Optical Fiber Communication: Revision

May, 2025

Contents

1 Differences

1.1 Single Mode and Multimode Step Index Fibers

Feature	**Single Mode Step Index Fiber**	**Multimode Step Index Fiber**
Core Size	8–10 μm	50–62.5 μm
Light Propagation	Single mode (one path)	Multiple modes
Bandwidth	High (low dispersion)	Lower (high dispersion)
Attenuation	Low (longer distances)	Higher (shorter distances)
Transmission Distance	Up to 100s of km	Up to a few km
Applications	Long-haul telecom, high-speed internet	LANs, data centers, short-range
Cost	More expensive	Less expensive
Light Source	Lasers	LEDs or less costly lasers

1.2 Skew and Meridional Ray

Parameter	**Meridional Ray**	**Skew Ray**
Path Relative to Axis	Passes through the fiber's central axis	Does not pass through the central axis
Acceptance Angle	Smaller, limited by critical angle	Larger
Propagation Loss	Lower (propagates near core center)	Higher (near core edge, often leaky)
Ray Abundance	Less numerous due to strict entry angle	More numerous due to wider entry angle
Ray Behavior	Bound: Confined in core by total internal reflection if angle ¿ critical angle; Unbound: Refracted into cladding if angle ¡ critical angle	Mostly leaky rays, partially reflected
Path Geometry	Simpler path, lies in a single plane	Helical path, complex 3D trajectory
Modal Dispersion	Lower	Higher

1.3 EDFA and SOA

Parameter	**EDFA**	**SOA**
Gain Medium	Erbium-doped silica fiber	Semiconductor (e.g., InGaAsP)
Amplification Bandwidth	20–40 nm (C-band: 1530–1565 nm, L-band: 1570–1625 nm)	40–100 nm (850–1600 nm)
Noise Figure	4–7 dB (Low)	6–10 dB (High)
Gain	20–40 dB (high gain)	10–30 dB (moderate gain)
Applications	Long-haul telecom, WDM systems, CATV, data centers	Metro networks, single-channel amplification, optical switching
Power Consumption	Higher (optical pumping at 980 nm or 1480 nm)	Lower (electrical pumping)
Best Use	Long-distance, high-capacity WDM systems	Short-range, compact, cost-sensitive applications
Size	Larger (meters of fiber)	Compact (chip-scale)
Polarization Dependence	Low (polarization-insensitive)	Moderate to high

1.4 SLED and ELED

Parameter	**SLED (Surface-Emitting LED)**	**ELED (Edge-Emitting LED)**
Definition	A semiconductor device emitting incoherent light perpendicular to the substrate surface through spontaneous emission.	A semiconductor device emitting partially coherent light from the edge of the chip via spontaneous emission.
Suitable Fiber Type	Primarily multimode fibers due to broad emission; less suited for single-mode fibers.	Multimode fibers; can be optimized for single-mode fibers with better coupling.
Coupling Efficiency	Low (5–20%); wide emission angle reduces efficiency with fiber coupling.	Higher (20–50%); narrower emission improves coupling to fibers.
Beam Shape	Broad, circular or slightly elliptical beam due to surface emission.	Narrow, elliptical beam from edge emission, more collimated.
Emission Directionality	Low directionality; emits over a wide angle (30–60°).	Higher directionality; emits in a narrower angle (10–30°).
Fabrication Complexity	Simpler; uses standard LED processes with surface emission design.	Moderate; requires precise edge cleaving or polishing and waveguide design.
Active Region Orientation	Active region parallel to substrate, emitting light perpendicular to surface.	Active region parallel to substrate, emitting light from cleaved or polished edge.
Application	Displays, short-range optical communication, general-purpose lighting, sensors.	Short-haul telecom, local area networks (LANs), fiber optic data links.

1.5 Homostructure and Heterostructure LED

Parameter	Homostructure LED	Heterostructure LED
Material Used (Type)	Single semiconductor material (e.g., GaAs); same material throughout.	Different semiconductor materials (e.g., GaAs/AlGaAs); distinct layers.
Band Gap	Uniform band gap across the structure.	Varying band gaps due to different materials in layers.
Structure	Single p-n junction with uniform composition.	Multiple layers (p-n or p-i-n) with different compositions.
Carrier Confinement	Poor; carriers spread, reducing efficiency.	Excellent; carriers confined to active region by heterojunctions.
Optical Confinement	Weak; no waveguide, light scatters.	Strong; heterostructure acts as optical waveguide.
Beam Direction	Broad, omnidirectional emission.	More directional, guided by structure.
Recombination Efficiency	Lower; high non-radiative recombination.	Higher; reduced non-radiative losses.
Application	Basic indicators, low-cost displays.	High-efficiency displays, fiber optics, lasers.

1.6 PN Junction Diode vs LED

Parameter	PN Junction Diode	LED (Light-Emitting Diode)
Material Used (Type)	Single semiconductor (e.g., Si, GaAs); same material for p and n regions.	Direct bandgap semiconductors (e.g., GaAs, GaN); same or different materials in heterostructures.
Band Gap	Indirect or direct; not optimized for light emission (e.g., Si: indirect).	Direct bandgap for efficient light emission.
Structure	Simple p-n junction with uniform composition.	P-n or heterostructure (e.g., GaAs/AlGaAs) with active region for luminescence.
Carrier Confinement	Moderate; carriers recombine in depletion region.	Strong; confined to active region for radiative recombination.
Optical Confinement	None; not designed for light emission.	Strong; structure enhances light output (e.g., via waveguide or surface design).
Beam Direction	N/A; no significant light emission.	Broad or directional, depending on design (surface or edge-emitting).
Recombination Efficiency	Low; mostly non-radiative recombination.	High; optimized for radiative recombination.
Application	Rectification, switching, signal processing in electronics.	Displays, lighting, optical communication, indicators.

1.7 Optical Band and Electrical Band Differences

Parameter	Optical Band	Electrical Band
Power Gain Drops At	0.5 of its mid value	0.707 of its mid value
Corresponding Value (dB)	3 dB drop at band edges ($10log_{10}(0.5)$)	3 dB ($10log_{10}(0.707^2)$)
Measured Items	Optical power (mW or dBm), signal-to-noise ratio	Voltage, current, power (W or dBm)
Relationship	$\sqrt{2}\times$ Electrical Bandwidth	$\frac{1}{\sqrt{2}}\times$ Optical Bandwidth
Power Dependency	$P_{\text{opt}} \propto I$ (e.g., in optical sources like LEDs)	$P_{\text{electric}} \propto I^2$ (e.g., resistive loads)

1.8 LED and Laser

Parameter	**LED**	**Laser**
Light Source	Incoherent, broad spectrum	Coherent, narrow spectrum
Wavelength Range	850–1300 nm	1310–1550 nm
Bandwidth	Low (50–200 MHz)	High (GHz to THz)
Data Rate	Up to 1 Gbps	10 Gbps and higher
Fiber Type	Multimode	Single-mode or Multimode
Transmission Distance	Short (up to 2 km)	Long (10–100 km)
Power Output	Low (0.1–10 mW)	High (1–100 mW)
Cost	Lower	Higher
Modulation	Simple (on-off keying)	Complex (e.g., QAM, coherent)
Spectral Width	Wide (30–60 nm)	Narrow (0.1–10 nm)
Applications	LAN, short-range systems	Long-haul, high-speed networks
Complexity	Simple setup	Requires precise control

1.9 PN, PIN, Avalanche Photodiode

Parameter	**PN Photodiode**	**PIN Photodiode**	**Avalanche Photodiode (APD)**
Structure	Simple p-n junction	P-type, intrinsic, n-type layers	P-n junction with high-field region
Depletion Region	Narrow	Wide (due to intrinsic layer)	Wide with avalanche multiplication
Response Speed	Moderate (1–10 ns)	Fast (0.1–1 ns)	Very fast (0.1–0.5 ns)
Sensitivity	Low	Moderate	High (due to internal gain)
Gain	No internal gain (M=1)	No internal gain (M=1)	High internal gain (M=10–100)
Noise	Low shot noise	Low shot noise	Higher noise (due to avalanche process)
Bias Voltage	Low (0–5 V)	Moderate (5–50 V)	High (50–200 V)
Bandwidth	Limited (100 MHz–1 GHz)	High (1–10 GHz)	High (1–10 GHz)
Applications	Low-speed, short-range systems	General-purpose, medium-range systems	Long-haul, high-sensitivity systems
Cost	Low	Moderate	High
Power Consumption	Low	Moderate	High (due to high bias voltage)
Quantum Efficiency	Moderate (50–70%)	High (70–90%)	High (70–90%)

1.10 Phase and Group Velocity

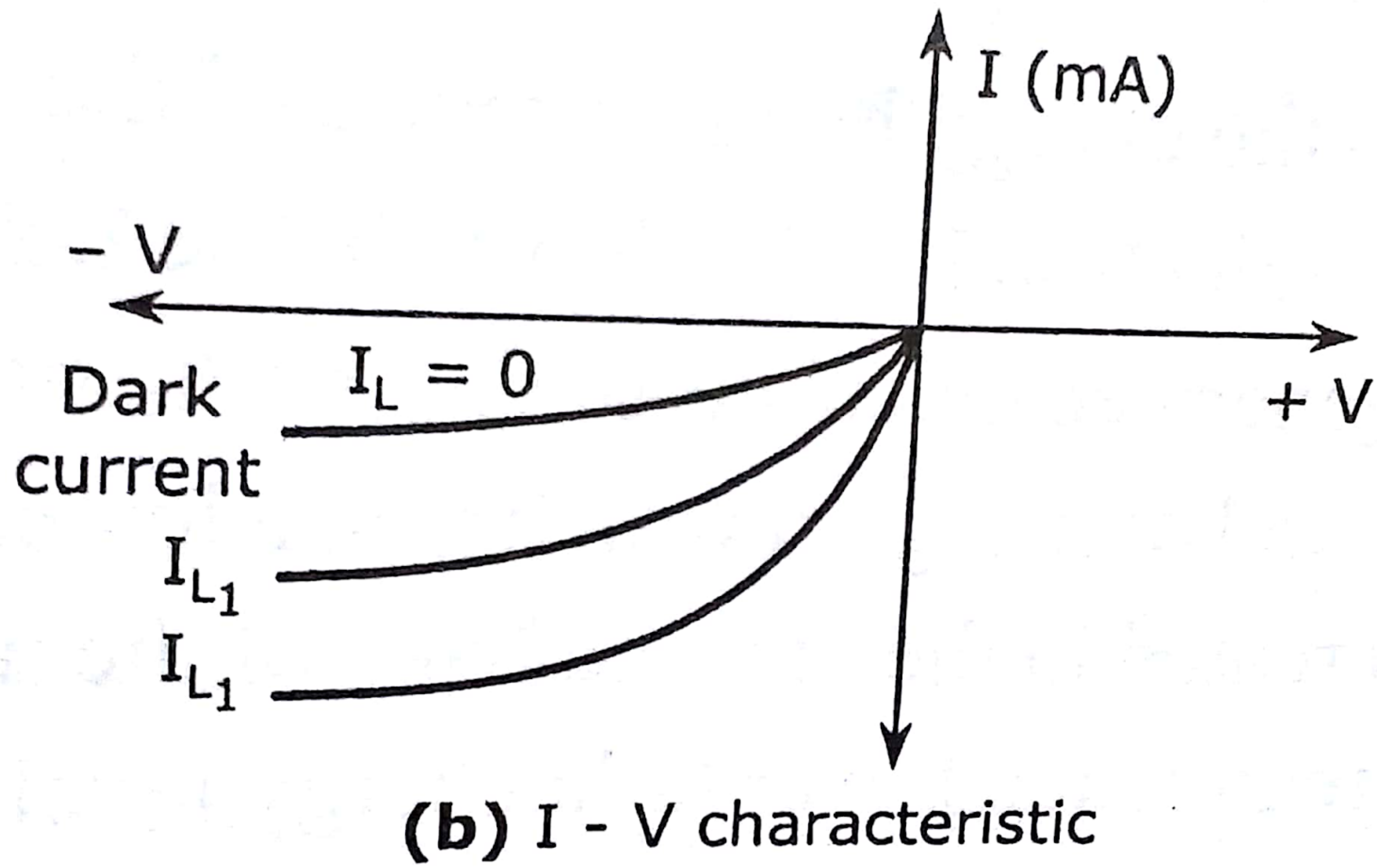
Parameter	Phase Velocity	Group Velocity
Definition	Speed of individual wave phase ($v_p = \frac{\omega}{k}$)	Speed of overall wave packet or signal ($v_g = \frac{d\omega}{dk}$)
Physical Meaning	Rate at which a single frequency component propagates	Rate at which information or energy travels
Relation to Refractive Index	$v_p = \frac{c}{n(\omega)}$, where $n(\omega)$ is the refractive index	$v_g = \frac{c}{n_g}$, where $n_g = n + \omega\frac{dn}{d\omega}$ is the group index
Dispersion Impact	Not affected by dispersion directly	Affected by material and waveguide dispersion, causing pulse broadening
Typical Value in Fiber	2×10^8 m/s (e.g., for silica, $n \approx 1.5$)	Slightly less than v_p, 1.98×10^8 m/s due to $n_g > n$
Role in Optical Fiber	Governs propagation of monochromatic waves	Determines signal transmission speed and data rate
Applications	Relevant for phase-matching in nonlinear optics	Critical for signal integrity, timing, and bandwidth in communication

1.11 CWDM and DWDM

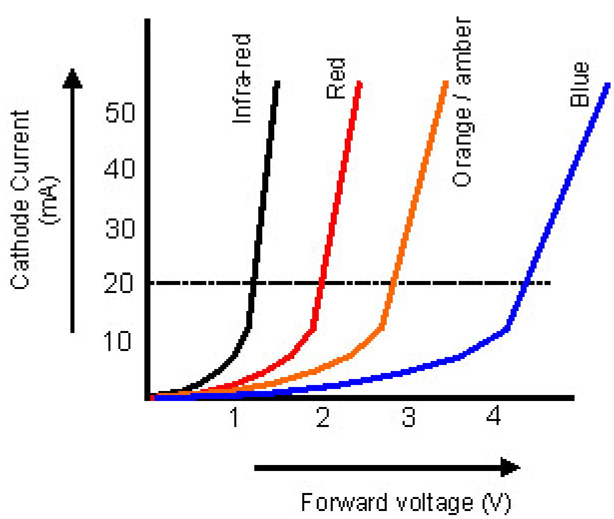
Parameter	CWDM	DWDM
Full Form	Coarse Wavelength Division Multiplexing	Dense Wavelength Division Multiplexing
Definition	A technology that multiplexes multiple optical signals with widely spaced wavelengths onto a single fiber to increase capacity	A technology that multiplexes many closely spaced optical signals onto a single fiber for high-capacity data transmission
Wavelength Spacing	Wide (20 nm)	Narrow (0.4–0.8 nm)
Number of Channels	Up to 18 (1270–1610 nm)	40–80 or more (C-band: 1530–1565 nm)
Transmission Distance	Short to medium (up to 80 km)	Long (100–1000 km with amplification)
Bandwidth per Channel	Lower (up to 10 Gbps)	Higher (10–100 Gbps)
Cost	Lower (simpler components)	Higher (precision components, amplifiers)
Laser Requirements	Uncooled lasers (less precise)	Cooled, high-precision lasers
Amplification	Limited (no EDFA support)	Supports EDFA for long distances
Applications	Metro networks, access networks	Long-haul, high-capacity networks

2 Graphs

2.1 IV Photodiode



2.2 IV LED



2.3 Attenuation

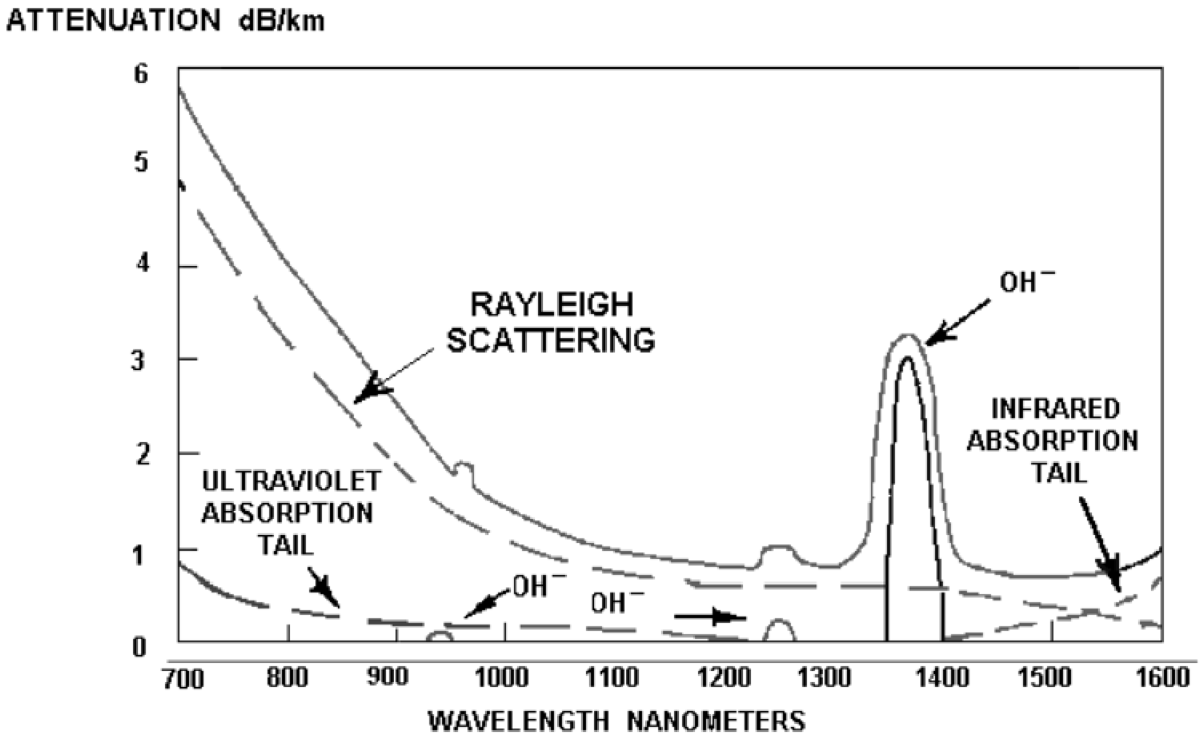


Figure 2-21.—Fiber losses.

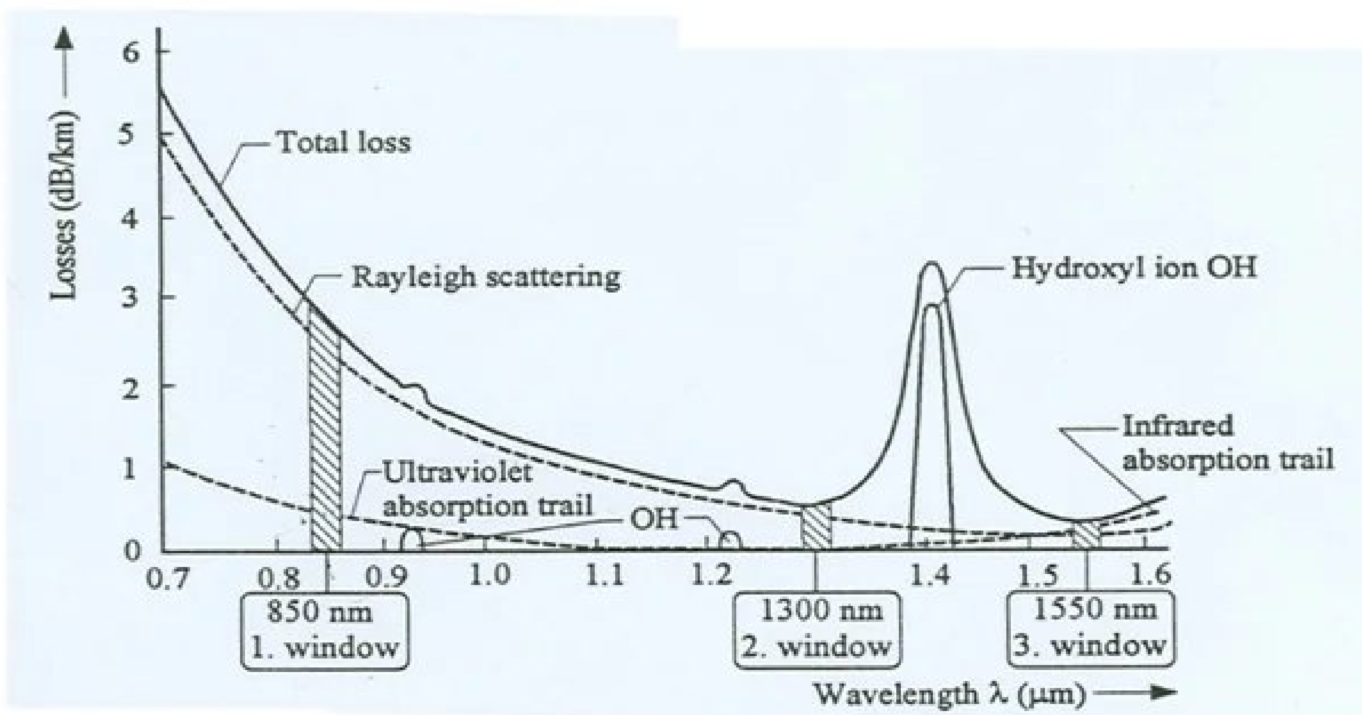
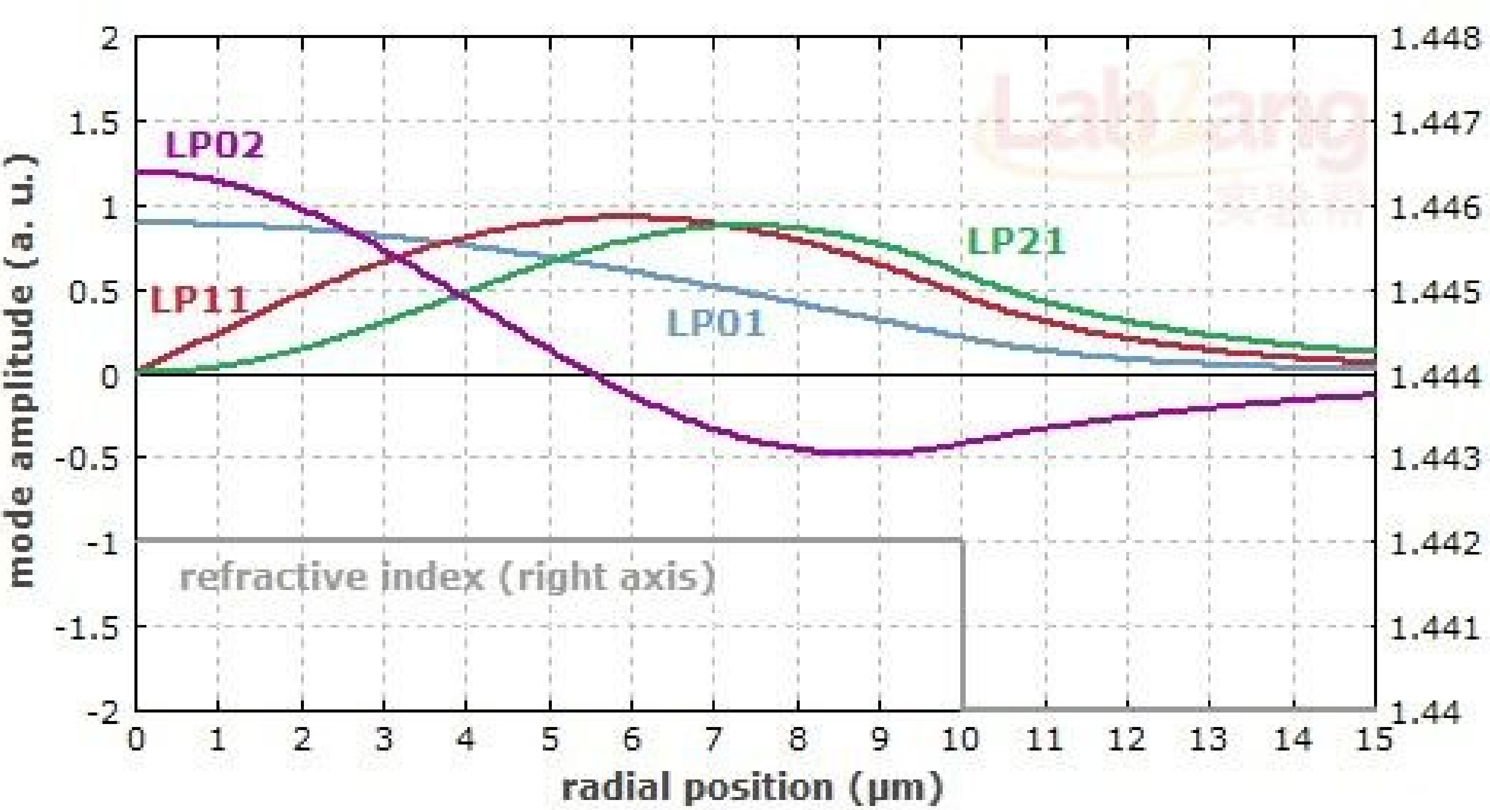
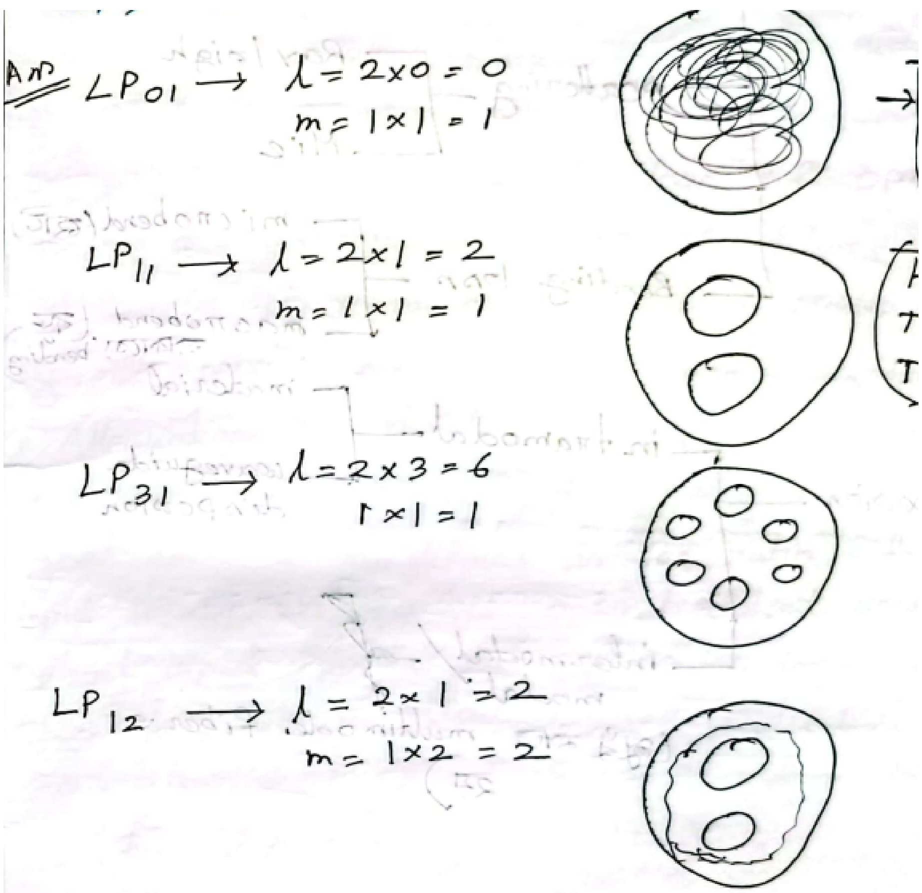


Figure 8- Optical communication windows

2.4 Detect LP



2.5 LP



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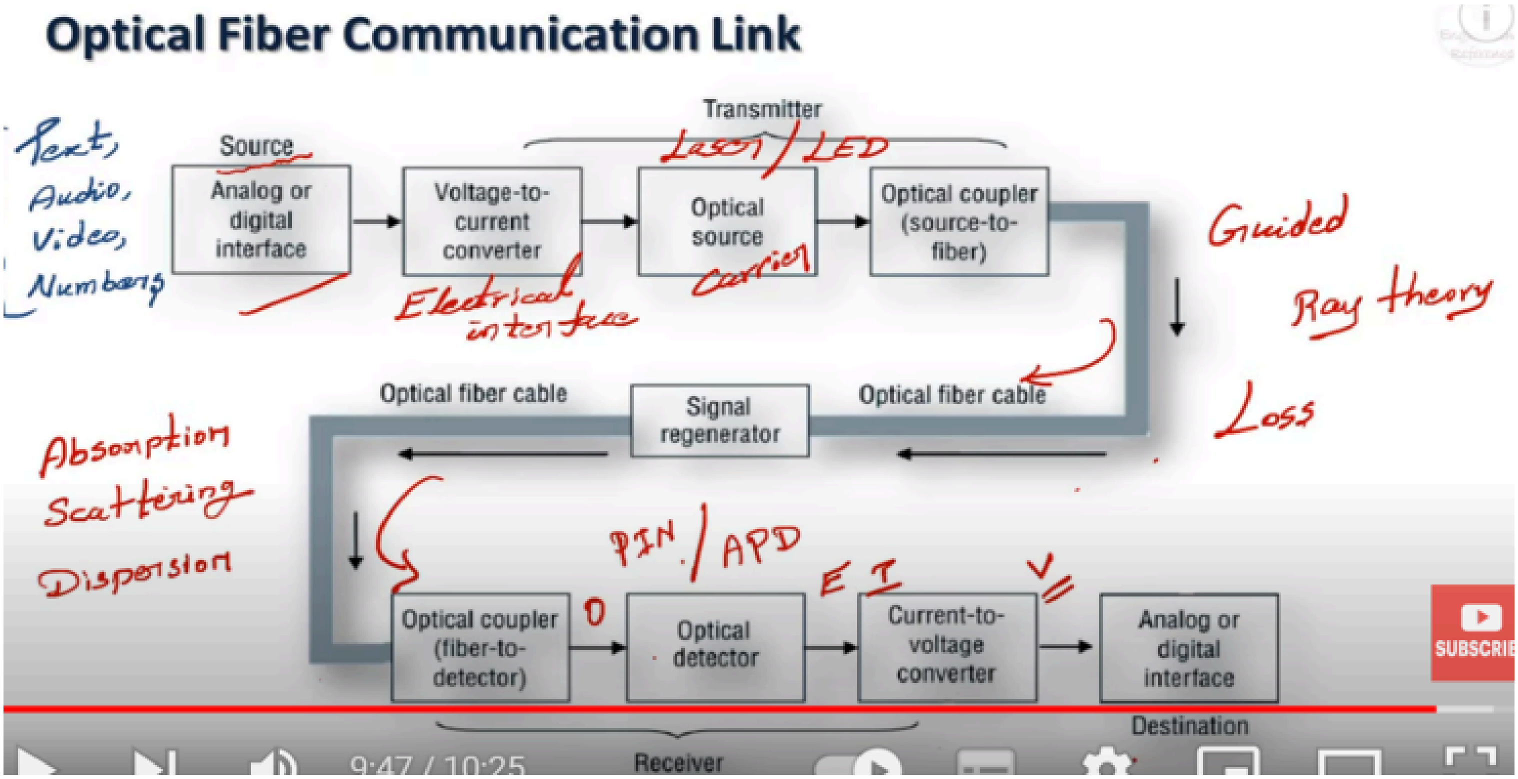
2.6 Optical Fiber Communication Diagram



3 Working Principle

3.1 LED

Step	Description
P-N Junction	LED has a p-n junction with p-type (hole-rich) and n-type (electron-rich) materials.
Forward Bias	Forward voltage pushes electrons (n-side) and holes (p-side) toward the junction.
Carrier Recombination	Electrons and holes recombine in the depletion region, releasing energy.
Light Emission	Energy released as photons via electroluminescence, based on bandgap E_g.
Wavelength	Light wavelength given by $\lambda = \frac{hc}{E_g}$, typically 850–1300 nm.
Light Coupling	Emitted light coupled into optical fiber using lenses or direct attachment.
Data Modulation	Light modulated (e.g., on-off keying) by varying current to encode data.

3.2 Preform Fabrication

Uses Chemical Vapor Deposition (CVD), specifically Inside Vapor Deposition.

Parameter	Description
Step 1: Substrate	Rotate a hollow glass tube (40 cm) in a lathe as the substrate.
Step 2: Material Injection	Inject $SiCl_4 + O_2$ and dopants (e.g., GeCl) into the tube.
Step 3: Soot Formation	Heat with a hydrogen burner (1600°C) to form SiO soot particles.
Step 4: Soot Deposition	Soot deposits on the tube's inner surface, building layers.
Step 5: Core vs. Cladding	Core: Doped SiO_2 (Ge, Al, P, Ti, higher RI); Cladding: Pure SiO or doped (F, B, lower RI).
Step 6: Collapse	Heat to 2000°C to collapse the tube into a solid preform rod.

3.3 Fiber Drawing Process

raws the preform into a thin fiber for optical communication.

Parameter	Description
Step 1: Drawing Tower	Place preform in a drawing tower.
Step 2: Softening	Heat preform tip (2000 degree C) with a gas burner or graphite heater to soften.
Step 3: Fiber Pulling	Pull softened glass into a thin fiber (125 µm diameter).
Step 4: Diameter Control	Use a Diameter Monitor to maintain 125 µm, adjusting pulling speed.
Step 5: Coating	Apply UV-curable polymer coating to protect the fiber.
Step 6: Curing	Cure coating with UV light.
Step 7: Tension Control	Use a Capstan to control pulling speed and tension.
Step 8: Winding	Wind the fiber onto a Take-up Reel.

3.4 Laser

Step	Description
Stimulated Emission	The core process of light generation. Electrons in a semiconductor (e.g., GaAs) absorb energy via electrical pumping, exciting them to a higher energy state (conduction band). *Spontaneous emission* occurs when electrons drop to a lower energy state, emitting random photons. *Stimulated emission* happens when an incoming photon of specific wavelength (λ) triggers an excited electron to drop, emitting a coherent photon with the same λ, phase, and direction. This produces the laser's coherent light, critical for high-speed optical fiber communication.
Population Inversion	Achieved by injecting a high current into the p-n junction, creating more electrons in the higher energy state than in the lower state, unlike thermal equilibrium. This inversion ensures stimulated emission dominates over absorption, amplifying the light output. In optical fibers, this enables high-intensity, narrow-spectrum light (e.g., 1310–1550 nm) for long-distance transmission.
Resonant Cavity (Fabry-Perot)	The laser's optical cavity, typically a Fabry-Perot resonator, consists of two parallel mirrors (cleaved facets of the semiconductor). Photons bounce between mirrors, stimulating further emissions and amplifying light at specific wavelengths ($\lambda = \frac{hc}{E_g}$). The Fabry-Perot cavity selects resonant modes, ensuring a narrow linewidth for coherence. Light exits one partially reflective mirror, coupled into the fiber for data transmission with modulation (e.g., QAM).