 5 km.

ATTENUATION IN OPTICAL FIBERS

- As the optical signal propagates down the optical fiber cable, it gets attenuated.

- The term ‘attenuation’ simply means the reduction in the signal strength.

- Attenuation is probably the most important parameter of an optical fiber cable. It limits the performance of an optical fiber communication system, as the optical power reaching the receiver is reduced.

ATTENUATION IN OPTICAL FIBERS

- Mathematically, the total power loss in an optical fiber cable is given by :

$$A(dB) = 10log\frac{P_{out}}{P_{in}}$$

- It can be easily seen that a 1-dB attenuation decreases the output power to about 79% of the input power, and 3-dB attenuation decreases the output power to 50% of the input power (Proof it).

- Attenuation is generally expressed in dB per unit length of the fiber cable. Attenuation is expressed as a positive dB value because by definition it is a loss.

ATTENUATION IN OPTICAL FIBERS

- Mathematically, the measured optical power in watts at a given distance from a power source can be determined as:

$$P = P_t \times 10^{-(A \times L)/10}, find\ it\ in\ dBm$$

where, P = measured optical power level (watts)
Pt = transmitted optical power level (watts)
A = cable attenuation (dB/km)
L = cable length (km)

ATTENUATION IN OPTICAL FIBERS

- **Example 19:** For a single-mode fiber cable having specified attenuation as 0.25 dB/km, determine the measured optical power at a distance of 100 km from a 0.1-mW optical source.

ATTENUATION IN OPTICAL FIBERS

- Loss in glass fibers is lowest at wavelengths around 1550 nm, in the infrared region of the spectrum.
- Loss in plastic fibers performs best at about 660 nm, which corresponds to visible red light.
- The maximum attenuation is at about 1400 nm, operation near this wavelength should be avoided.
- Optical fibers are not always used at the wavelength exhibiting lowest loss.
- Many short-range systems use a wavelength of about 820 nm, as LEDs for this wavelength are less costly than those designed for longer wavelengths.
- On the other hand, long-distance high-data-rate links may be limited more by dispersion than by power loss. In this case, they can operate at the lowest-dispersion wavelength of 1300 nm.

TRANSMISSION LOSSES IN OPTICAL FIBER CABLE

- Various types of optical signal transmission losses in optical fiber cables result in less output power than required.
- thereby reducing the overall system capacity, net transmission bandwidth, transmission data rate, and operating efficiency.
- Some of the major transmission losses in optical fiber cables may be categorized as follows:

1. Absorption los.
2. Scattering (Linear and non-linear) losses
3. Bending losses
4. Coupling losses

Absorption Losses

- Due to the presence of impurities in the fiber material, some part of propagating light can be absorbed and converted into heat.
- Absorption loss is directly related with the actual composition of the material and the manufacturing process used.
- Optical fibers are normally made of silica-based glass material. As light energy passes through the fiber, it may be partially absorbed by this material itself. This is called *intrinsic absorption*.
- There may be some impurities within the fiber material which may absorb some part of light energy. This is called *extrinsic absorption*.

Scattering Losses

- Scattering loss occurs due to transfer of the optical power available within one guided propagation mode into a different mode of propagation.

- The scattering may happen when a light beam propagating within the fiber strikes at an imperfection in a core material and then changes its direction.

- This scattering effect prevents attainment of desired total internal reflection at the intersection of the fiber core and the cladding. This may result in a power loss.

Bending Losses

- Bending an optical fiber too sharply can increase fiber losses by causing some of the light to meet the intersection to the fiber core and the cladding at less than the critical angle of incidence, thereby preventing the desired phenomenon of total internal reflection.

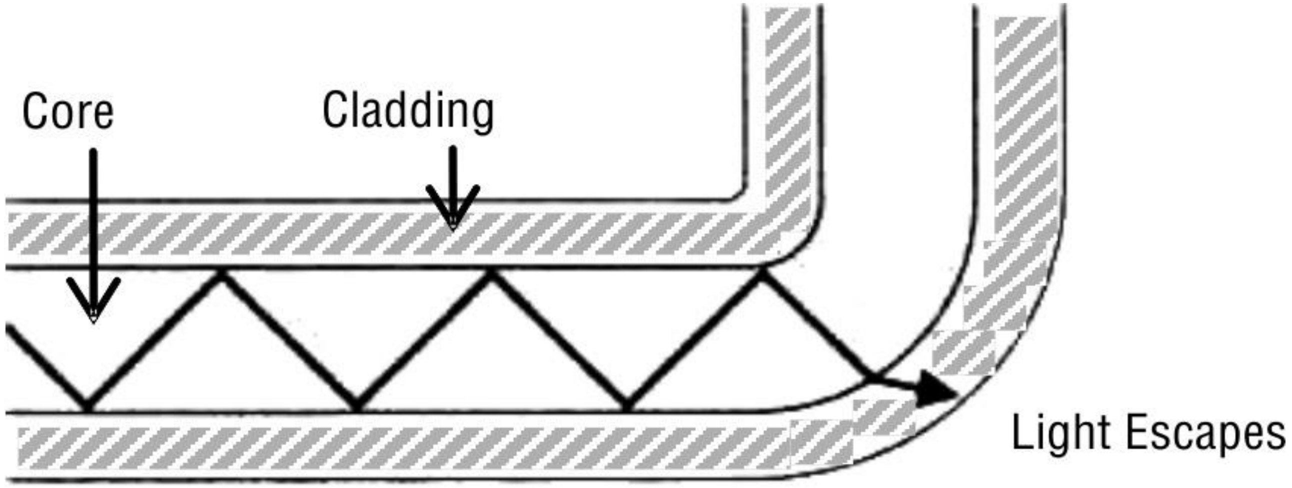


Fig. 25: Bending an optical fiber

Bending Losses

- Losses vary greatly with the type of fiber.

- Plastic fiber may have losses of several hundred decibels per kilometer.

- Graded-index multimode glass fiber has attenuation figure of about 2–4 dB/km, while single mode glass fiber has attenuation figure of about 0.4 dB/km or less.

Coupling Losses

- In optical fiber cables, coupling losses can occur at any of the following three types of optical junctions:

1) connections between light source and the fiber at the transmitter end (source-to-fiber power launching)
2) fiber-to-fiber interconnections (to extend the length of the optical fibers)
3) connections between the fiber and the photodetector at the receiver end

Coupling Losses

- In an optical fiber communication system, the losses in splices and connectors can easily be more than in the fiber cable itself. Coupling losses are normally caused by the imperfect physical connections in optical fiber communication system. Junction losses are most often caused by one of the following alignment problems:

1) lateral or axial misalignment
2) gap misalignment
3) angular misalignment
4) imperfect surface finishes

Coupling Losses

- *Lateral or axial misalignment*. Lateral or axial misalignment or displacement is the lateral or axial displacement between two pieces of adjoining fiber cables.

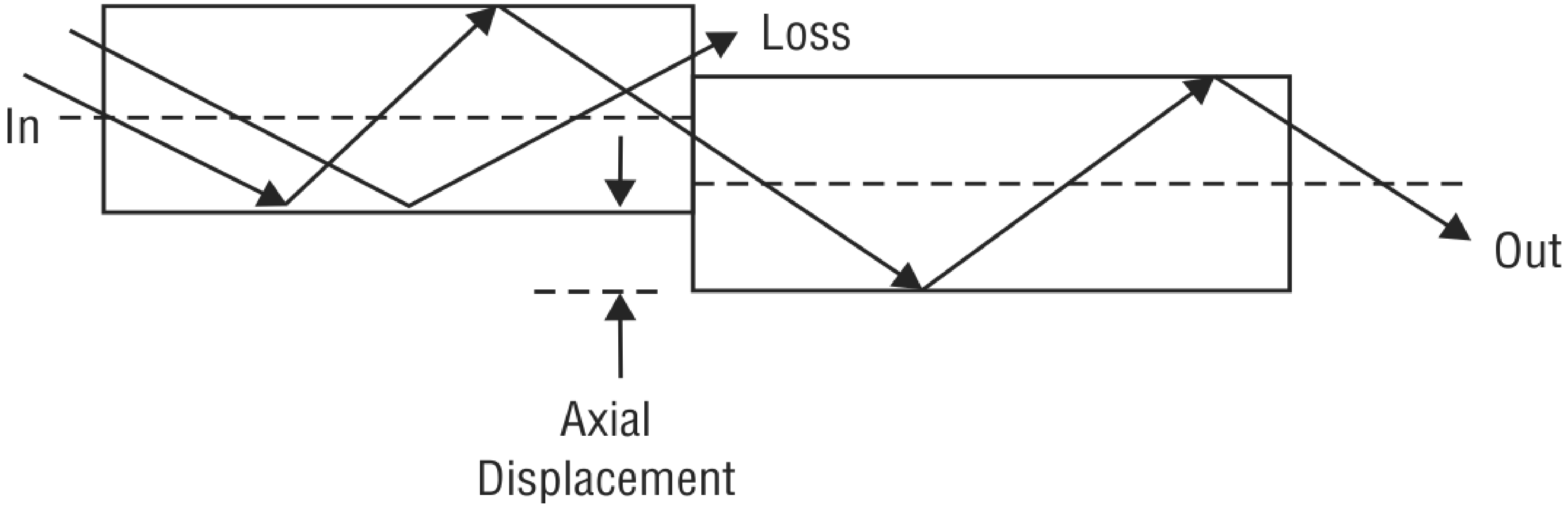


Fig. 26: Lateral misalignment in optical fibers

Coupling Losses

- *Gap misalignment*. Gap misalignment or displacement occurs when splices are made in optical fibers, and the optical fibers should actually touch. If the fibers are kept far apart, there will be more loss of optical signal.

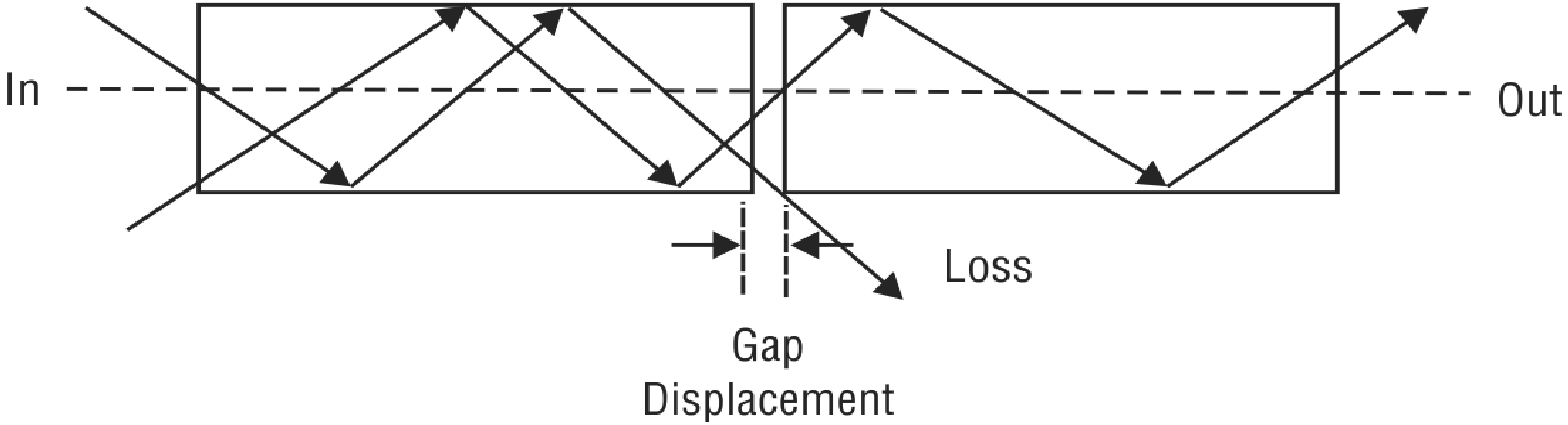


Fig. 27: Gap misalignment in optical fibers

Coupling Losses

➢ *Angular misalignment*. Angular misalignment or displacement is shown in Fig. 28.

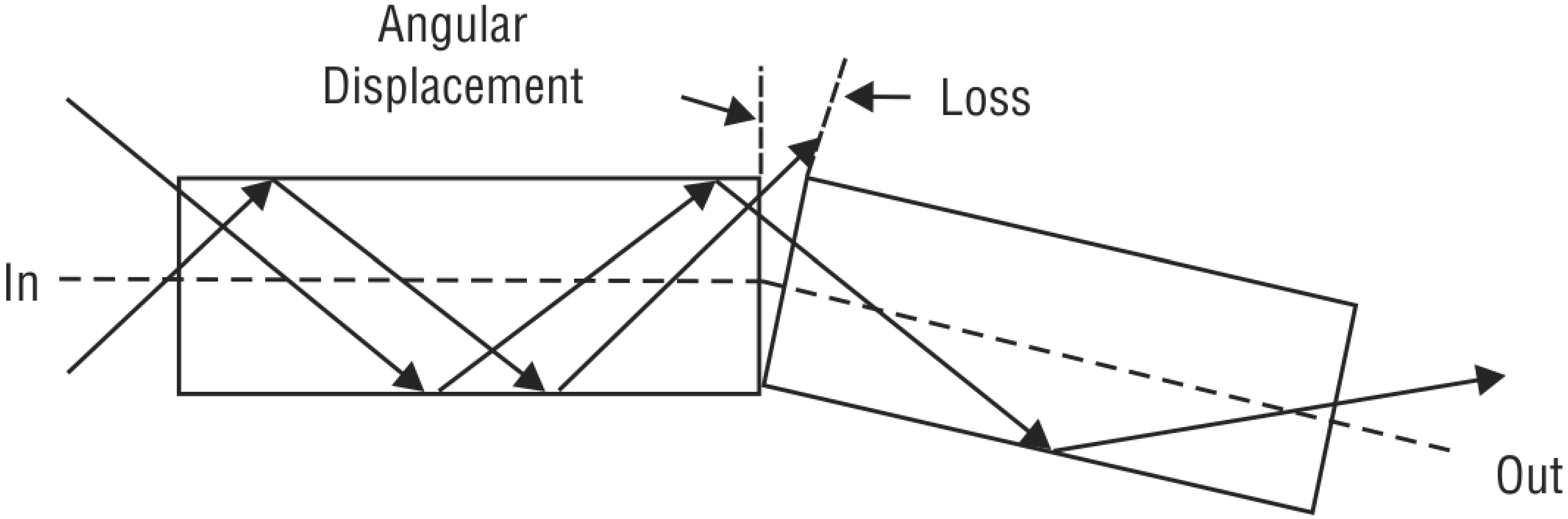


Fig. 28: Angular misalignment in optical fibers

Coupling Losses

- 4. *Imperfect surface finish.* Imperfect surface finish is shown in Fig. 29.

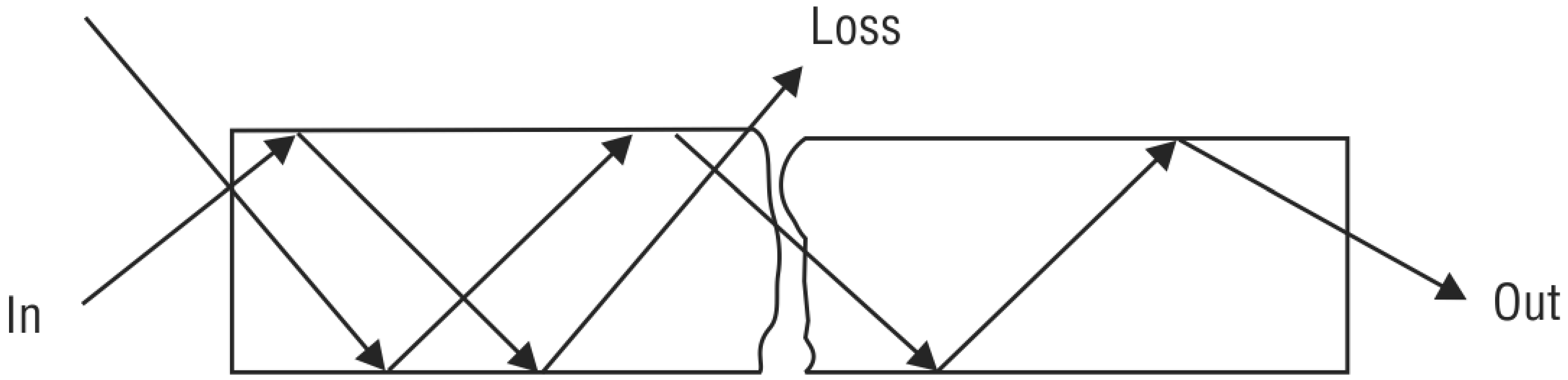


Fig. 29: Imperfect surface finish in optical fibers

Comparison of Optical Fibers

- Optical fibers can be categorized either based on propagation modes as single mode or multimode or based on their refractive index profiles as step-index and graded-index.
- Although there are a wide variety of combinations of propagation modes and index profiles, there are only three practical configurations of optical fibers as follows.

1. Single-mode step-index optical fiber
2. Multimode step-index optical fiber
3. Multimode graded-index optical fiber

Comparison of Optical Fibers

➢**Advantages of Single-mode Step-index Fibers**

1. *Minimum dispersion*
2. *Higher information transmission rates*

➢**Disadvantages of Single-mode Step-index Fibers**

1. The size of the fiber core is extremely small, which leads to difficult coupling.
2. Due to extremely small size of the fiber core, it is mandatory to use a highly focused optical source such as laser.
3. The manufacturing process of single-mode step-index fibers is quite complex.
4. Single-mode step-index fibers are relatively expensive.

Comparison of Optical Fibers

➢ **Advantages of Multimode Step-index Fibers**

1. Easy to couple light into and out of it.

2. The manufacturing process of multimode step-index fibers is relatively simple.

3. Multimode step-index fibers are inexpensive.

➢ **Disadvantages of Multimode Step-index Fibers**

1. Light rays traverse several paths, different from each other within the optical fiber cable, which results in spreading out of the transmitted optical pulse by the time it arrive at the receiving end.

2. The transmission bandwidth and achievable rate of information are quite less than that are possible with other types of optical fiber cables.

Comparison of Optical Fibers

➢**Pros and Cons of Multimode Graded-index Fibers**

1. It is relatively much easier to couple light into and out of a multimode graded-index fiber in comparison with that of a single-mode step-index fiber. However, the same is more difficult than that is possible with a multimode step-index fiber.

2. There is greater possibility of distortion in the received optical pulses because of dispersion in multimode graded-index fibers, which occurs due to multiple propagation as compared to that in single-mode step-index fibers but relatively lesser than in multimode step-index fibers.

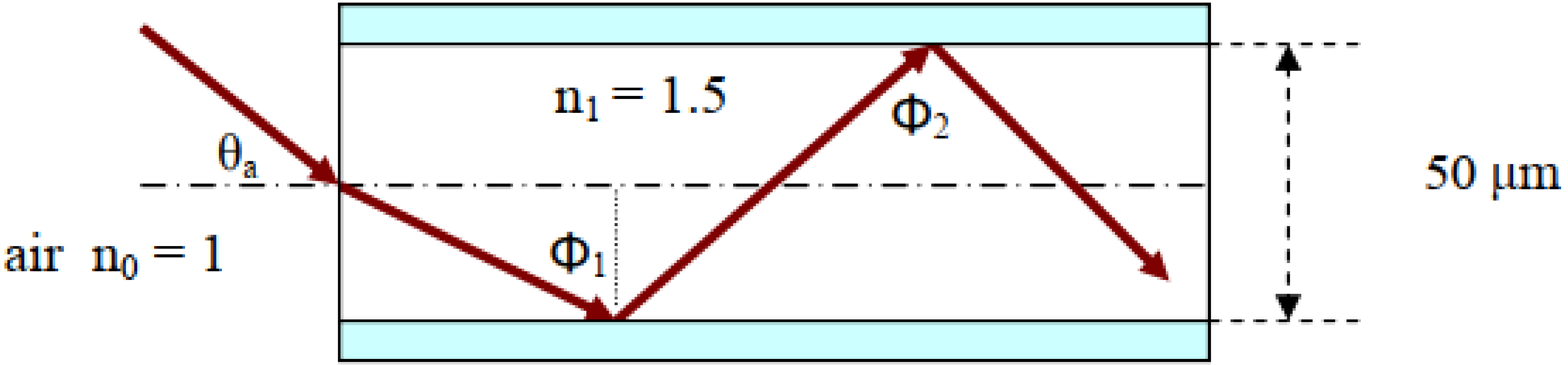
HW

1) For a glass core ($n1$ = 1.5) and quartz cladding ($n2$ = 1.41) interface, find the angle of refraction if the incidence angle is 38°.
2) In an optical fiber cable, the core has a refractive index of 1.5 and the cladding has a refractive index of 1.45. Determine the critical angle for a ray moving from the core to the cladding.
3) For a glass core ($n1$ = 1.5) and quartz cladding ($n2$ = 1.38) optical fiber cable, determine the critical angle of incidence for a light ray moving from the fiber core to the cladding.
4) In an optical fiber cable, the core has a refractive index of 1.5 and the cladding has a refractive index of 1.45. Show that its numerical aperture is 0.384.

HW

6) In an optical fiber cable, the core has a refractive index of 1.5 and the cladding has a refractive index of 1.45. What is the maximum angle (from the axis of the fiber) at which the light will be accepted?

7) Find the value of acceptance angle, critical angle $\varphi 1$ and $\varphi 2$. Given that n2 = 1.48, $\lambda = 1310\ and\ \Delta = 0.01$.



HW

8) A step-index profile optical fiber has an acceptable angle of 20° in air medium. It has a relative refractive index difference value of 3%. Determine the critical angle at the core-cladding interface and numerical aperture of the fiber.

9) A typical step-index profile optical fiber has a fiber core having radius = 4 μm and refractive index = 1.46. The relative refractive index difference is specified as 0.3%. Determine the normalized frequency parameter V at the following operating wavelength a)1300 nm and b)1550 nm.

10) A step-index profile optical fiber has the specification of a normalized V-parameter as 26.6 at a given wavelength of 1300 nm. If the diameter of the fiber core is 50 μm, then determine the numerical aperture.

OPTICAL SOURCES AND TRANSMITTERS

REQUIREMENTS FOR AN OPTICAL SOURCE

- The fundamental function of an optical source is to transform electrical energy (i.e., the current) into an equivalent optical energy (i.e., light pulse) as efficiently as possible.

- There are mainly two types of optical sources: monochromatic incoherent sources such as light emitting diodes (LEDs), and monochromatic coherent sources such as laser diodes (LDs).

REQUIREMENTS FOR AN OPTICAL SOURCE

- The light output must be focused (i.e., highly directional) so that it can be launched into an optical fiber efficiently.
- The size and configuration of an optical source should be compatible to couple light efficiently into an optical fiber.
- The optical source must have linear output. Output signal depends on input signal.
- Optical sources should be able to generate optical signals at wavelengths where the fiber attenuation is minimum.

REQUIREMENTS FOR AN OPTICAL SOURCE

- They should have narrow linewidth to produce negligible fiber dispersion.

- Optical sources must generate a stable output optical signal which should not vary with operating temperature and other environmental conditions.

- Optical sources should be highly reliable and inexpensive.

REQUIREMENTS FOR AN OPTICAL SOURCE

- **Semiconductor materials used for fabrication of optical sources should comply with the following criteria:**

➢ The semiconductor materials must possess desired characteristics for the purpose of carrier injections.

➢ The semiconductor materials used may be of either direct or indirect bandgap semiconductor materials having suitable impurities. This will result in a relatively higher probability of radiative transitions. Consequently, they exhibit quite high internal quantum efficiency.

➢ It is desirable that the semiconductor materials produce light in a desired wavelength region that is applicable for available optical fibers and photodetectors (usually in the region 800–1700 nm).

REQUIREMENTS FOR AN OPTICAL SOURCE

- For a semiconductor material having bandgap energy level of Eg (eV), the emission wavelength λ (in microns) can be given as:

$$\lambda(\mu m) = \frac{1.24}{E_g(eV)}$$

- HW) Find the relationship between eV and J.

LIGHT EMITTING DIODES (LEDs)

- Basically, light emitting diodes (LEDs) are semiconductor p–n junction devices which are made to operate under forward bias condition.
- The light produced by LEDs generally consists of many propagation modes.
- They can be directly intensity modulated with requirement of very less complex drive circuitry.
- LEDs operate at lower transmission data bit rates as low as about 50 Mbps.

LIGHT EMITTING DIODES (LEDs)

Table 1: Properties of commercially available LEDs

Parameter	*Siemens IRED*	*Fujitsu FED130k4TF*	*Lasertron QLD3M504*	*UDT IR-1550*
Peak wavelength (nm)	900	1300	1300 (TE cooler)	1550
Spectral width (nm)	40	140	90	210
Typical frequency response (MHz)	100	240	200	100
Forward voltage (V)	1.3	1.5	1.8	1.5
Typical forward current (mA)	120	100	150	100
Optical output power (mW)	0.02 (fiber SI 200/280)	0.02 (50/125 fiber pigtail)	0.05 (50/125 fiber pigtail)	0.009 (GI fiber pigtail)

LIGHT EMITTING DIODES (LEDs)

- **Some benefits of LEDs are given below:**

- *Simpler Fabrication* – Due to no requirement of having mirror surfaces or striped geometry in some LED structures, it is fairly simple to fabricate them.
- *Simple Drive Circuitry* –LEDs require lower value of drive currents which too is less dependent on operating temperature. So, drive circuitry is quite simple.
- *Linearity* – Ideally, an LED exhibits quite linear optical output power characteristics with respect to input electric current. This has an advantage in analog communications.

LIGHT EMITTING DIODES (LEDs)

- *Less Temperature Dependence* – Since an LED is not a threshold operating device, so any increase in operating temperature may not cause an increase in threshold current requirement above the specified operating point.
- *Reliability* – An LED is insensitive to regular degradation in its performance. Moreover, it is immune to modal noise and self-pulsation phenomena.
- *Cost* – LED is less costly due to simpler construction.

LIGHT EMITTING DIODES (LEDs)

1) Edge Emitting LED (ELED) structure.

- In the ELED, the light is taken out through an edge of the structure which is directly coupled to the optical fiber.
- The edge is a guiding layer with low refractive index and located on both sides of the active layers together with stripe contact type geometrical structure.
- The fiber is axially positioned so that the output optical power can be effectively coupled.

LIGHT EMITTING DIODES (LEDs)

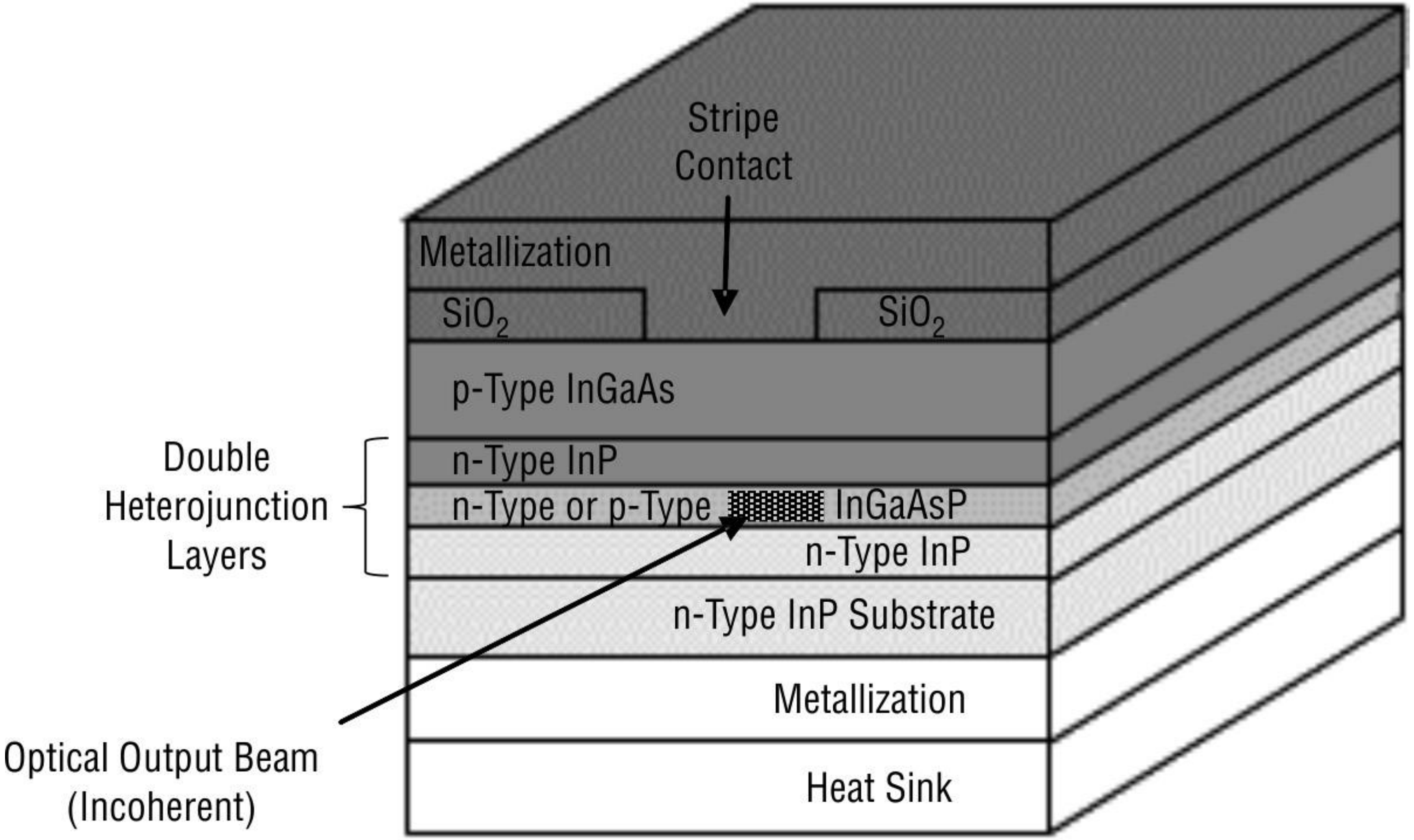


Fig. 1: Edge emitting LED structure

LIGHT EMITTING DIODES (LEDs)

- Edge-emitting LED is a double heterostructure (structure that has junctions between different band gap materials).

- It is used to achieve carrier confinement and recombination in an active layer but additional layers of relatively low refractive index are included to produce optical guide.

- A large fraction of the photons is therefore confined between two plates of material and emerge at the edge of the device as a highly incoherent beam.

LIGHT EMITTING DIODES (LEDs)

- There is a narrow strip which is just below the semiconductor substrate. It acts as a primary active region.
- An appropriate part of the semiconductor substrate is cut and polished in such a way that the actual emission strip layer appears across the front end and back side.
- The rear edge of the semiconductor substrate is also polished in such a way that it becomes highly reflective, whereas the front side is coated with anti-reflective material.
- In this way, the light will only emit from the front edge and will get reflected from the rear side.

LIGHT EMITTING DIODES (LEDs)

- The dimensions of the active regions and strips are carefully designed so that they match with the specified diameters of fiber core (usually 50–100 μm).
- Typically, the length of the active regions is chosen as 100–150 μm and the width of the strips is kept as 50–70 μm.
- This enables it to emit light at a relatively narrower angle that is preferred, to achieve higher coupling efficiency as compared to that which can be obtained with surface emitting LEDs.

LIGHT EMITTING DIODES (LEDs)

2) Burrus Type Surface Emitting LED structure

- In Burrus type surface emitting LED (SLED) structure, a well is etched across the surface of the semiconductor substrate.
- An optical fiber is kept quite close to the emitting surface of SLED structure for efficient transfer of optical power.
- the emitting area is defined by oxide isolation, with the metal contact area (a circle having diameter of about 10–15 μm).
- The surface layer is kept as thin as possible (10–15 μm) to minimize re-absorption.

LIGHT EMITTING DIODES (LEDs)

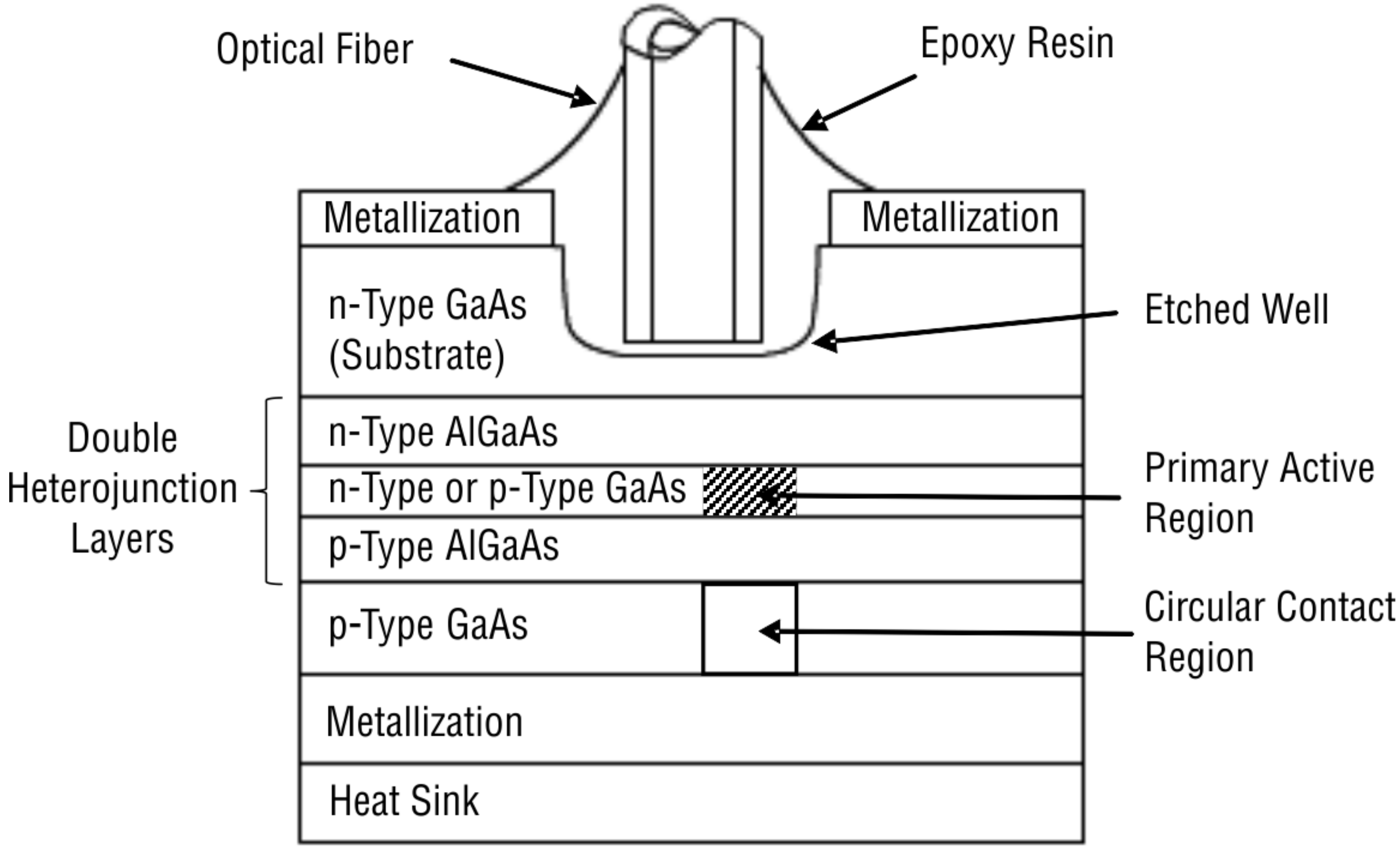


Fig. 2: Surface emitting LED (SLED) structure

LIGHT EMITTING DIODES (LEDs)

- In SLED structure, the emitting area is defined by oxide isolation, with the metal contact area (a circle having diameter of about 10–15 μm).
- The surface layer is kept as thin as possible (10–15 μm) to minimize re-absorption. A planar GaAs/AlGaAs double heterojunction LED exhibits a lifetime of 9 × 107 hours at 25°C.
- The edge emitting LED (ELED) shows more temperature dependence as compared to that exhibited by surface emitting LED (SLED).
- The surface emitting LED provides comparatively higher optical power output. However, both edge-emitting as well as surface-emitting LED structures have linear output power characteristics at medium drive current levels.

LIGHT EMITTING DIODES (LEDs)

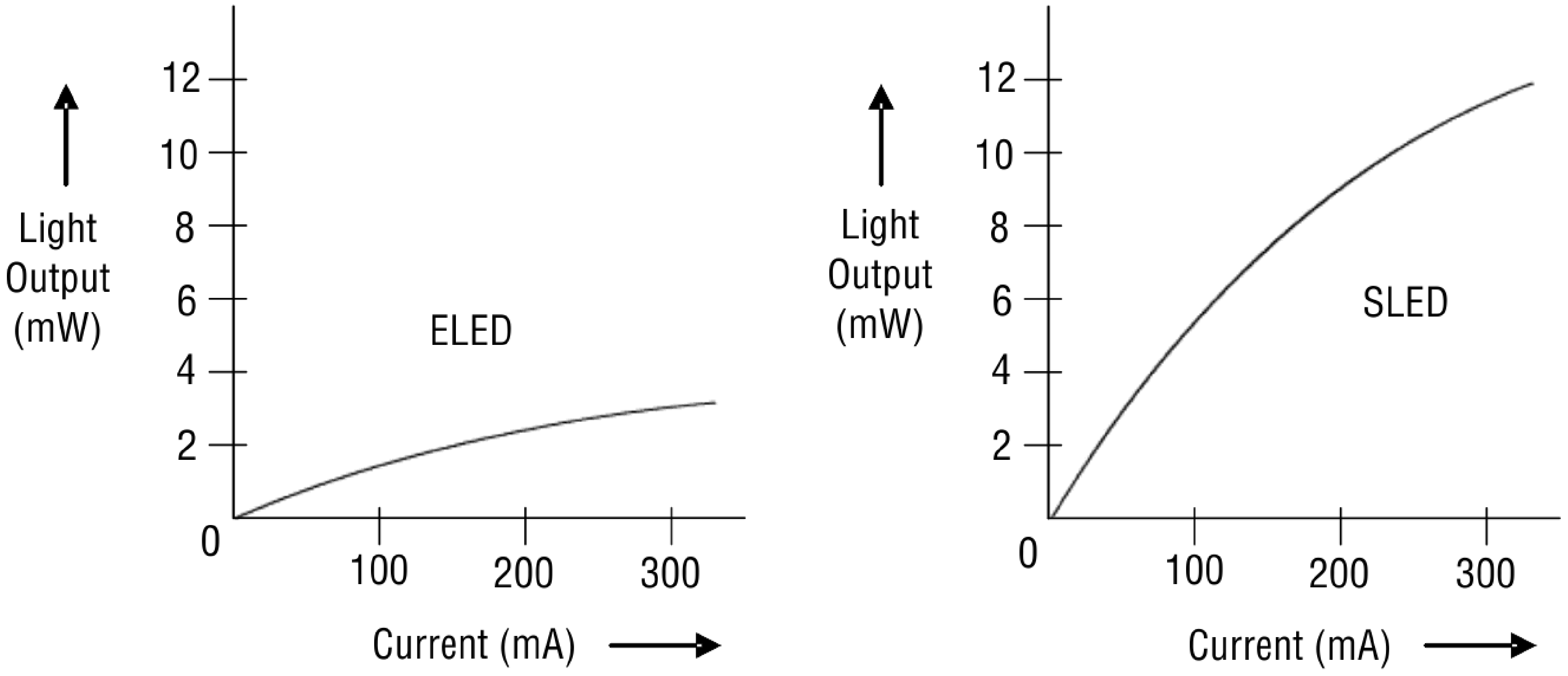


Fig. 3: Output optical power vs input electric current

LIGHT EMITTING DIODES (LEDs)

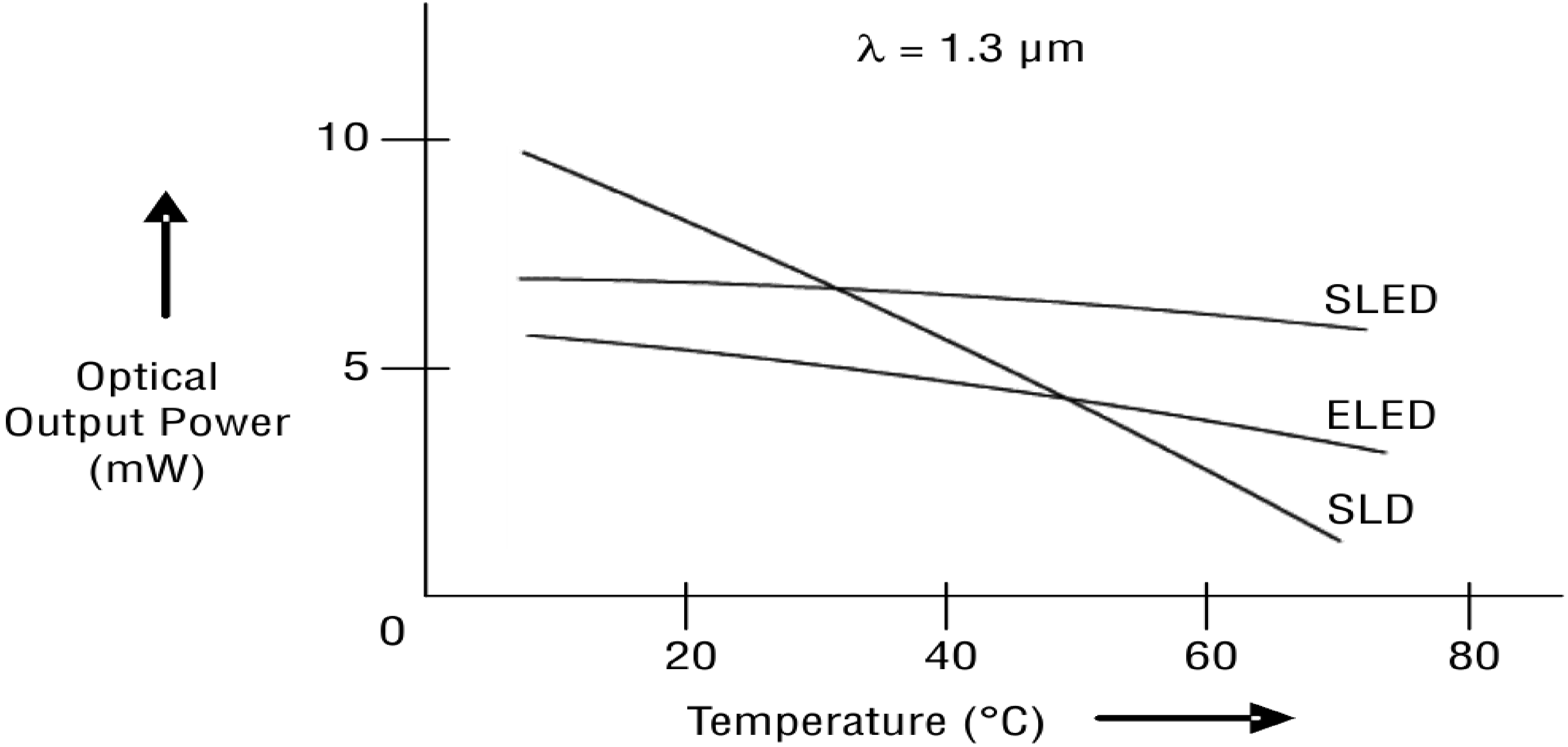


Fig. 4: Optical output power versus temperature for SLED and ELED

LIGHT EMITTING DIODES (LEDs)

- The spectral linewidth of an LED operating at room temperature is usually 25–40 nm in 800–900 nm optical band.
- However, at 1100–1700 nm optical band, the linewidth increases to about 50–160 nm.

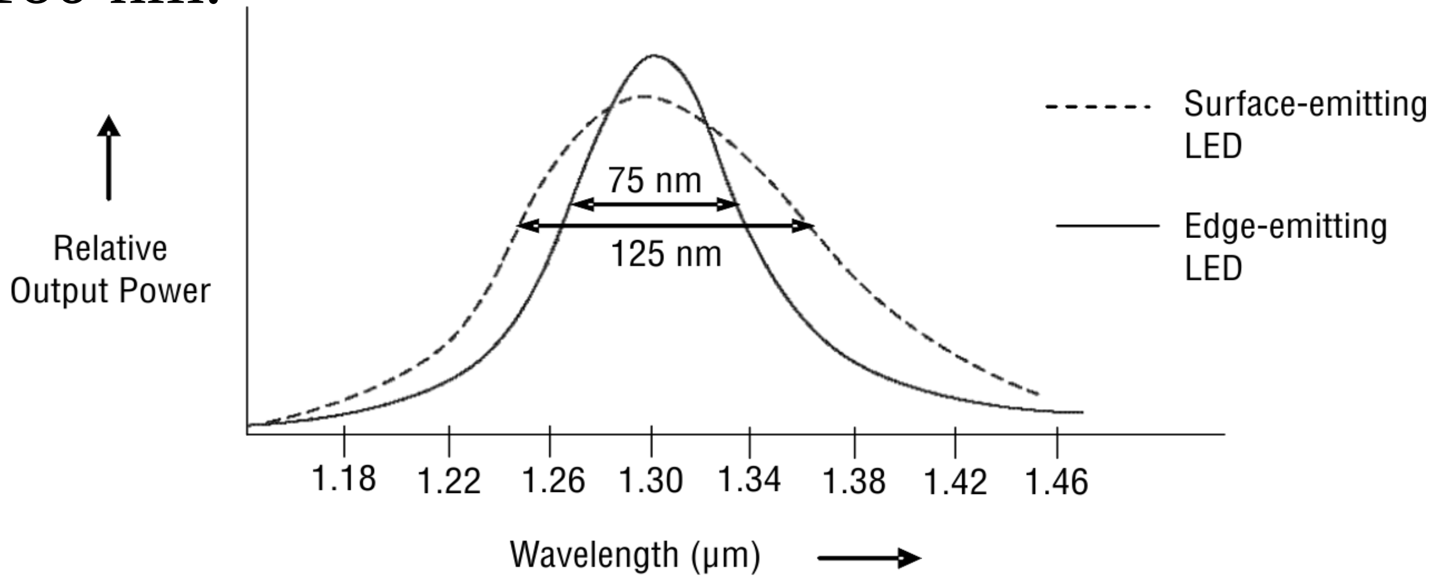


Fig. 5: LED spectral width characteristics

LIGHT EMITTING DIODES (LEDs)

- When an LED is modulated by an electrical signal, the output optical power is constant at low modulation frequencies.
- However, at high modulation frequencies, the output optical power falls due to the delay in the recombination process of electrons and holes.
- The modulation response is described by the relationship:

LIGHT EMITTING DIODES (LEDs)

$$P(f) = \frac{P_o}{\sqrt{1 + (2\pi f \tau)^2}}$$

- $P(f)$ denotes the optical power output as a function of modulation frequency.
- Po is the output power at dc current.
- f is the modulation frequency.
- τ is the carrier lifetime.

LIGHT EMITTING DIODES (LEDs)

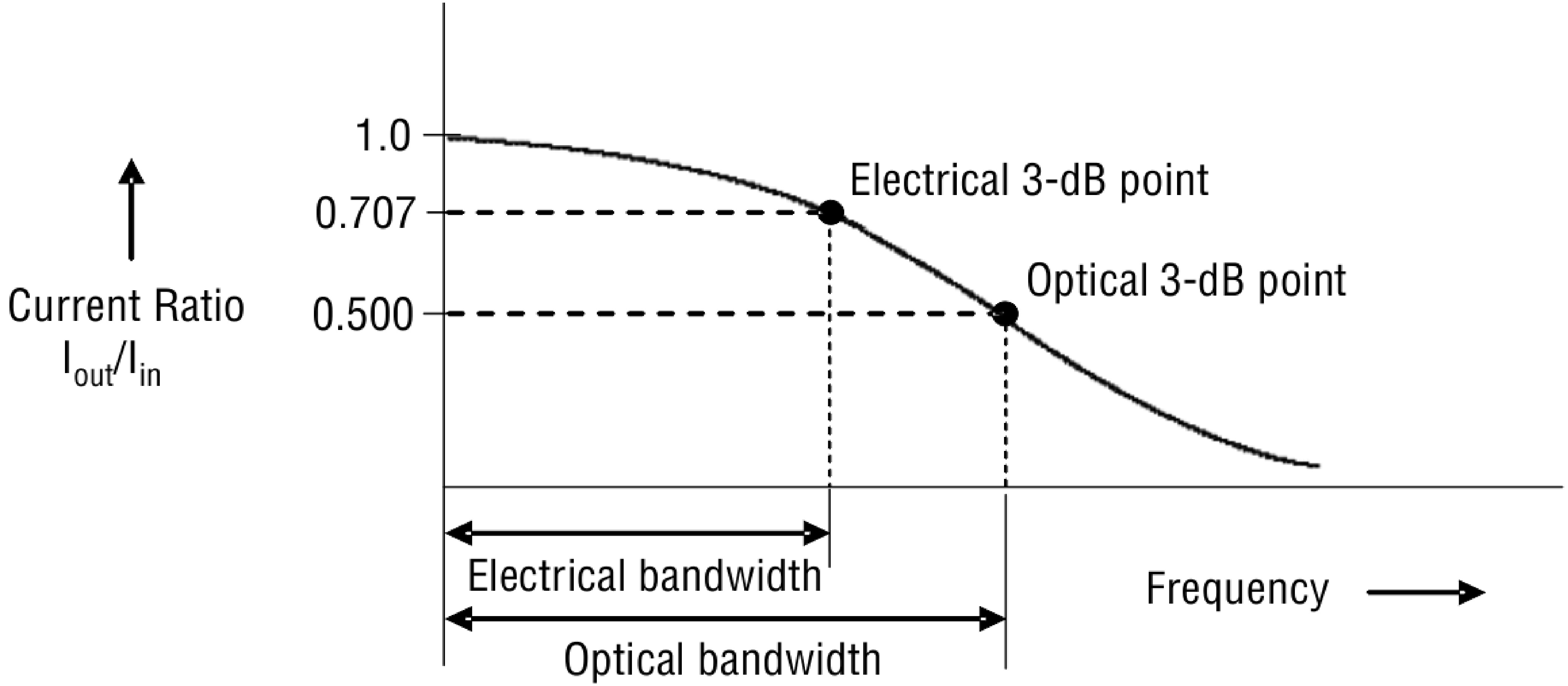


Fig. 6: 3-dB optical vs electrical bandwidth

LIGHT EMITTING DIODES (LEDs)

- In case of heterojunction LED structure, the carrier lifetime is given by:

$$\frac{1}{\tau} = \frac{1}{\tau_r} + \frac{1}{\tau_{nr}} + \frac{2V}{d}$$

where, τ_r represents the radiative lifetimes (i.e., recombination times), τ *nr* represents the non-radiative lifetimes, *V* denotes the recombination velocity, and *d* represents thickness of active region.

LIGHT EMITTING DIODES (LEDs)

- By definition, the internal quantum efficiency, η_{int} (also known as conversion efficiency) represents the fraction of charges that recombine radiatively.
- In other words, it is the ratio of the rate of radiative transitions to the rate of total transitions.

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

LIGHT EMITTING DIODES (LEDs)

- some part of light produced is likely to get absorbed within a region through which it flows, another part of it might have been lost due to scattering of light, whereas some other part may undergo through wither normal reflection or total internal reflection at the interface of external air and the semiconductor surface.

LIGHT EMITTING DIODES (LEDs)

- **Example 1)** Find the carrier lifetime of a double heterojunction LED structure in which the recombination velocity for both electrons and holes is 8 m/sec, the radiative recombination time is 12 ns, and the non-radiative recombination time is 35 ns. The thickness of the active layer is 0.4 µm.
- **Example 2)** If the radiative and non-radiative recombination times of a double heterodyne LED are specified as 12 ns and 35 ns, respectively, then find the internal quantum efficiency.
- **Example 3)** Find the 3-dB modulation bandwidth of a double heterojunction LED structure for a specified carrier lifetime of 6.6 ns.

LASER DIODE (LD)

- LASER is Light Amplification by Stimulated Emission of Radiation.
- LD exhibits much better performance in terms of high transmission data rate for long-haul optical fiber communication networks.
- However, it has the disadvantage of having complex drive circuits, temperature-dependent optical power output, lower reliability and being expensive.

LASER DIODE (LD)

- Some of the distinct advantages of laser diodes are:

- Higher optical power output (of the order of mW), mainly due to amplifying effect of stimulated emissions.

- Narrow bandwidth (less than or equal to 1 nm) which helps to minimize the impact of material dispersion (for example, group velocity dispersion).

LASER DIODE (LD)

- Modulation capabilities up to GHz range.
- Coherent output which allows heterojunction coherent detection in high-capacity system.
- Efficient coupling of optical power output into the low numerical aperture fibers by focusing the light into a tiny spot by using an external lens.
- Size of injection laser diode is compatible with optical fiber.
- Better error performance.

LASER DIODE (LD)

Table 2: Properties of commercially available LDs

Parameter	*LDT-60008*	*Fujitsu FLD130F1CJ*	*Siemens SFH4423*	*Lasertron QLM3S860*	*Lasertron QLM5S990*
Peak wavelength (nm)	1300	1300	1305±25	1300	1550 (DFB laser)
Spectral width (nm)	5	1	3.5	4	0.1
Typical frequency response (MHz)	500	500	500	400	5000
Forward voltage (V)	2.0	1.2	1.3	1.5	1.8
Typical forward current (mA)	20	20	25	20	10
Optical output power (mW)	0.03 (MM fiber)	0.03 (SM fiber)	0.004 (SM fiber)	0.02 (SM fiber)	0.05 (SM fiber)

LASER DIODE (LD)

- The LD laser diode can be considered as an optical oscillator (or, an optical resonator) because an electromagnetic wave is formed within a cavity that provides highly coherent monochromatic light radiations at its output.
- This means stimulated emission process (sometimes known as lasing) with properties such as identical energy (as well as frequency), same polarization and in phase to that of incident photon.
- To achieve only stimulated emission rather than spontaneous emission or absorption, it is essential to increase the radiation density as well as the population density of the upper energy states as compared to that of the lower energy states.

LASER DIODE (LD)

- The amplification of light occurs when an incident photon collides with an atom existing in the excited energy state which is responsible for stimulated emission of a secondary photon.
- Consequently, by following the same process these photons enable the release of two more photons and so on. Ultimately, this phenomenon effectively leads to avalanche multiplication condition.
- In case the electromagnetic waves (em waves) accompanied with these photons are in phase with one another, then the necessary condition of amplified coherent light emission is met.

LASER DIODE (LD)

- Some other aspects which must be considered in order to achieve the laser action.
- The first aspect is that all the photons must be confined within the laser medium.
- The second aspect is that all the photons must remain in phase with each other so as to obtain coherent emission of light.
- To accomplish these aspects, two mirrors are normally placed for reflection of photons on both sides of the amplifying medium.

LASER DIODE (LD)

- In the laser cavity, oscillations usually occur over a very small range of frequencies (i.e., narrow spectral band).
- The cavity gain is just adequate to compensate for transmission losses. It may be recalled that the laser structure forms a resonant cavity which acts as an amplifying medium for population inversion to exist and emissions to begin.
- Ultimately the light emission levels increases because the standing electromagnetic waves between the end mirrors occurs only at those frequencies for which L is an integral number of $\lambda/2$. Therefore, the resonance condition along the axis of the cavity is given by:

LASER DIODE (LD)

$$L = \frac{\lambda q}{2n}$$

- L is the optical spacing between mirrors
- λ is the emission wavelength.
- q is an integer.
- n represents the refractive index of amplifying medium.

LASER DIODE (LD)

- The desired frequency of oscillations that can occur within the laser cavity can be computed using various integer values of q.
- In fact, each frequency of oscillation corresponding to an integer value constitutes a propagation mode.
- The separation between different modes are described by a frequency interval df, given by

LASER DIODE (LD)

$$df = \frac{c}{2nL}$$

- It is possible that laser oscillations can take place in a direction that is exactly transverse to the cavity axis which may produce resonant modes.
- The laser modes consist of a sequence of wavelength peaks that correspond to different longitudinal modes.
- The spectral spacing between these modes (typically of the order of a few tenths of a nm) depends on the length of the cavity. This is why laser is known as a multimode optical source device.

LASER DIODE (LD)

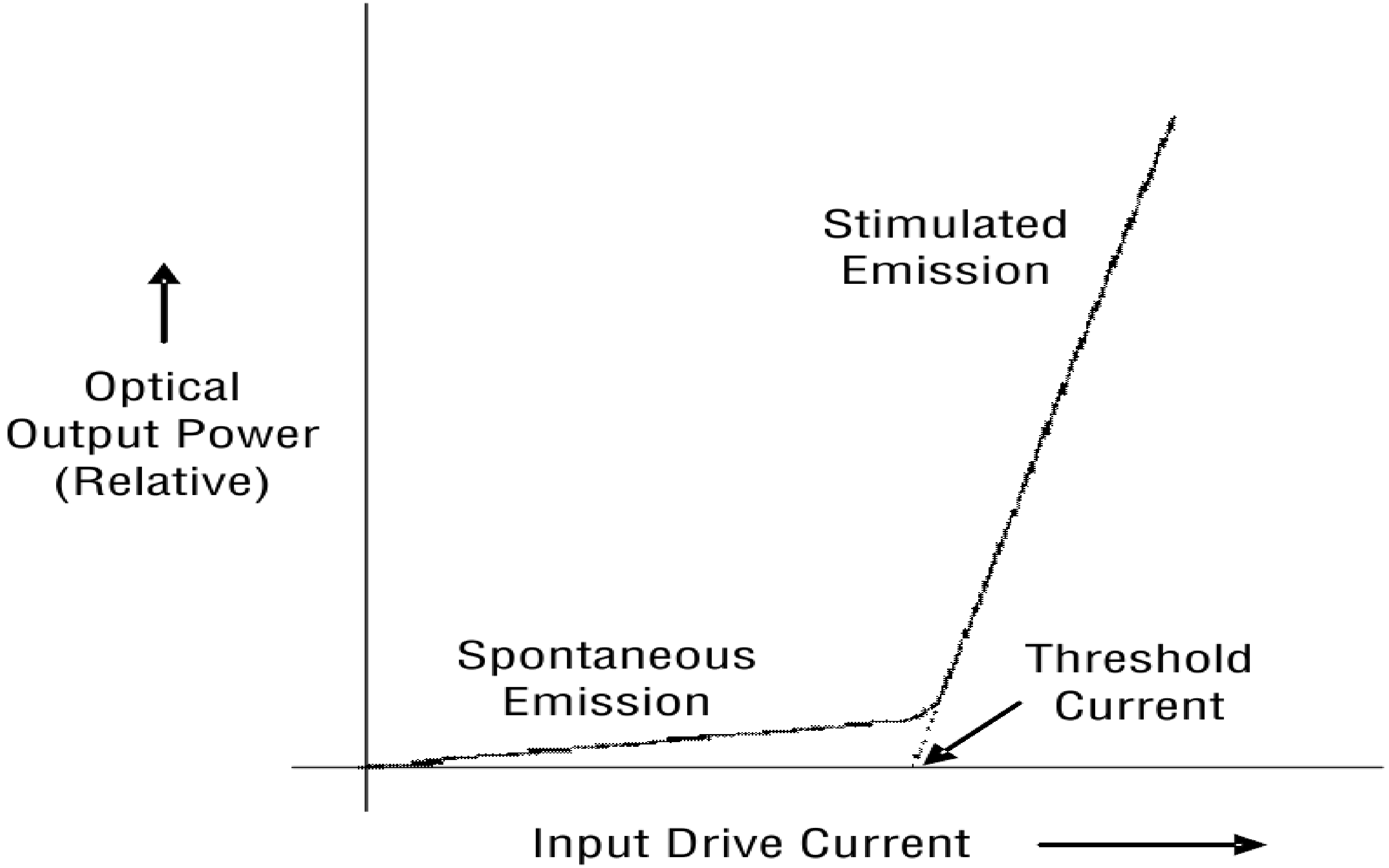


Fig. 7: Lasing characteristics

LASER DIODE (LD)

- Laser diodes are much more sensitive to variations in operating temperature as compared to that of LEDs.
- They require higher current to operate which means quite complex drive circuits with possibility of more heat dissipation due to larger current.
- When we consider analog transmission, it becomes imperative to study the noise behavior of the injection laser diode operation, known as laser noise. Various types of noise sources in the laser device are as follows:

LASER DIODE (LD)

- *Frequency or phase noise*: It occurs due to discrete as well as random spontaneous or stimulated transitions.
- *Relative intensity noise* (RIN): This is also known as instabilities in light output. These may be caused by temperature variations, or from spontaneous emission contained in laser output.
- *Self pulsation*: These are random intensity fluctuations which create a noise source.

LASER DIODE (LD)

- *Optical feedback*: It is reflection of light back into the laser device which occurs from undesired external reflections
- *Mode partition noise*: It occurs when various propagation modes are not well stabilized in multimode laser diodes.

OPTICAL RECEIVERS

REQUIREMENTS FOR A PHOTODETECTOR

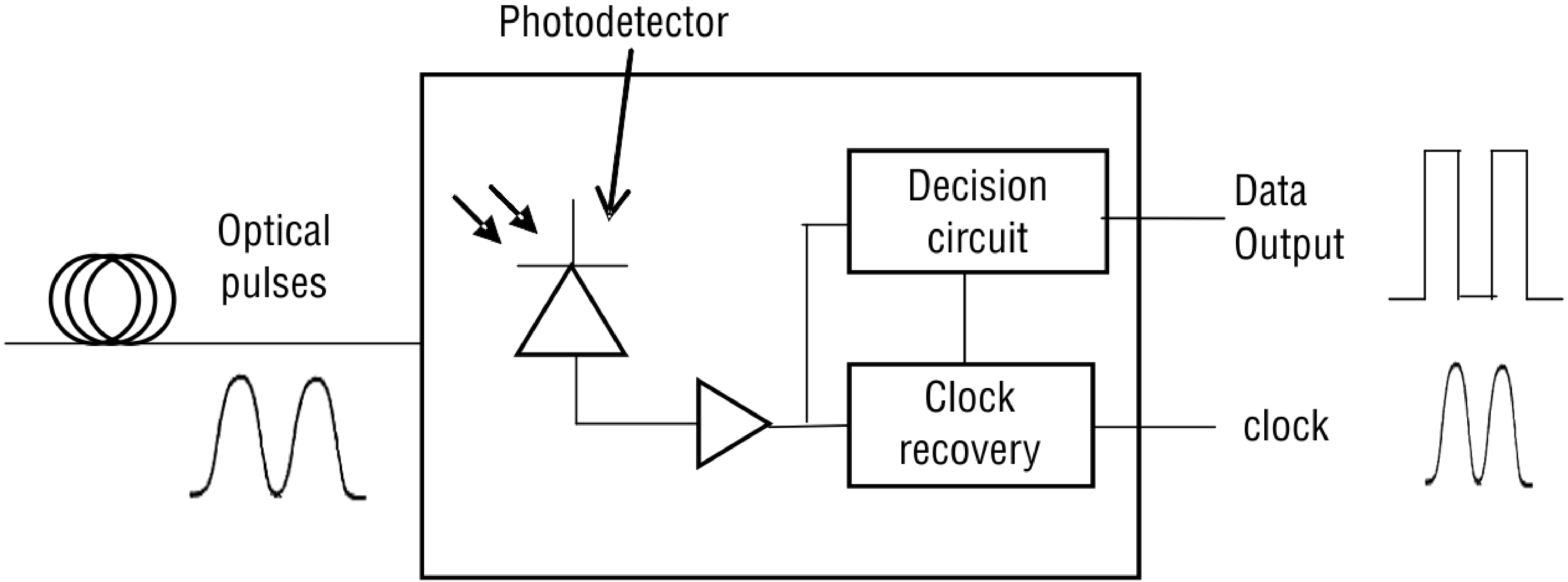


Fig. 1: A photodetector in an optical receiver

REQUIREMENTS FOR A PHOTODETECTOR

- Higher degree of sensitivity at the operating wavelengths
- Fast response to obtain a suitable bandwidth of the order of few GHz
- Linear response with regard to wide range of input optical signals so as to reproduce the received signal with high fidelity
- Low noise –minimum introduction of noise due to leakage and dark currents
- High quantum efficiency– A large electrical response to the given optical power

REQUIREMENTS FOR A PHOTODETECTOR

- Stability of performance characteristics against changes in ambient conditions such as operating temperature
- Small in size for efficient coupling with the optical fiber
- Compact for easy packaging
- Requirement of low bias voltage or currents
- Highly reliable operation at room temperature for several years
- Economical to use

TYPES OF PHOTODETECTORS

1. Semiconductor photodiodes without internal gain
(a) p–n junction semiconductor photodiode
(b) p–i–n semiconductor photodiode
2. Semiconductor photodiodes with internal gain
(a) Avalanche photodiode (APD)
(b) Silicon-reach through Avalanche photodiode
3. Metal–Semiconductor–Metal (MSM) photodetector

P–N Junction Photodiode

- An electron–hole pair is created in a p–n semiconductor photodiode provided the energy of the incident photon is more than semiconductor band gap energy level Eg.
- Indirect band gap semiconductor material is more suitable for making a p–n diode.
- For an ordinary p–n junction to function as a p–n photodiode, it must be adequately reverse-biased such that adequate absorption of incident photons can take place at operating wavelength.

P–N Junction Photodiode

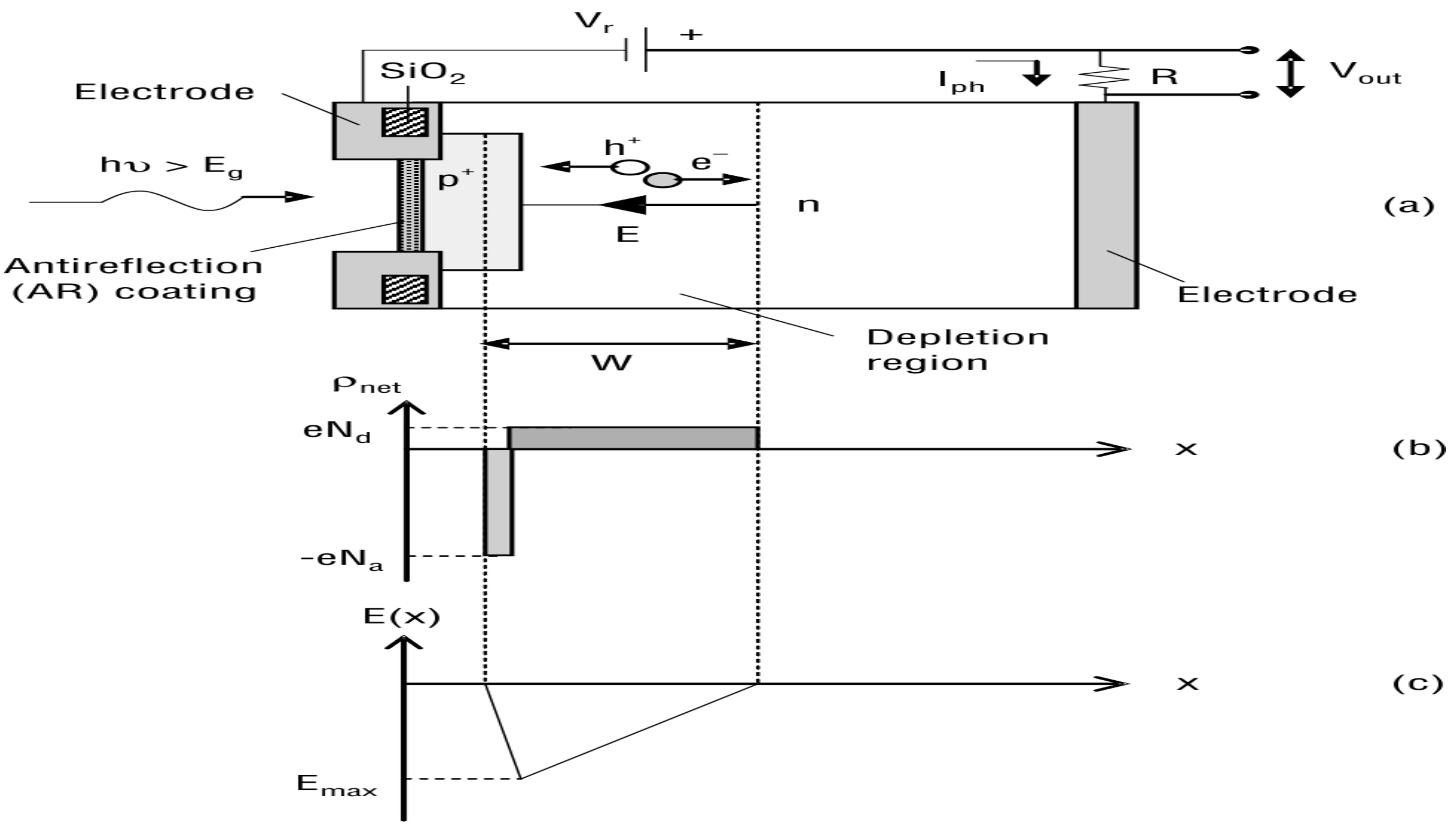


Fig. 2: (a) A reverse-biased p–n junction semiconductor photodiode, (b) Net space–charge distribution,(c) The E-field distribution across depletion region

P–N Junction Photodiode

- The depletion region is formed by immobile holes in the n-type and immobile electrons in the p-type semiconductor materials.
- The width of the depletion region, denoted by *W*, depends on the doping concentration (lower the doping concentration, wider will be the depletion region) for a specified applied reverse bias voltage.
- When an optical pulse (in the form of light signal) is incident on its p-region (say), then new electron–hole pairs are created due to absorption of photons by the semiconductor material. There is a large built-in electric field because of external reverse bias voltage across the p–n junction.

P–N Junction Photodiode

- This results in an acceleration of movement of additionally generated electrons and holes in opposite directions within the depletion region.
- These charge carriers tend to drift to the n-side and p-side of the p–n junction semiconductor, respectively.
- This leads to net flow of current due to movement of charge carriers across the junction.
- It is quite obvious that the amount of current is dependent on the amount of the incident optical power.
- Therefore, we can say that a reverse biased p–n junction semiconductor device can function as a photodetector.

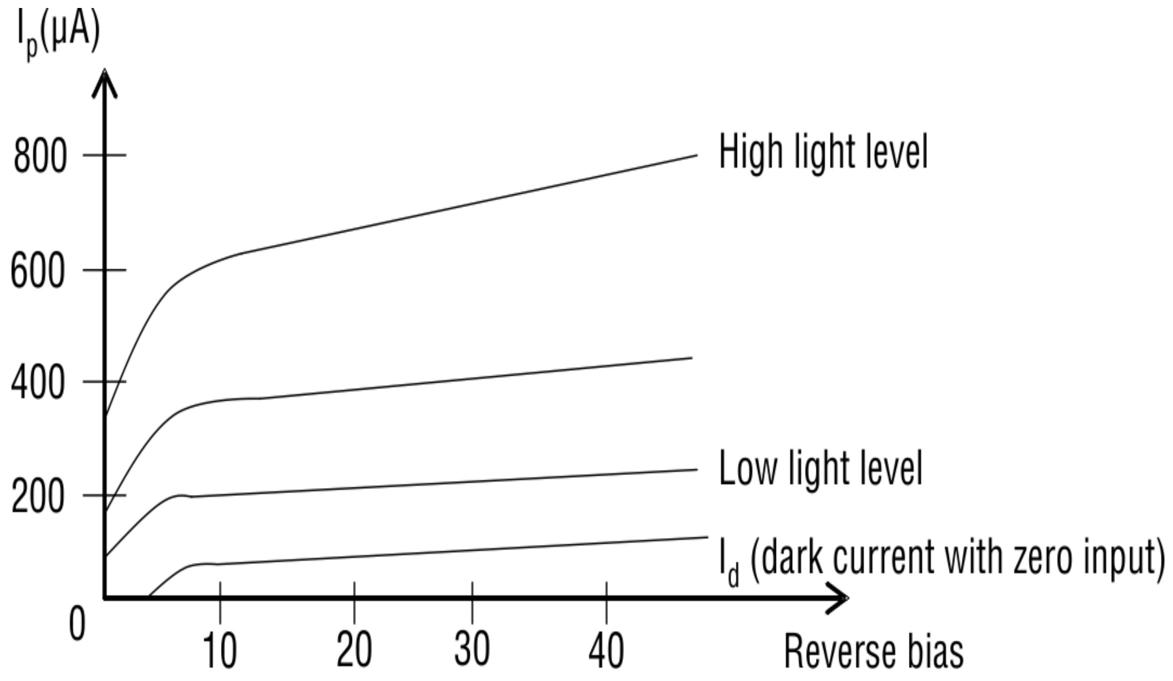
P–N Junction Photodiode

- The photocurrent I_P is directly proportional to the incident optical power level *Pin*, that is,

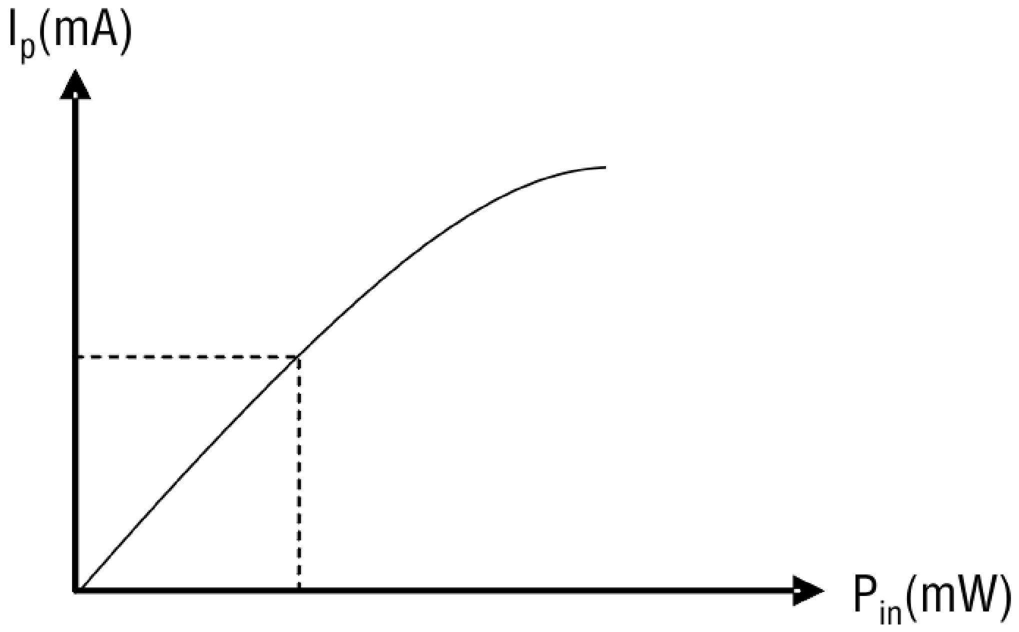
$$\boldsymbol{I_P = RP_{in}}$$

- The proportionality constant *R* is known as the *responsivity* of the photodetector and is expressed in Amp/Watts.

P–N Junction Photodiode



Output characteristics of a photodiode



Input characteristics of a photodiode

Fig. 3: Input–output characteristics of a photodiode

P–N Junction Photodiode

- Responsivity vs wavelength characteristics

$$\boldsymbol{R} = \eta \frac{\lambda(\boldsymbol{\mu m})}{\mathbf{1.24}}$$

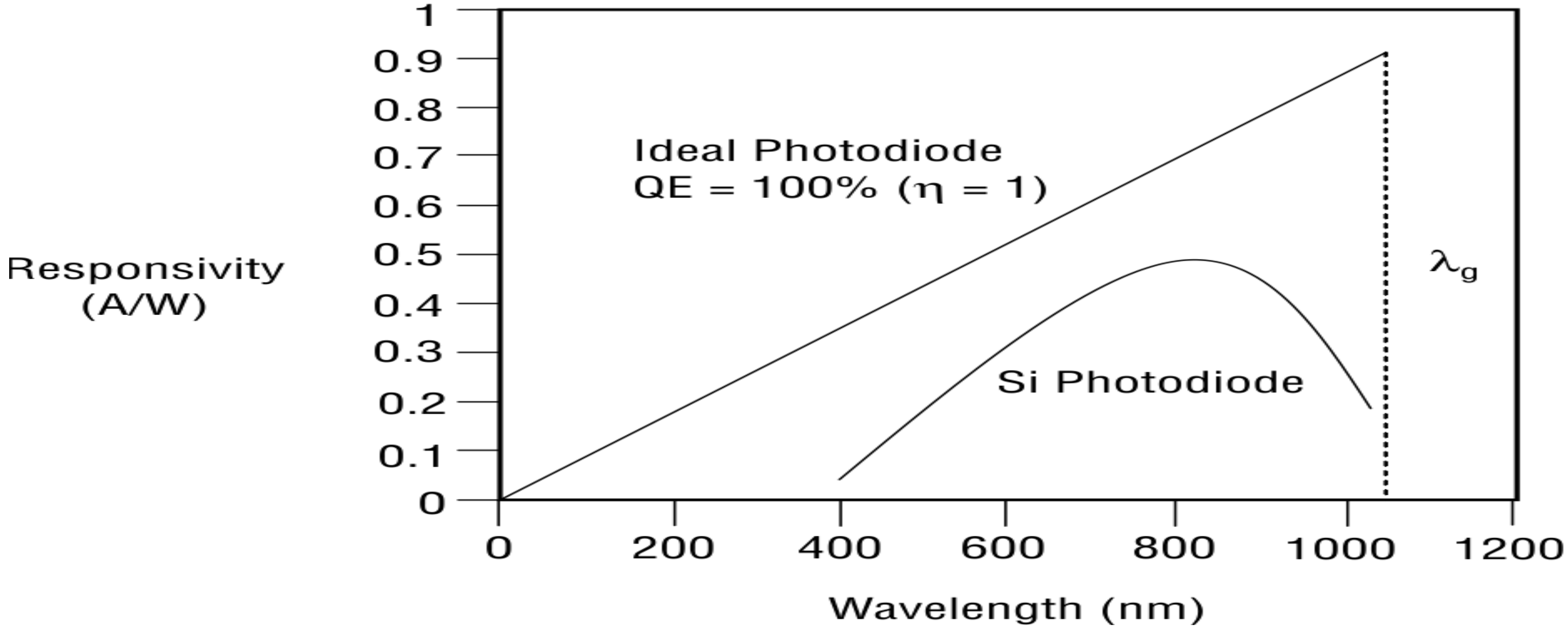


Fig. 4: Responsivity vs wavelength curve

P–N Junction Photodiode

Bandwidth characteristics

- In the context of a photodiode, the term *bandwidth* signifies the maximum frequency, or bit rate, that can be detected by it with almost zero-bit error rate.
- In other words, the bandwidth of a photodetector can be calculated by determining its response time to changes in the incident optical power. Mathematically

$$\boldsymbol{BW_{PD} = \frac{1}{2\pi(\tau_{tr} + \tau_{RC}}}$$

P–N Junction Photodiode

- Here, τ_{tr} is the transit time given by the relationship $\tau_{tr} = \frac{W}{v_d}$.
- W *is* the width of the depletion region of the reverse-biased photodiode, and v_d represents the drift velocity of the charge carriers.
- Both the parameters: W and v_d need to be optimized in order to obtain maximum bandwidth.

P–N Junction Photodiode

- τ_{RC} signifies the time constant of equivalent RC circuit which is given by the relationship:

$$\tau_{RC} = C_P(R_S + R_L)$$

- where *Rs* is the internal series resistance, *RL* is the external load resistance, and *Cp* represents the value of electrical parasitic capacitance.
- For higher bandwidth, τ_{tr} should be reduced by decreasing width of depletion region (*W*). But the quantum efficiency starts decreasing by a significant amount in case the depletion region width *W* is reduced, and is given as:

P–N Junction Photodiode

$$\eta = 1 - e^{-\alpha W}$$

- α represent the absorption coefficient.

P–N Junction Photodiode

Photodiode response

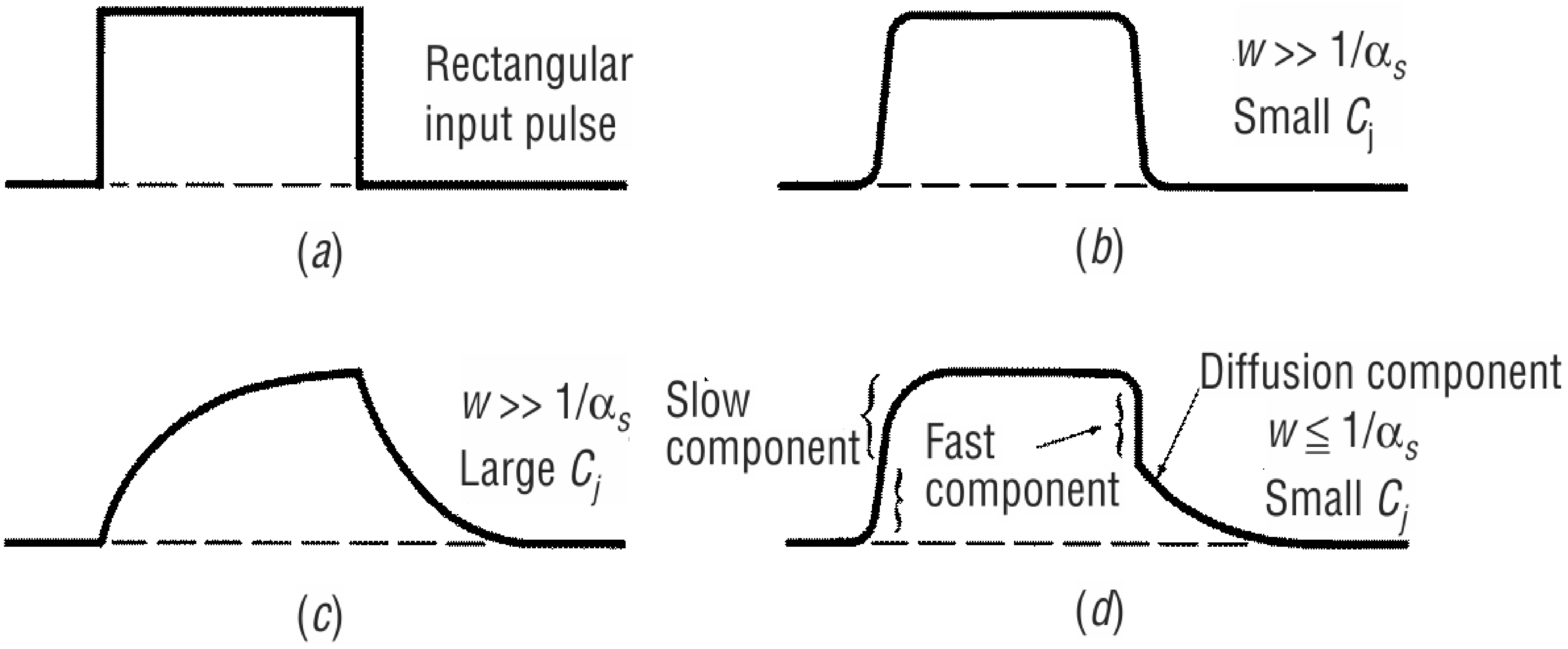


Fig. 5: P-N semiconductor Photodiode response to an optical pulse

P–N Junction Photodiode

- In an ideal photodiode, in order to obtain high quantum efficiency, the width of depletion region across p–n junction must be much larger than $1/\alpha$ for type of semiconductor material used in the p–n photodiode so as to ensure the absorption of most of the incident light.
- The bandwidth that can be obtained with a p–n photodiode is quite often restricted by the value of transit time τ_{tr}.

P–N Junction Photodiode

- **The response of a photodetector depends on three major factors as given below:**

1. Transition time of photon carriers within the depletion region of p–n photodiode.

2. Diffusion time of photon carriers outside the depletion region of p–n photodiode.

3. RC time constant of the low pass filter circuit connected externally at the output of the photodiode.

P–N Junction Photodiode

- **Example 1) (a)** Find the maximum energy band gap a semiconductor material being used as a photoconductor so that it is quite sensitive to an incident light having $\boldsymbol{\lambda}$ = 600 nm. **(b)** A photodetector having an active area of 0.05 cm2 is illuminated with the incident light with an intensity of 20 mW/cm2. Assume that each incident photon generates one electron–hole pair. Determine the number of photons emitted per second.
- **Example 2)** The radius of an active light receiving region of a p–n photodiode is specified as 0.02 cm. It has been observed that when light intensity of 0.1 mW/cm2 is incident on it, it produces a photocurrent of 56.6 nA. Calculate the responsivity.
- **Example 3)** A photodiode has specified responsivity of 0.45 A/W. When radiation intensity of wavelength 700 nm is incident on it, find the quantum efficiency
- **Example 4)** The transit time is one of the main factors that limit the bandwidth of a p–n photodiode. If the depletion region width = 10 μm and drift velocity of charged carriers = 105 m/s, then determine the transit time of the PD.

P–I–N PHOTODIODE

- The p–n junction semiconductor photodiode has two drawbacks.
- One is depletion layer capacitance which is not sufficiently small to allow photo detection at high modulation frequencies.
- Narrow space–charge layer (at most a few microns).
- This implies that the long wavelengths incident photons are absorbed outside space–charge layer which leads to low quantum efficiency.

P–I–N PHOTODIODE

- To increase the depletion region width such that almost the whole incident optical power is absorbed in it, a region of very lightly-doped, or may be undoped (i.e., pure) semiconductor material is inserted between the p-type and n-type semiconductor materials.
- It is the property of an intrinsic layer that it has less doping and wider region (typically 5–50 µm).
- Since the middle layer comprises of an intrinsic semiconductor material, such a structure is often referred to as the p–i–n photodiode.

P–I–N PHOTODIODE

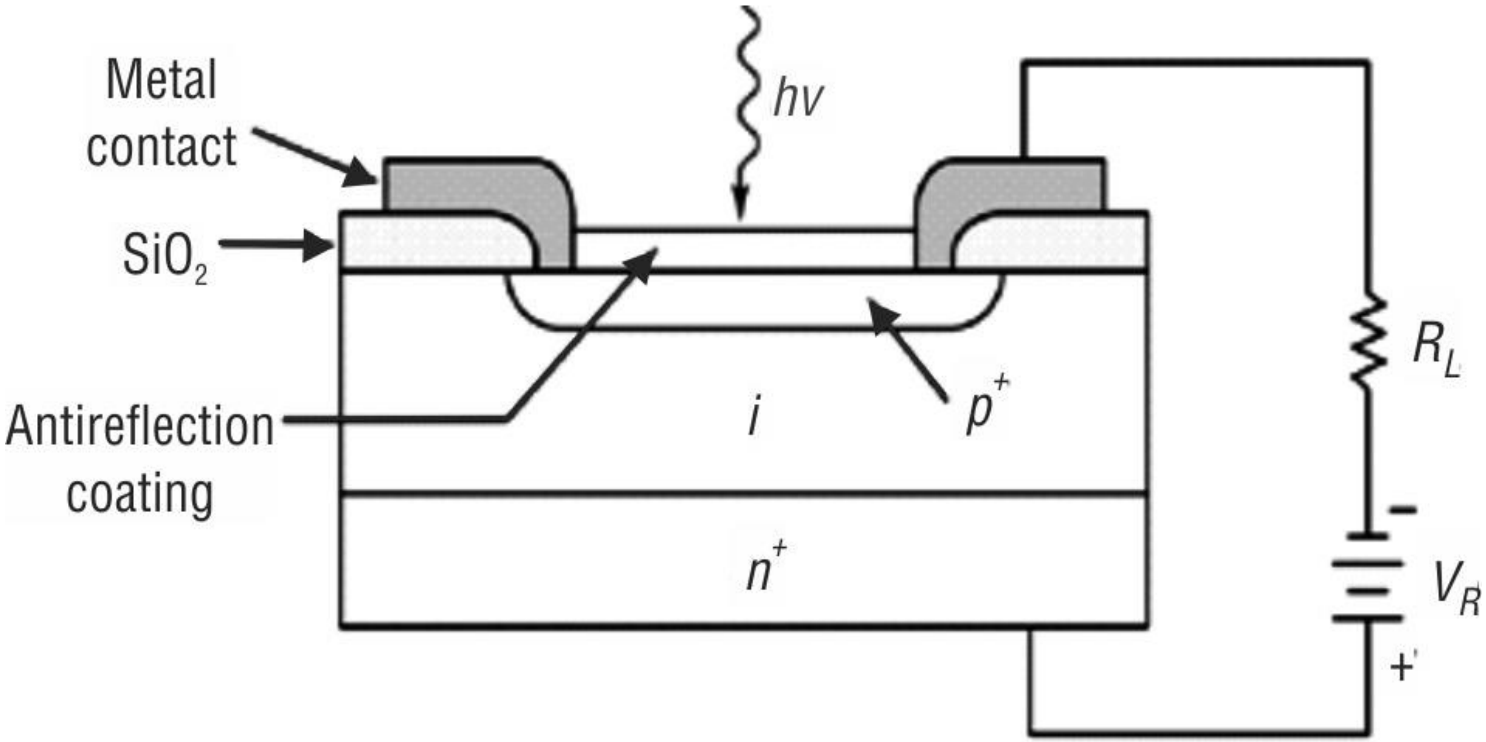


Figure 6: Operation of a p–i–n photodiode

P–I–N PHOTODIODE

- An important feature of the operation of the p–i–n photodiode is that it allows deep penetration of incident light at operating wavelength.
- A relatively shorter wavelength photon is incident near the surface of an externally reverse-biased p–i–n photodiode.
- This photon is completely absorbed by it.
- One of the main benefits of p–i–n photodiode is that small depletion region capacitance enables operation at relatively higher modulation frequencies.
- Moreover, the p–i–n photodiode offers reasonably higher quantum efficiency.

P–I–N PHOTODIODE

- There are certain advantages of p–i–n photodiode as listed below:
- *High quantum efficiency.*
- *High power efficiency.*
- *High bandwidth efficiency.*
- *Requirement of small reverse-biasing applied voltage (usually, 5V).*
- *Decrease in dark current due to low thermally generated charge carriers.*
- *Small diffusion current.*

P–I–N PHOTODIODE

- Some disadvantages of p–i–n photodiode as follows:
- Rise in transit time due to high *W* (width of i-layer). This results in decrease in bandwidth efficiency.
- Increase in response time because charge carriers takes longer time to be drifted across relatively wider depletion region.

P–I–N PHOTODIODE

- **Example 5:** The responsivity curve of a commercial InGaAs p–i–n photodiode is given below. If the dark current is 5 nA, then what would be the incident optical power at *l* = 1550 nm so as to deliver 10 nA photocurrent (which is twice that of dark current)?

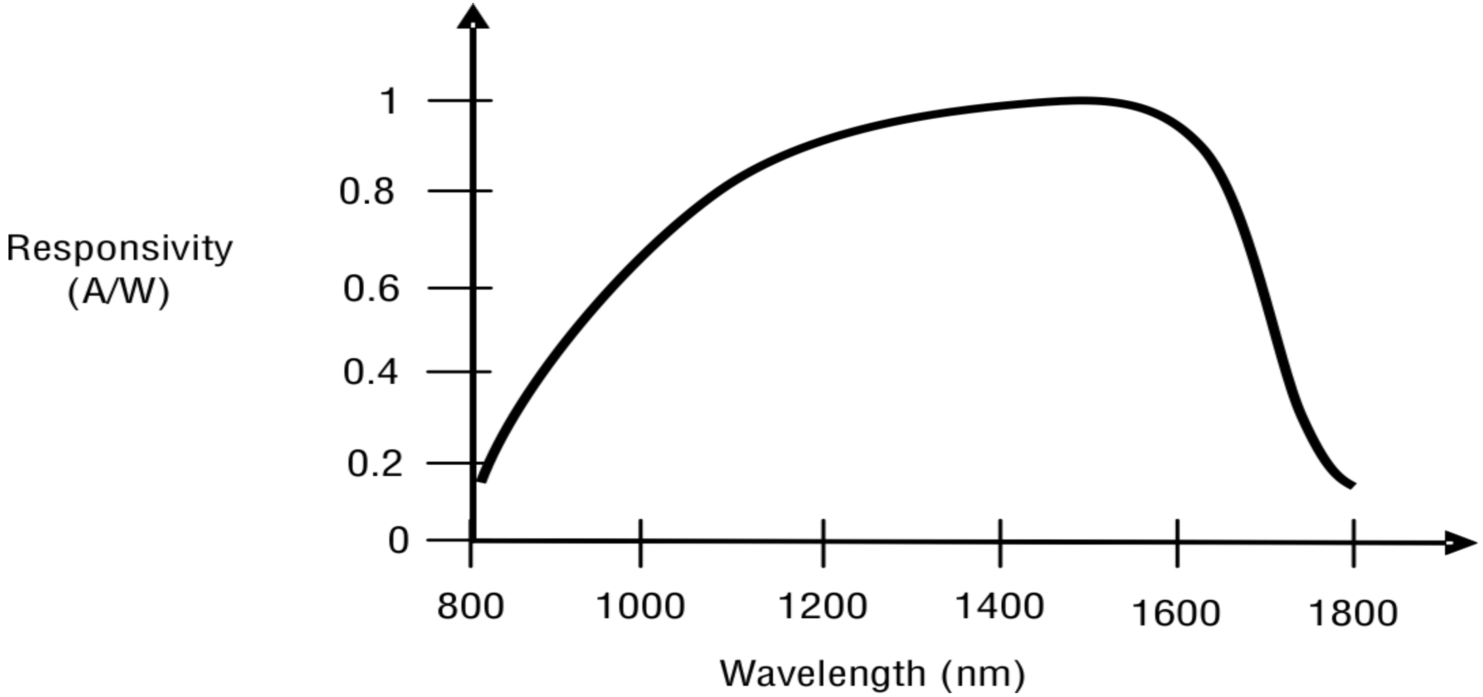


Figure 7: Responsivity curve of InGaAs p–i–n photodiode

AVALANCHE PHOTODIODE (APD)

- For reliable operation, it is imperative to say that all semiconductor photodetectors do need a certain minimum value of output photocurrent.

- This translates into requirement of a minimum input optical power, given by the relationship $P_{in} = I_p/R$.

- This implies that semiconductor photodetectors having large value of responsivity, R, will always be a better choice because they would then need less amount of input optical power, P_{in}.
- The responsivity of a p–i–n photodiode is limited by $R = \eta\lambda(\mu m)/1.24$. Obviously, the maximum value, $R_{max} = \lambda(\mu m)/1.24$ will be obtained at $\eta = 1$.

AVALANCHE PHOTODIODE (APD)

- Avalanche photodiodes (APDs) can achieve a much larger value of *R* because they have been designed to offer an *internal current gain*.

- APDs are used when the amount of available optical power is limited at the input of an optical receiver.

- The phenomenon, known as *impact ionization*, is responsible for internal current gain in APDs.

AVALANCHE PHOTODIODE (APD)

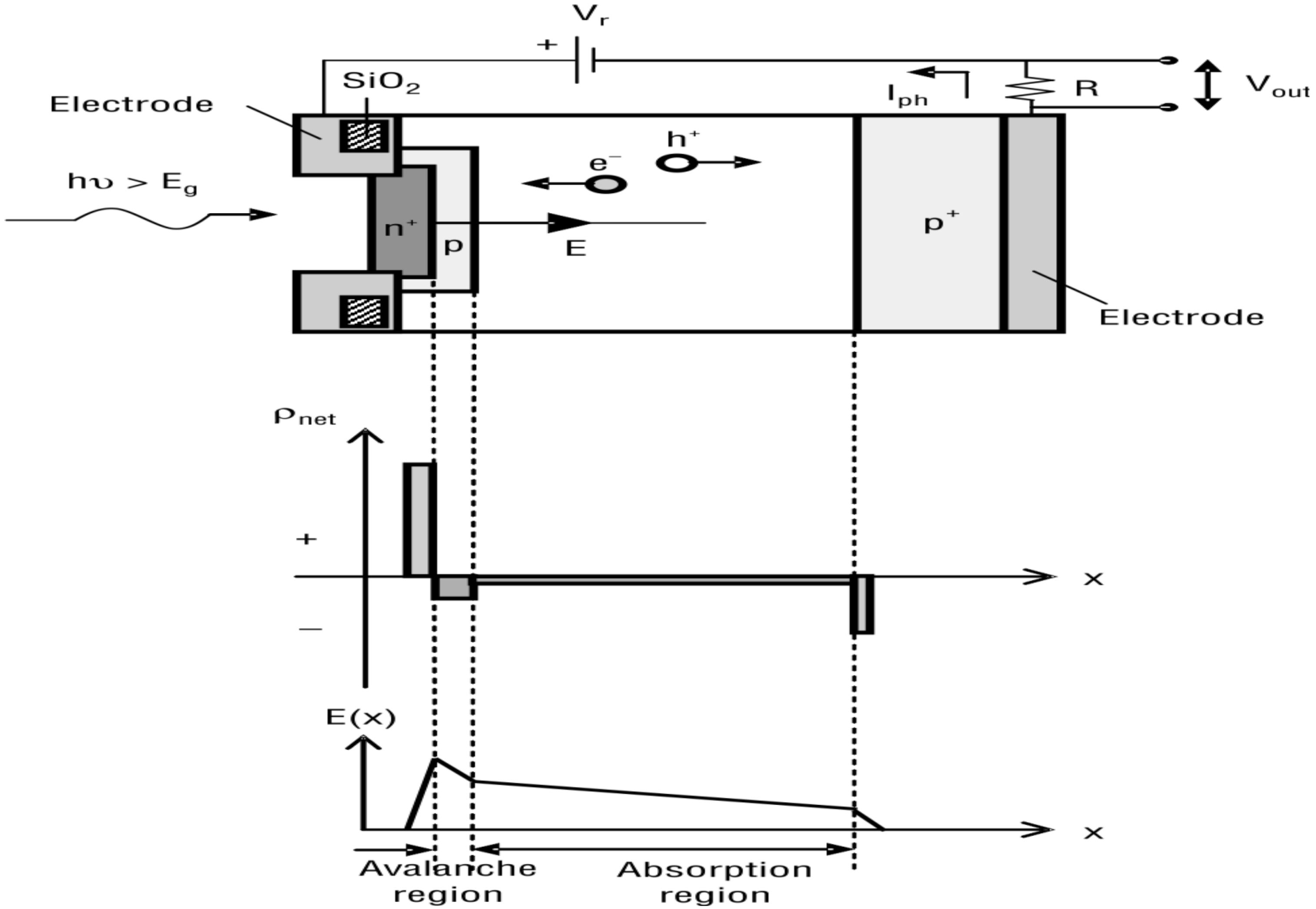


Figure 9: Avalanche photodiode (APD) and its operation

AVALANCHE PHOTODIODE (APD)

Some of the characteristics of the APD are as follows:

- The responsivity of an APD is amplified by the multiplication factor *M*, also known as average APD gain, and is given by:

$$\boldsymbol{R_{APD} = M.R = M\frac{\eta\lambda(\mu m)}{1.24}}$$

AVALANCHE PHOTODIODE (APD)

- The intrinsic bandwidth of an APD is dependent on the multiplication factor M because the transit time τ_{tr} rises significantly due to additional time required for creation and gathering of secondary electron–hole pairs, as given by:

$$M.BW = \frac{1}{2\pi K_A \tau_{tr}}$$

$$K_A = \frac{no.electrons}{no.of\ holes}$$

AVALANCHE PHOTODIODE (APD)

- The APD gain reduces at relatively higher frequency (way?).
- The avalanche process is noisy because the multiplication factor *M*is dependent on many factors such as the width of the gain region, accelerating voltage, and the ratio of concentration of electrons to that of holes during the process of impact ionization.
- Average APD gain, represented by the factor *M* is random because the process of impact ionization is quite random.

AVALANCHE PHOTODIODE (APD)

- APD is more sensitive (at least 10 times) as compared to that of a p–i–n photodetector, both having almost similar bandwidth.
- APD requires a relatively high reverse voltage—an increase in power consumption.
- The overall response of APD is limited due to an asymmetric output pulse shape.
- The basic operation of an APD is renowned by a uniform gain-bandwidth product.

AVALANCHE PHOTODIODE (APD)

Drawbacks of APD

- Difficulty in fabrication process because of quite complex structure.
- Additional noise contribution due to random nature of gain mechanism.
- Requirement of relatively high reverse-bias voltage of the order of 50-400 V, and too depends on the operating wavelength.
- Effect of temperature on avalanche gain.

AVALANCHE PHOTODIODE (APD)

- **Example 6:** The output current of an APD is measured as 100 nA corresponding to an incident optical power of 5 nW. The operating wavelength is 1.5 µm. Find its responsivity.
- **Example 7:** The data sheet of an APD specifies that responsivity = 20 A/W and quantum efficiency = 70%. Determine the avalanche multiplication factor for operating wavelength of 1.5 µm.
- **Example 8:** Consider a silicon p–i–n photodetector and an APD to detect light at λ = 850 nm. For an incident light intensity of 0.1 mW/mm2, the photocurrent generated by the p–i–n photodetector and APD are 10 µA and 500 µA, respectively. In both cases, the active area is 0.2 mm2. Compute the quantum efficiency and the avalanche multiplication factor.
- **Example 9:** Consider a silicon p–i–n photodetector and an APD to detect light at λ = 850 nm. For an incident light intensity of 0.1 mW/mm2, the photocurrent generated by the p–i–n photodetector is 10 µA and that of APD is 500 µA respectively. Find the avalanche multiplication factor.

RECEIVER NOISE

- There are various sources of noise which lead to continuous variations in the photocurrent, *Ip* despite constant input optical power.

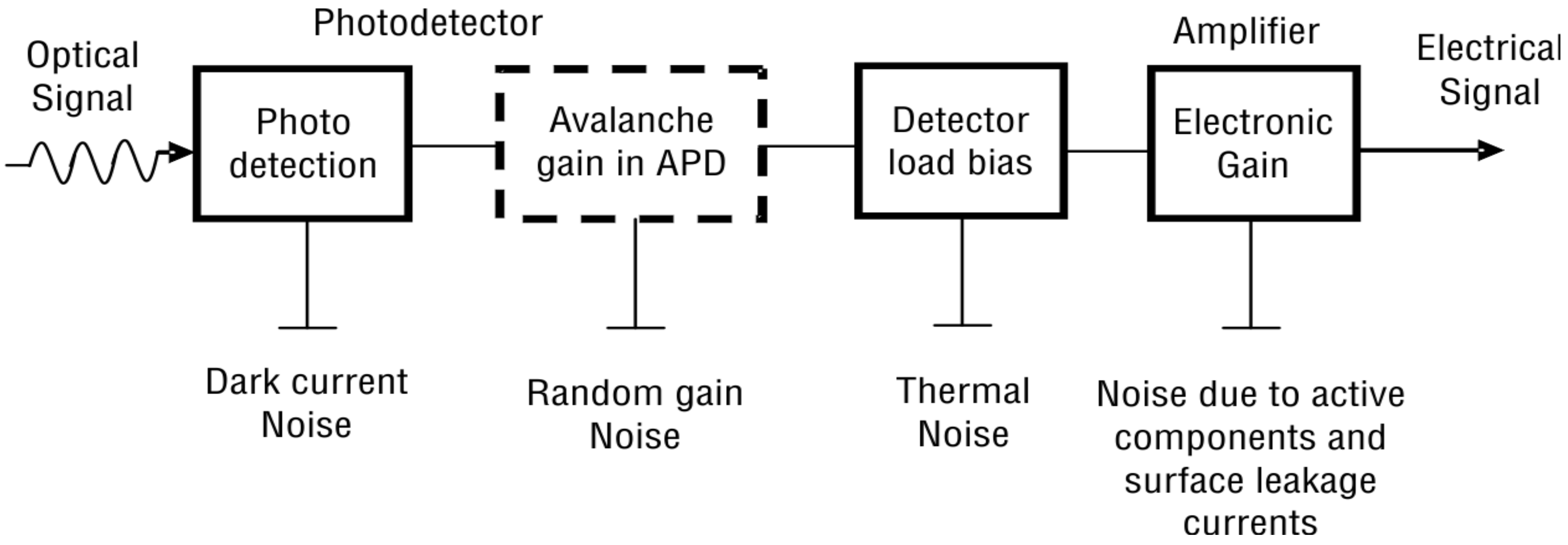


Figure 10: Optical receiver front-end showing noise types

RECEIVER NOISE

- ***1)Shot Noise.*** The actual number of photons arriving at a particular time is unknown and so is a completely random variable.
- Hence, the number of photo-generated electrons at any particular instance is a random variable.
- Generally, the actual number of electrons are not exactly same as the average number of electrons.
- This contributes to noise, known as shot noise.

RECEIVER NOISE

- the photocurrent produced by a constant incident optical power signal can be expresses as:

$$I(t) = I_P + i_s(t)$$

$i_s(t)$ represents the variations in the photocurrent due to shot noise.

- The current density of the shot noise ($i_{sN}(t)$) is given as:

$$i_{sN}(t) = \sqrt{2qI_p}\ \text{A}/\sqrt{Hz}.$$

RECEIVER NOISE

- ***2) Thermal noise.*** Due to change in operating temperature of photodetectors, the actual number of electrons may not be identical to the average number of electrons any instant of time.
- This gives rise to noise, known as thermal noise. Electron motion due to temperature occurs in a random manner, which gives rise to variations in the photocurrent even when no external bias voltage is applied to the photodetector.
- There is another type of variation in the photocurrent due to the load resistor, which forms part of the front-end circuit of an optical receiver. This gives rise to an additional noise component which is often referred to as Johnson noise (sometimes known as Nyquist noise), which is similar to thermal noise.

RECEIVER NOISE

- Therefore, we can say that the total photocurrent is given as:

$$I(t) = I_P + i_s(t) + i_{th}(t)$$

$i_{th}(t)$ represents the variations in the photocurrent due to thermal noise.

- The current noise density of the thermal noise is given as:

$$i_{thN}(t) = \sqrt{\frac{4kT}{R_L}} \quad \left(\frac{A}{\sqrt{Hz}}\right)$$

RECEIVER NOISE

- **3) Dark-current noise.**

$$I_{dN} = \sqrt{2qI_d}\ \left(\frac{A}{\sqrt{Hz}}\right)$$

- **4) 1/f noise.** A photodiode also generates another type of noise that occurs in complete darkness (absence of incident optical power) other than the dark current noise in a photodetector. Known as 1/f noise.

$$I_{1/fN} = \frac{K_{1/f}I^{\alpha}}{f^{\beta}}\ \left(\frac{A}{\sqrt{Hz}}\right)$$

K, α and β are found empirically.

RECEIVER NOISE

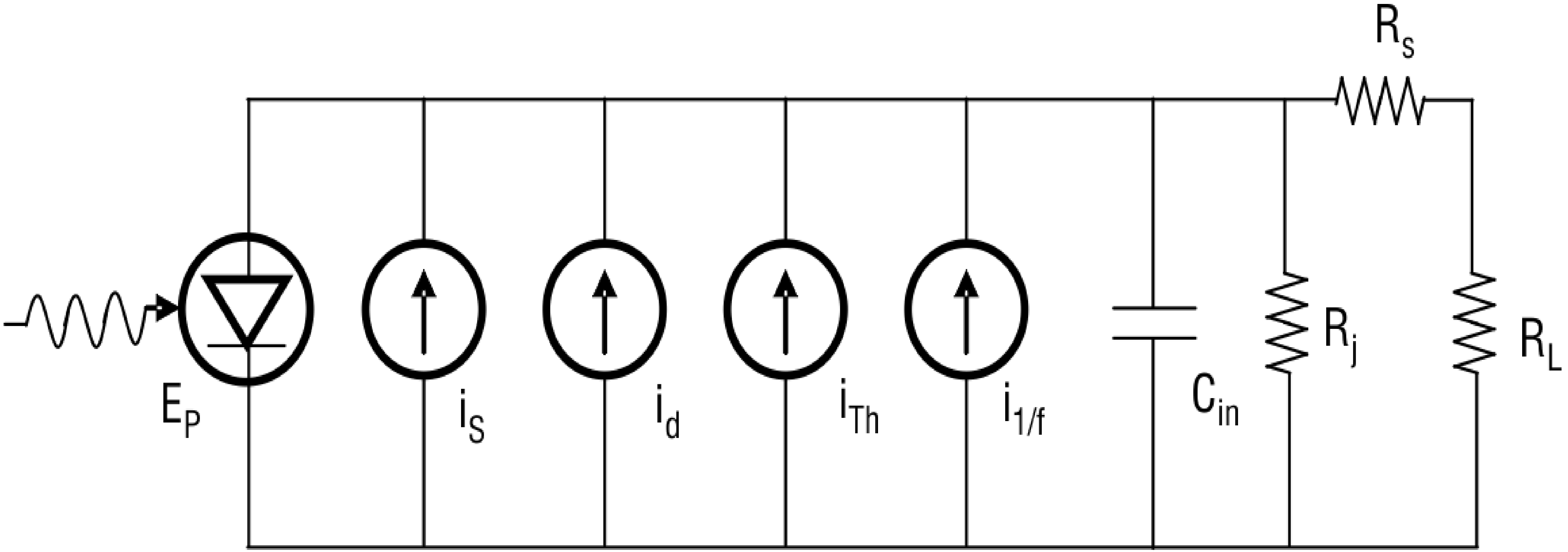


Figure 10: Generalized equivalent circuit of noise in photodetector

RECEIVER NOISE

- It may be noted that each noise component is an independent random process approximately by Gaussian statistics. The overall noise is given by:

$$i_{noise} = \sqrt{i_s^2 + i_d^2 + i_{th}^2 + i_{1/f}^2}$$

- The signal-to-noise ratio (SNR) is one of the performance determining parameter of an optical receiver.

RECEIVER NOISE

$$SNR = \frac{R^2 . P_{in}^2}{i_{nois}^2}$$

- H.W1) Find the SNR for thermal noise, shot noise and dark current noise for pin PD.

- HW2) Find the SNR while considering all types of the noise.

RECEIVER NOISE

- The SNR of the APD while considering only shot noise is given as:

$$SNR(APD)_{shot} = \frac{R_{APD}\, P_{in}}{2\, q\, F_s BW_{APD}}$$

- F_s is the excess noise factor of the APD.

- The SNR of the APD while considering only thermal noise is given as:

$$SNR(APD)_{shot} = \frac{M^2 R_{APD}^2\, P_{in}}{\frac{4kT}{R_L}\, BW_{APD}}$$

- **Ex 10)**A semiconductor photodetector has responsivity R = 0.5 A/W for an incident optical power of 10 µW. It has dark current of 2 nA. Determine the value of the shot-noise current density for a specified bandwidth of 1 MHz.

- **Ex 11)** An optical receiver has 20 MHz bandwidth operating at a wavelength of 1100 nm. It uses an In GaAs p–i–n photodiode producing a photodiode current of 4 nA with quantum efficiency of 90%. The load resistor of the circuit is 1 kΩ. Assuming negligible surface leakage current, find the value of dark current and thermal noise current if the incident optical power is 300 nW.

Receiver Sensitivity

- Receiver sensitivity is the minimum average input received optical power that a photodetector can detect for it to operate at a given (BER).

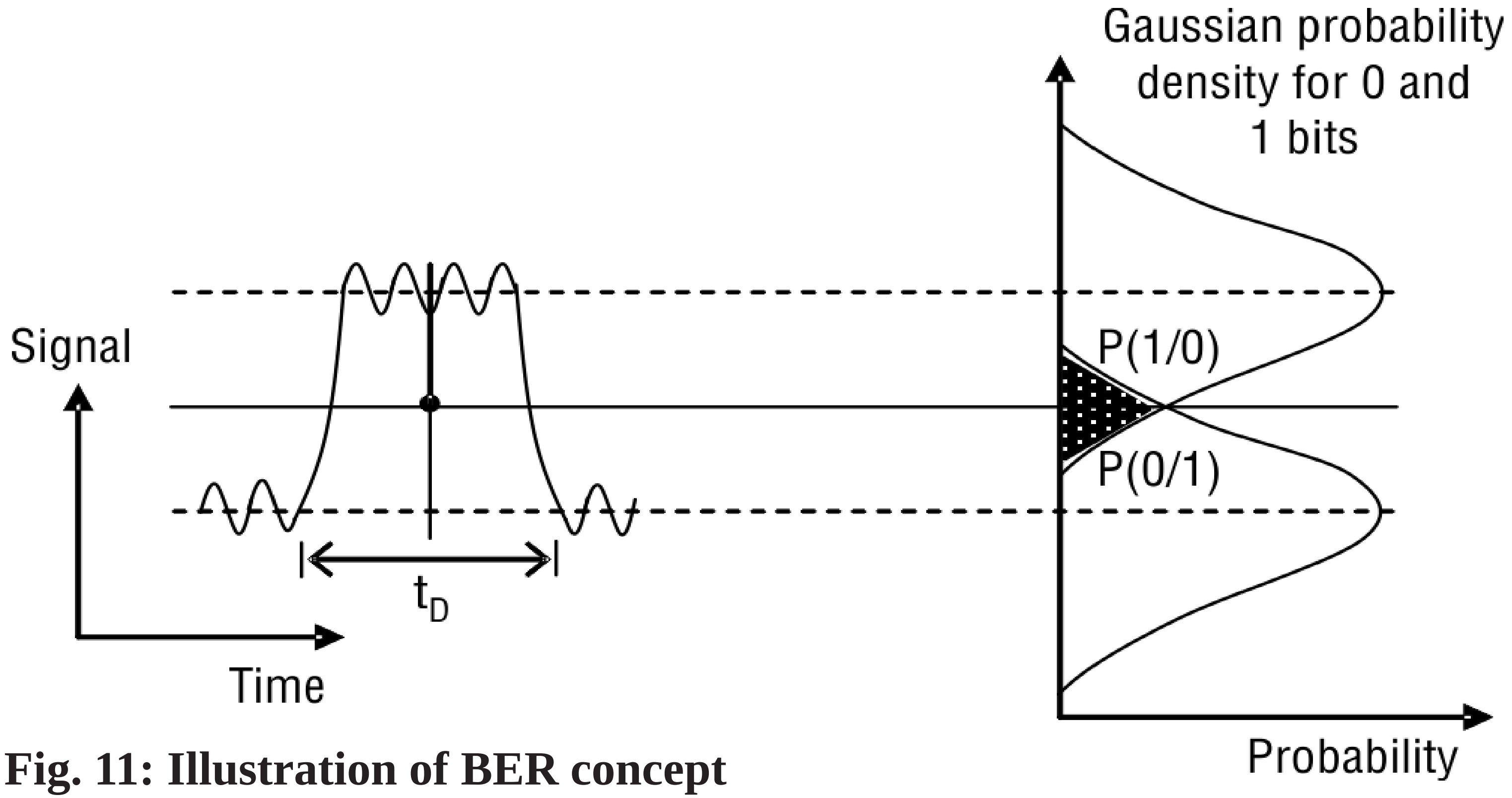


Fig. 11: Illustration of BER concept

Receiver Sensitivity

- ➢ The minimum BER depends on the Q parameter:

$$BER = \frac{1}{2}\,\mathrm{erfc}\left(\frac{Q}{\sqrt{2}}\right)$$

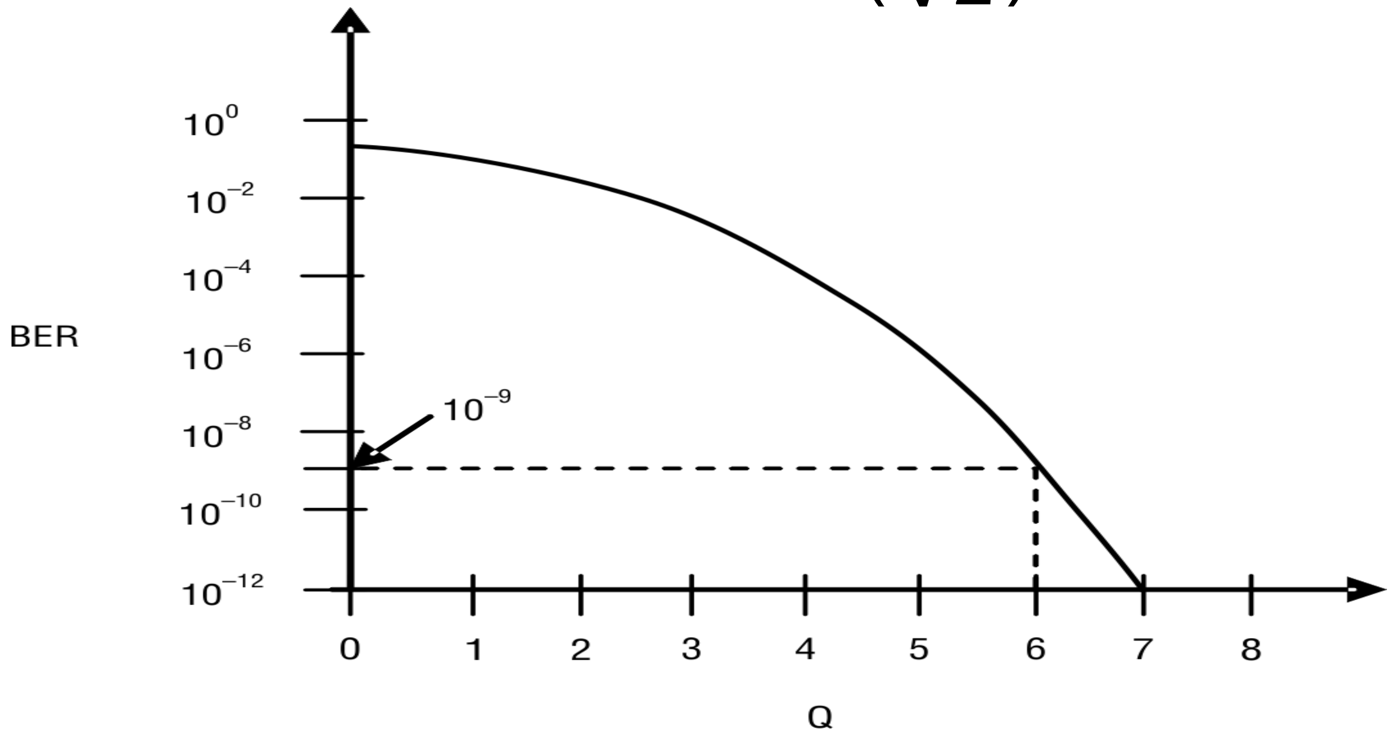


Fig. 12: BER vs Q