PROGRESSIVE EDUCATION SOCIETY'S
MODERN COLLEGE OF ENGINEERING, PUNE
(An Autonomous Institute Affiliated to Savitribai Phule Pune University)

Department of First Year B.Tech.

Unit – 6: Lasers and Fiber Optics

Importance of Lasers and Fiber Optics in Engineering

Lasers and fiber optics are transformative technologies with profound importance in engineering, revolutionizing communication, manufacturing, healthcare, and beyond. Lasers provide precise and controlled beams of light, enabling applications such as cutting, welding, and 3D printing in manufacturing, as well as advanced techniques in surveying and metrology. They are crucial in healthcare for surgeries, diagnostics, and treatments like laser eye correction and cancer therapy. Fiber optics, on the other hand, form the backbone of modern communication networks, enabling high-speed, long-distance data transmission with minimal signal loss. This technology powers the internet, telecommunications, and cable TV systems. In addition, fiber optics are vital in sensors for monitoring structural health in bridges, aircraft, and buildings. Together, lasers and fiber optics drive innovation, offering efficiency, precision, and reliability across diverse engineering disciplines.

Subtopics in Unit – 6

Lasers and Fiber Optics	**6.1. Basics of lasers** *6.1.1. Understanding light* *6.1.2. What is a laser?* *6.1.3. Properties of a laser* **6.2. Basic mechanism of a laser** *6.2.1. Essential components of a laser* *6.2.2. Working principle of a lasr* *6.2.3. Population inversion* **6.3. Types of lasers** **6.4. Ruby laser** **6.5. Applications of laser** **6.6. Introduction to fiber optics** **6.7. What are optical fibers?** *6.7.1. Propagation mechanism in an optical fiber* *6.7.2. Optical fiber parameters* **6.8. Types of optical fibers** **6.9. Advantages of optical fiber communication over conventional** **6.10. Applications of optical fibers in medical field: Endoscopy**

Lasers

6.1. Basics of Lasers

6.1.1 Understanding Light

Light is a form of energy emitted by atoms and is composed of tiny particles called photons. Atoms, the fundamental units of matter, consist of a central nucleus surrounded by electrons orbiting in defined paths.

The nucleus is held together by strong nuclear forces between positively charged protons and neutral neutrons. Due to the positive charge of protons and the neutrality of neutrons, the nucleus as a whole carries a positive charge. Negatively charged electrons are drawn to the nucleus by electrostatic forces, causing them to orbit at varying distances, each corresponding to a distinct energy level. Electrons in orbits farther from the nucleus possess higher energy, while those closer have lower energy. To transition to a higher energy level, electrons must absorb additional energy, which can be supplied by heat, electric fields, or light.

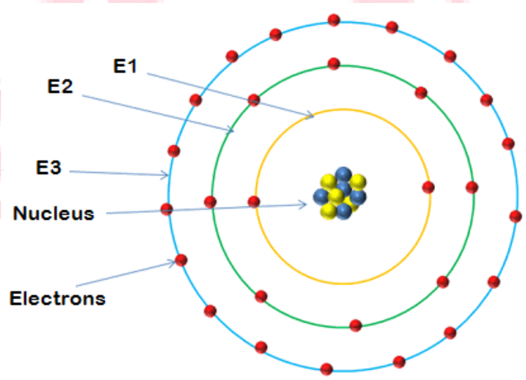

Figure 6.1. Structure of an atom.[1]

Light exhibits both wave-like and particle-like behavior, a duality recognized through Einstein's description of photons as particles whose flow constitutes a wave. Sources of light include natural ones like the sun and artificial ones such as candles and electric lamps. Man-made light sources, like incandescent bulbs, emit visible light when an electric current heats a filament to a high temperature, a breakthrough achieved by Thomas Edison in 1879. This combination of physical properties and diverse origins underpins light's versatility and its technological applications.

6.1.2 What is a Laser?

Laser stands for **Light Amplification by Stimulated Emission of Radiation**. A laser is a device that amplifies light by increasing its intensity and also generates highly directional light. Some lasers generate visible light but others generate ultraviolet or infrared rays which are invisible.Unlike ordinary light sources, lasers produce a coherent, monochromatic, and highly directional beam of light. This is achieved through a process called stimulated emission, which was first theorized by Albert Einstein in 1917. Lasers differ fundamentally from conventional light sources due to their ability to amplify light and produce an intense, well-defined beam. This makes lasers suitable for precision tasks in science, medicine, communication, and industry.

When an electron transitions from a higher energy level to a lower one, it emits light or a photon. The energy of the emitted photon corresponds to the energy difference between the levels. This loss of energy is attributed to the entire atom, so it can be viewed as the atom moving from a higher to a lower energy state.

Laser light differs from conventional light in several ways. Unlike ordinary light sources like the sun or incandescent lamps, lasers exhibit extraordinary properties not found in these sources. Conventional light sources, such as electric bulbs or tube lights, emit light in multiple directions and without coherence, whereas lasers produce highly directional, monochromatic, coherent, and polarized beams of light. In conventional light sources, excited electrons emit photons at different times and in different directions, leading to a lack of phase coherence between them. In contrast, the photons emitted by laser electrons are in the same phase and travel in the same direction.

In 1917, Einstein laid the theoretical foundation for the development of lasers by predicting the possibility of stimulated emission. In 1954, C.H. Townes and his colleagues made Einstein's prediction a reality by developing a microwave amplifier based on stimulated emission, known as a MASER (Microwave Amplification by Stimulated Emission of Radiation). While the maser operates on principles similar to a laser, it generates microwaves rather than light. In 1958, C.H. Townes and A. Schawlow expanded the maser concept to include light, and in 1960, T.H. Maiman constructed the first working laser device.

6.1.3 Properties of a Laser

1. Monochromaticity: A laser emits light of a single wavelength (or color), unlike ordinary light, which contains multiple wavelengths.

2. Coherence: The light waves in a laser are highly coherent, meaning the waves are in phase both spatially and temporally. This coherence is critical for applications requiring precision.

3. Directionality: Laser beams are highly directional, producing a narrow, focused beam that spreads minimally over long distances.

4. High Intensity: Lasers can concentrate a significant amount of energy into a small area, resulting in a high intensity that is suitable for cutting, welding, and medical applications.

6.2. Basic Mechanism of a Laser

6.2.1. Essential Components of a Laser

1. Active Medium:
   - The material where the laser action takes place (e.g., gas, liquid, solid, or semiconductor).
   - Examples: Ruby crystal (solid), CO_2 (gas), or Nd:YAG (solid).
2. Energy Source (Pump):
   - Provides energy to excite electrons in the active medium.
   - Methods include:
     - Optical pumping (light sources such as flash lamps).

- Electrical pumping (electric discharge).
- Chemical reactions.

3. Optical Cavity (Optical Resonator):
   - Composed of two mirrors surrounding the active medium:
     - Fully Reflective Mirror: Reflects all the light.
     - Partially Reflective Mirror: Allows a fraction of the light to exit as the laser beam.

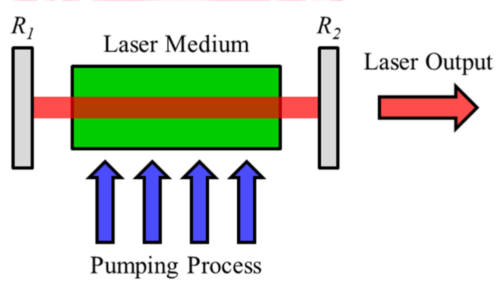

Figure 6.2. Components of a laser.[2]

6.2.2 Working Principle of a Laser

In lasers, photons interact with atoms in three main ways:

1. Absorption of Radiation
2. Spontaneous Emission
3. Stimulated Emission

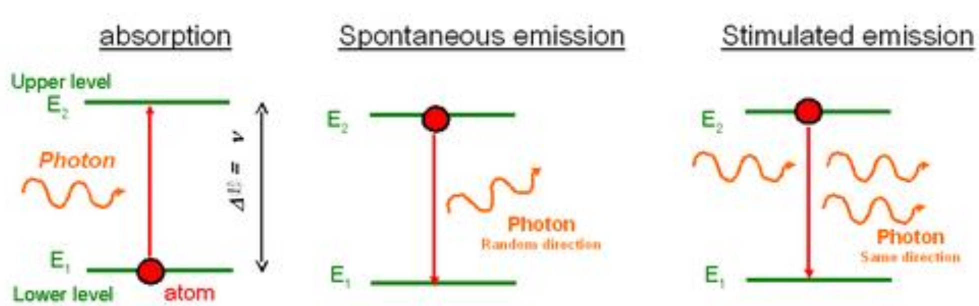

Figure 6.3. Illustration of ways in which photons interact with atoms.[2]

1. Absorption of Radiation

This process occurs when electrons in an atom's lower energy state absorb energy from photons and jump to a higher energy state.

- Energy Levels: Electrons close to the nucleus are in a low-energy state, while those farther away are in a high-energy state. Electrons need additional energy to move from a lower energy level to a higher one. This energy can come from heat, an electric field, or light.
- How It Works: Consider two energy levels, E_1 (lower energy level) and E_2 (higher energy level). When a photon with energy equal to the difference between these levels ($E_2 - E_1$) hits an atom, the electron in the lower energy level absorbs this energy and transitions to the higher energy level.
- Condition for Absorption: Absorption happens only if the energy of the incoming photon matches the energy gap between the two levels ($E_2 - E_1 = h\nu$).

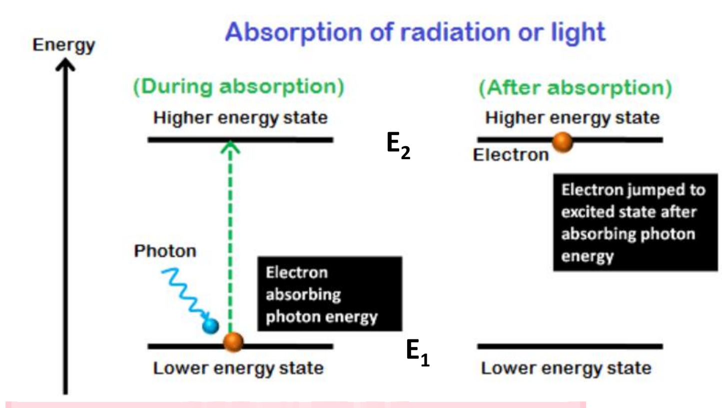

Figure 6.4. Process of absorption of radiation or light.[1]

2. Spontaneous Emission

Spontaneous emission is the natural process by which electrons in a higher energy state (excited state) return to a lower energy state (ground state) by releasing energy in the form of photons.

- Excited State and Lifetime: When an electron is in the excited state, it cannot remain there indefinitely. The duration an electron can stay in this state is called its lifetime, which is extremely short—approximately 10^{-8} seconds. Once this brief period ends, the electron transitions back to the ground state, releasing a photon.

- Uncontrolled Process: In spontaneous emission, the transition from the excited state to the ground state happens naturally, without external influence. This means we cannot predict or control when an excited electron will emit a photon.
- Nature of Emitted Light: The photons released during spontaneous emission form incoherent light. Incoherent light consists of photons that have random directions and phases. Unlike a laser beam, these photons do not travel in a uniform direction or with a consistent phase relationship.

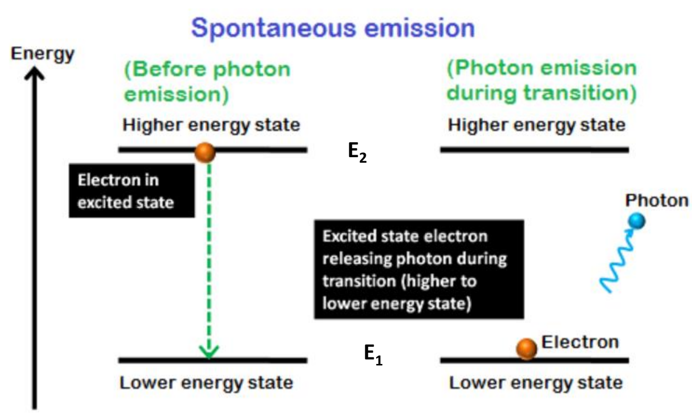

Figure 6.5. Process of spontaneous emission.[1]

3. Stimulated Emission

Stimulated emission is a key process in quantum mechanics where an incoming photon interacts with an excited electron, prompting the electron to return to a lower energy level (ground state). As the electron transitions, it releases its energy into the electromagnetic field, generating a new photon. Importantly, this newly emitted photon is identical to the incoming photon in frequency, polarization, phase, and direction. This unique property of stimulated emission forms the foundation of lasers.

Comparison to Spontaneous Emission

- **Spontaneous Emission**: In spontaneous emission, electrons in an excited state naturally return to the ground state after a brief lifetime (around 10^{-8} seconds). This occurs without any external influence. The photon emitted during this process has the same energy as the energy difference between the excited and ground states but is emitted in a random direction with varying phase relationships. The resulting light is incoherent, meaning the photons are not synchronized in phase or direction.
- **Stimulated Emission**: Stimulated emission, unlike spontaneous emission, is an induced process. An external photon interacts with an excited electron, causing the electron to release energy and emit a photon before the natural lifetime of the excited state ends.

Properties of Emitted Photons:

All photons produced in stimulated emission are identical:

- Same energy
- Same frequency
- In phase (oscillating together)
- Traveling in the same direction

This makes the light produced coherent and is the foundation of laser light.

Mechanism of Stimulated Emission

1. **Excited State and External Photon**:
   - Electrons in an atom or molecule absorb energy and move to a higher energy level (excited state).
   - A photon with energy equal to the difference between the excited and ground states ($E_2 - E_1$) interacts with the excited electron.
2. **Forced Transition**:
   - The external photon "stimulates" the electron to drop to the lower energy level, releasing energy as a photon.

3. **Emission of Identical Photon**:
   - The emitted photon is identical to the stimulating photon in energy, direction, phase, and polarization.

For stimulated emission to take place, the necessary condition is that $N_2>N_1$, where N_1 is the charge population in E_1 state, and N_2 is the charge population in E_2 state. Therefore, we need something called population inversion to happen, which is a key factor for lasing action to occur.

6.2.3 Population Inversion

Definition: Population inversion is a condition where the number of electrons in a higher energy state exceeds the number of electrons in a lower energy state. This is a crucial requirement for laser operation, as it allows stimulated emission to dominate over absorption.

Population Inversion is achieved through pumping: External energy is supplied to excite electrons to higher energy levels. Methods include optical, electrical, and chemical pumping.

Metastable State

Definition:

- A metastable state is an excited state of an atom or molecule where electrons have a longer lifetime compared to other excited states.
- Typical lifetime: ~10^{-3} seconds (much longer than typical excited states, which are ~10^{-8} seconds).

Need for Metastable State:

- Provides sufficient time for electrons to accumulate in the excited state.
- Facilitates achieving population inversion, as electrons can "wait" in this state until stimulated emission occurs.

Evolution to Three-Level and Four-Level Lasers

1. **Three-Level Laser**:
   - Introduced to address the limitations of two-level systems.
   - **Mechanism**:
     - Electrons are pumped from the ground state (E1) to a higher energy state (E3).
     - They quickly decay non-radiatively to a metastable state (E2).
     - Stimulated emission occurs as electrons transition from E2 to E1.
   - **Challenge**:
     - Requires intense pumping to depopulate the ground state (E1).
     - Less efficient as the ground state is heavily populated.
   - **Example**: Ruby Laser.

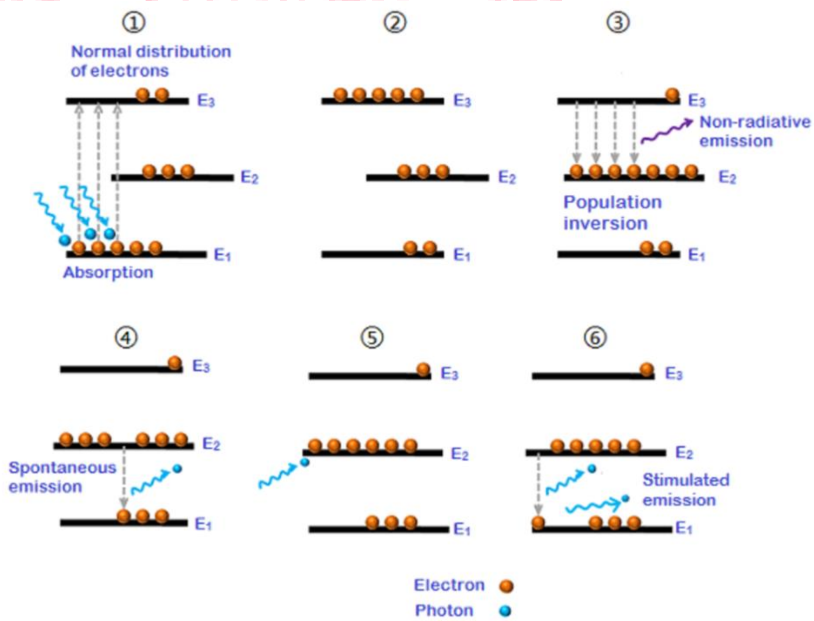

Figure 6.6. A 3-level laser diagram.[1]

2. **Four-Level Laser**:
   - Developed to overcome the inefficiencies of three-level systems.
   - **Mechanism**:

- Electrons are pumped from the ground state (E0) to a higher energy state (E3).
- They decay non-radiatively to a metastable state (E2).
- Stimulated emission occurs as electrons transition from E2 to a lower intermediate state (E1).
- E1 quickly decays to the ground state (E0), ensuring minimal population at E1.

- **Advantage**:
  - Easier to achieve population inversion as E1 remains nearly empty.
  - More efficient than three-level lasers.
- **Examples**: Nd:YAG Laser, CO2 Laser.

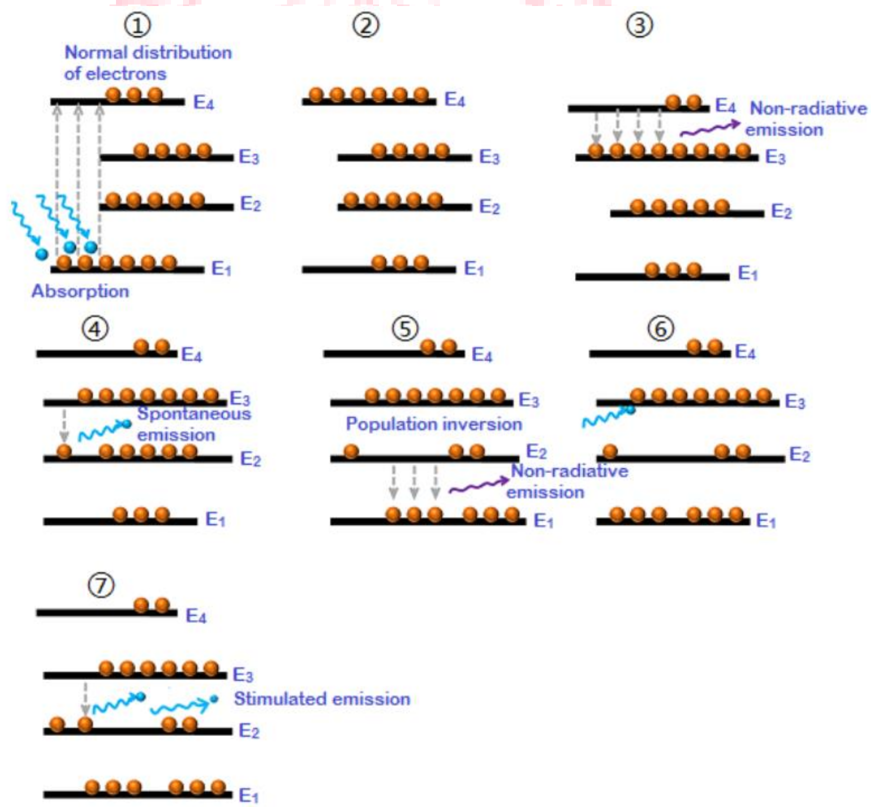

Figure 6.7. A 4-level laser diagram.[1]

3. **Higher-Level Lasers**:
   - Used in advanced laser systems for specific applications.
   - Allow multiple energy levels to enhance flexibility and efficiency in achieving population inversion.
   - **Example**: Dye Lasers (tunable lasers).

6.3. Types of Laser

Table 6.1. A comprehensive summary of types of laser.

Type	Medium	Key Applications	Unique Feature	Working Principle
Solid-State	Crystal (e.g., Ruby, Nd:YAG)	Surgery, endoscopy, cutting, holography, tattoo removal	High energy output	Photon amplification in doped crystals by optical pumping.
Gas	Gas (e.g., He-Ne, CO_2)	Alignment, barcode scanning, industrial cutting, engraving, skin resurfacing	Stable and precise	Electric current excites gas atoms to emit coherent light.
Semiconductor	Laser diodes, GaAs, AlGaInP, VCSELs (Vertical-Cavity Surface-Emitting Lasers)	Electronics, pointers, data transmission, 3D sensing	Compact and cost-effective	Photon emission from electron-hole recombination in diodes.
Dye	Liquid dye	Dermatology, spectroscopy	Tunable wavelength	Pump light excites dye molecules to emit variable light.
Fiber	Doped optical fiber	Telecom, materials	Energy-efficient and robust	Amplified photon emission in doped optical fibers.

6.4. Ruby Laser

A ruby laser is a type of solid-state laser that employs a synthetic ruby crystal as its lasing medium. It holds historical significance as the first successful laser, developed by Theodore Maiman in 1960.

The ruby laser is notable for being one of the few solid-state lasers capable of producing visible light, emitting a deep red beam with a wavelength of 694.3 nm.

Construction of ruby laser

A ruby laser consists of three important elements: laser medium, the pump source, and the optical resonator.

Laser medium or gain medium in ruby laser

In a ruby laser, a single crystal of ruby ($Al_2O_3 : Cr^{3+}$) in the form of cylinder acts as a laser medium or active medium. The laser medium (ruby) in the ruby laser is made of the host of sapphire (Al_2O_3) which is doped with small amounts of chromium ions (Cr^{3+}). The ruby has good thermal properties.

Pump source or energy source in ruby laser

The pump source in a ruby laser system is responsible for providing energy to the laser medium. In a ruby laser, achieving population inversion is essential for laser emission. Population inversion refers to the condition where the number of electrons in the higher energy state exceeds those in the lower energy state. To create this state, energy must be supplied to the laser medium (ruby).

In a ruby laser, a flashtube is used as the pump source. The flashtube supplies the necessary energy to the laser medium. When electrons in the lower energy state of the ruby medium absorb this energy, they transition to a higher energy state or excited state.

Optical Resonator

The ends of the cylindrical ruby rod are flat and parallel, and the rod is positioned between two mirrors. These mirrors are coated with an optical layer to enhance their reflective properties. The process of applying thin metal layers to glass substrates to create reflective surfaces is known as silvering. Each mirror is coated differently to serve a specific purpose.

One end of the rod features a fully silvered mirror that completely reflects light. The other end has a partially silvered mirror, which reflects most of the light but allows a small portion to pass through, producing the output laser beam.

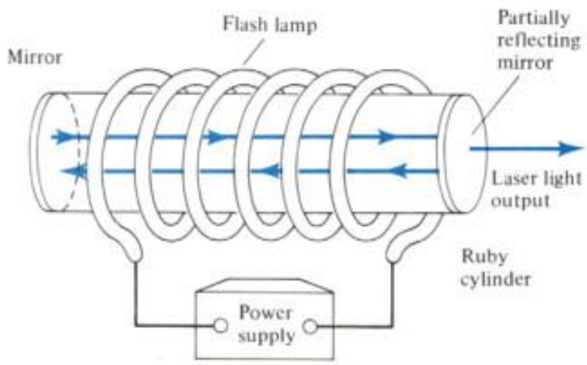

Figure 6.8. Ruby laser diagram.[3]

Working of Ruby Laser

The ruby laser is a three-level solid-state laser that employs the optical pumping technique to supply energy to the laser medium. Optical pumping uses light as an energy source to excite electrons from a lower energy level to a higher energy level.

In a ruby laser medium, there are three energy levels: E1, E2, and E3, with N electrons distributed among them.

- E1 (ground state or lower energy state): The lowest energy level.
- E2 (metastable state): An intermediate energy level with a longer electron lifetime.
- E3 (pump state): The highest energy level, where electrons are initially excited.

At the start, most of the electrons reside in the ground state (E1), while only a small fraction occupy the higher energy levels (E2 and E3).

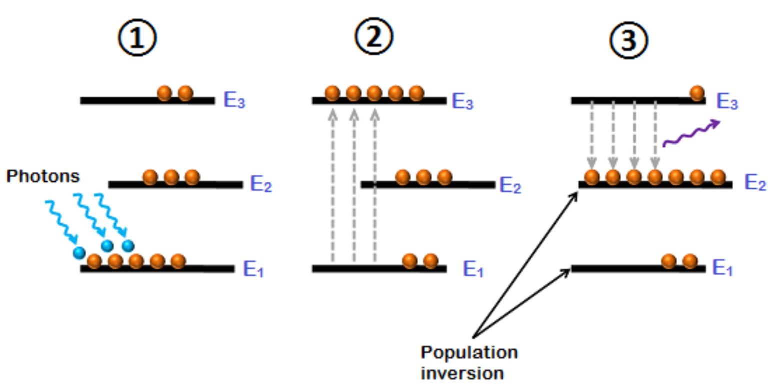

Figure 6.9. Pumping in ruby laser.[1]

When light energy is supplied to the laser medium (ruby), electrons in the lower energy state, or ground state (E1), absorb this energy and jump to a higher energy level known as the pump state (E3).

The pump state's lifetime (E3) is extremely short, approximately 10^{-8} seconds, so electrons quickly transition to a lower energy level called the metastable state (E2), releasing energy without emitting radiation. The metastable state has a significantly longer lifetime, about 10^{-3} seconds, which allows electrons to accumulate there faster than they leave. This accumulation creates a condition known as population inversion, where more electrons occupy the metastable state than the ground state.

After some time, electrons in the metastable state (E2) return to the ground state (E1), releasing energy in the form of photons through a process called spontaneous emission. These emitted photons can interact with other electrons in the metastable state, triggering them to fall to the ground state and release additional photons. This process is called stimulated emission, and it results in the emission of two photons.

When these photons interact further with electrons in the metastable state, the number of photons multiplies, leading to the generation of millions of photons through continuous interactions.

In the active medium (ruby), spontaneous emission generates initial light. This light reflects back and forth between two mirrors, stimulating more electrons to transition to the ground state and emit additional photons. This process of stimulated emission amplifies the light.

Finally, the amplified light escapes through a partially reflecting mirror, producing the coherent and intense beam known as laser light.

6.5 Applications of Laser

1. Holography

- **Definition:** Holography is a photographic technique that records and reconstructs light wavefronts to create 3D images, using the principle: interference and diffraction. It consists of two steps: recording and reconstruction.

- **Process:**
    1. A laser beam is split into two parts: the object beam and the reference beam.
    2. The object beam illuminates the object, and its reflected light interferes with the reference beam.
    3. The interference pattern (hologram) is recorded on a photographic plate.
    4. A laser beam reconstructs (diffraction) the 3D holographic image.

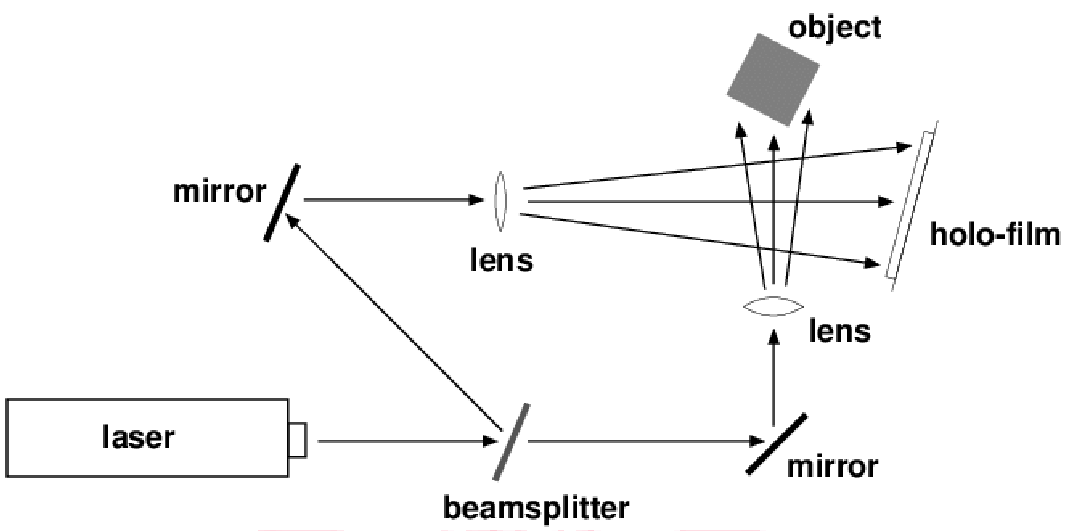

Figure 6.10. Hologram recording layout.[4]

- **Lasers Used:** Helium-Neon (He-Ne) lasers (wavelength: 632.8 nm) and diode lasers.
- **Examples:** Security holograms on passports, credit cards.

2. Cutting

- **Definition:** Laser cutting is a thermal process where a focused laser beam melts or vaporizes material to create precise cuts.
- **Process:**
    1. A high-powered laser beam is directed onto the material.
    2. The material absorbs the laser energy, heating up and melting/vaporizing.

3. A jet of gas (e.g., oxygen, nitrogen) removes the molten material, creating a clean cut.

- **Lasers Used:** CO_2 lasers (power: 500 W–10 kW), Fiber lasers (1–12 kW), Nd:YAG lasers.
- **Examples:** Cutting steel for automobile parts, precision cutting in jewelry making.

3. Drilling

- **Definition:** Laser drilling is a process of creating holes by melting and vaporizing material using a laser.
- **Process:**
  1. A pulsed laser beam focuses on the material's surface.
  2. The intense heat melts and vaporizes the material to create a hole.
  3. Successive pulses deepen the hole as required.
- **Lasers Used:** Nd:YAG lasers, Fiber lasers (pulse duration: 10–100 ns).
- **Examples:** Drilling micro-holes in turbine blades, medical implants.

4. Micromachining

- **Definition:** Micromachining uses lasers to manufacture tiny, precise components at the micron level.
- **Process:**
  1. A highly focused laser beam ablates material layer by layer.
  2. Patterns or structures are created with sub-micron precision.
- **Lasers Used:** Excimer lasers (wavelength: 193–308 nm), Femtosecond lasers (pulse duration: <10 fs).
- **Examples:** Microfluidic devices, etching circuits on silicon wafers.

5. Medical Applications

- **Definition:** Lasers are used for diagnostic, therapeutic, and surgical procedures in medicine.
- **Processes and Lasers Used:**
    - **Surgery:** High-power CO_2 lasers (10.6 µm) for tumor removal and LASIK surgeries.
    - **Dermatology:** Nd:YAG lasers (1064 nm) for skin resurfacing, tattoo removal.
    - **Dentistry:** Erbium lasers (2940 nm) for cavity preparation.
    - **Cancer Treatment:** Diode lasers (810 nm) for photodynamic therapy.
- **Examples:** LASIK surgery for vision correction, laser ablation of tumors.

6. Optical Fiber Communication

- **Definition:** Lasers are used to transmit data over long distances through optical fibers.
- **Process:**
    1. A laser generates light pulses representing binary data.
    2. The light travels through optical fibers, undergoing minimal loss.
    3. Detectors at the receiving end convert light back into electrical signals.
- **Lasers Used:** Semiconductor lasers, Distributed Feedback (DFB) lasers (wavelength: 1.3–1.55 µm).
- **Examples:** Internet connectivity, submarine fiber-optic cables.

Table 6.2. A comprehensive summary of applications of laser.

Application	Definition	Process	Laser Type	Examples
Holography	3D imaging using interference of light waves	Beam splitting, interference pattern recording, reconstruction	Helium-Neon (632.8 nm), Diode lasers	Security holograms on passports, credit cards
Cutting	Precision cutting by melting/vaporizing material	Focused beam heats material, gas jet removes molten material	CO_2 lasers (500 W–10 kW), Fiber lasers (1–12 kW)	Cutting steel, intricate designs in jewelry
Drilling	Creating holes via thermal melting and vaporization	Pulsed laser heats material, vaporizes to form holes	Nd:YAG lasers, Fiber lasers	Micro-holes in turbine blades, PCB drilling
Micromachining	Precision manufacturing of tiny components	Layer-by-layer ablation with sub-micron precision	Excimer lasers (193–308 nm), Femtosecond lasers	Microfluidic devices, watch components
Medical Applications	Use of lasers for surgical and diagnostic purposes	Cutting, ablation, coagulation, and resurfacing	CO_2 (10.6 µm), Nd:YAG (1064 nm), Diode lasers	LASIK, tumor ablation, tattoo removal
Optical Fiber Communication	Data transmission using light through optical fibers	Light pulses represent data, transmitted with minimal loss	DFB lasers (1.3–1.55 µm), Semiconductor lasers	Internet, submarine communication cables

Fiber Optics

6.6. Introduction to Fiber Optics

Fiber optics refers to the technology of transmitting information as light pulses through flexible, transparent fibers made of glass or plastic. This innovation revolutionized data transmission by enabling high-speed, high-capacity communication over long distances with minimal loss.

The core principle of fiber optics is total internal reflection, a phenomenon where light traveling within the fiber is confined and guided along the length of the fiber, even if it bends or twists.

6.7. What are Optical Fibers?

Optical fibers are the wires and strands made of transparent dielectrics such as glass or plastic which guide light over longer distances using the phenomenon of Total Internal Reflection (TIR).

An optical fiber consists of two main parts:

1. **Core**: The central region where light is transmitted. It is made of highly pure glass or plastic. The refractive index of the core typically ranges from **1.48 to 1.50**.
2. **Cladding**: Surrounds the core and has a lower refractive index (e.g., **1.46 to 1.48**) to enable total internal reflection. The core always has a higher refractive index than the cladding.

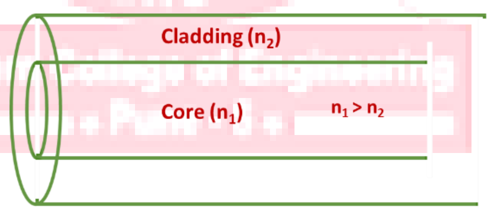

Figure 6.11. Main components of an optical fiber.

Modern optical fibers are categorized based on their applications, structures, and modes of light propagation. They are widely used in telecommunications, medical imaging, and sensors.

6.7.1 Propagation Mechanism in an Optical Fiber

The basic principle of light propagation in an optical fiber is total internal reflection (TIR).

Total internal reflection

Consider a ray of light moving from a denser medium to rarer medium. As a result the incident ray of light bends away from the normal. Hence the angle of refraction is greater than the angle of incidence. As the angle of incidence increases the angle of refraction also increases. For a particular angle of incidence θ the refracted ray grazes the interface separating the two media. The corresponding angle of incidence θ is called Critical Angle (θ_c). If the angle of incidence is greater than the critical angle then all the light is turned back into the same medium and is called Total Internal Reflection.

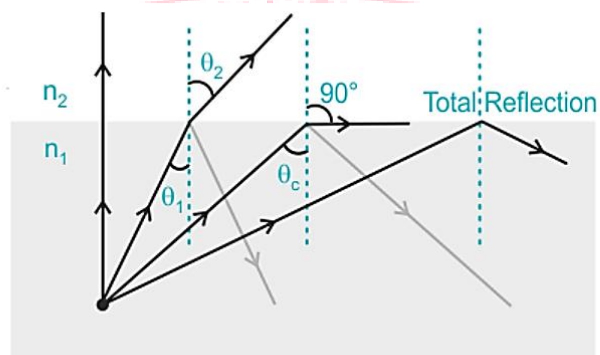

Figure 6.12. Illustration of TIR.[5]

For an optical fiber, consider a ray of light propagate from medium of refractive index of denser medium of n_1 to refractive index of rarer medium n_2. Let θ_1 be the angle of incidence and θ_2 be the angle of refraction, then From Snell's law:

$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

For total reflection, angle of incidence = critical angle (θ_c) and $\theta_2 = 90°$

$$\therefore n_1 \sin\theta_c = n_2 \sin 90°$$

$$\therefore \theta_c = \sin^{-1} (n_2/ n_1)$$

Propagation of light: Angle of acceptance and Numerical aperture

Acceptance angle (θ_0) is the maximum angle of incidence with which the ray is sent into the fiber core which allows the incident light to be guided by the core. It is also called as waveguide acceptance angle or acceptance cone half angle.

Acceptance cone in optical fibers is a geometric representation of the range of angles within which light can enter the fiber core and still be guided through it. This concept is directly related to the numerical aperture (NA) of the fiber, which defines the light-gathering ability of the fiber. It is the conical region around the fiber axis within which incident light must fall to be refracted into the core and guided through the fiber by total internal reflection at the core-cladding boundary.

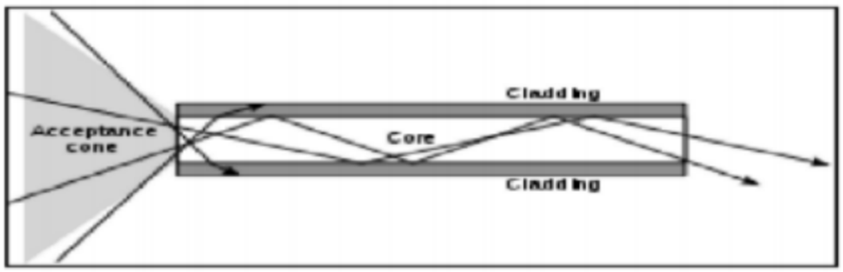

Figure 6.13. Acceptance cone.[5]

Numerical aperture (NA) of an optical fiber is a dimensionless number that characterizes the range of angles over which the fiber can accept light. The numerical aperture represents the light-gathering capability of optical fiber and it is given by $NA = \sin\theta_0$. To understand the propagation of light through an optical fiber, consider an optical fiber with the core made of refractive index n_1 & cladding made of material refractive index n_2. Let n_0 be the refractive index of the surrounding medium ($n_1 > n_2 > n_0$).

Let a ray of light AO enter into the core at an angle of incidence θ_0 w.r.t fiber axis. Then it is refracted along OB at an angle θ_1 & meets the core-cladding interface at a critical angle of incidence ($\theta = 90 - \theta_1$). Then the refracted ray grazes along BC.

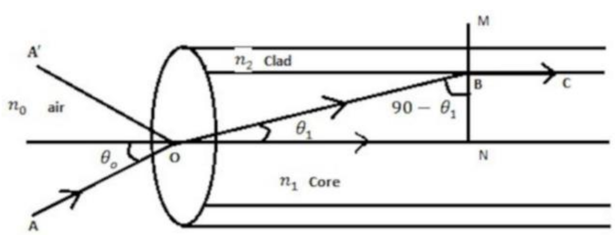

Figure 6.14. Geometry of light propagation through an optical fiber.[5]

On applying Snell's law at O,

$$n_o \sin \theta_o = n_1 \sin\theta_1$$

$$\sin \theta_o = \sin\theta_1 (n_1/n_o) \quad \text{-------------1)}$$

On applying Snell's law at point B, we get

$$n_1 \sin(90 - \theta_1) = n_2 \sin 90°$$

$$n_1 \cos \theta_1 = n2$$

$$\cos \theta_1 = n_2/n_1 \quad \text{-------------- 2)}$$

From trigonometric identity

$$\sin^2 \theta_1 + \cos^2 \theta_1 = 1$$

$$\sin \theta_1 = \mathrm{sqrt}(1-\cos^2 \theta_1)$$

using Eq. 2:

$$\sin \theta_1 = \mathrm{sqrt}(1-(n_2^2/ n_1^2))$$

$$\sin \theta_0 = (\mathrm{sqrt}(n_1^2 - n_2^2))/n_0$$

Since numerical aperture (NA)= $\sin \theta_0$

$$NA = (\mathrm{sqrt}(n_1^2 - n_2^2))/n_0$$

If the fiber is in air $n_0 = 1$ then,

$$NA = \sin \theta_0 = \mathrm{sqrt}(n_1^2 - n_2^2)$$

Light is transmitted through the fiber only when the angle of incidence

$$\theta_i \le \theta_0$$

$$\sin\theta_i \le \sin\theta_0$$

$$\sin\theta_i \le \mathrm{sqrt}(n_1^2 - n_2^2)$$

$$\sin\theta_i \le NA$$

This is the condition for propagation. When the above condition is satisfied, light will be transmitted through the optical fiber with multiple total internal reflections.

Numericals: Example and Practice Problems: Acceptance Angle and Numerical Aperture

Worked-out Problem:

Example: Calculate the numerical aperture and acceptance angle of an optical fiber having n_1 = 1.49and n_2 = 1.44. (Ans: NA = 0.38275, θ_0 = 22.5°)

Sol: Given:

$n_1 = 1.49$

$n_2 = 1.44$

Formula:

NA = sqrt $(n_1^2 - n_2^2)$

∴ NA = sqrt$((1.49)^2 – (1.44)^2)$

∴ NA = 0.38275

Angle of acceptance (θ_0)=$\sin^{-1}$(0.38275)

∴ $\theta_0 = 22.5°$

Final Answer: NA = 0.38275, θ_0 = 22.5°

Problems:

6.1. In an optical fiber, the core material and clad have n_1=1.6 and n_2=1.3, respectively. What is the value of critical angle? Also calculate the value of angle of acceptance cone. (Ans: θ_0 = 54.34°, $2\theta_0$ = 137.732°)

6.2. A fiber cable has an acceptance angle of 30° and a core index of refraction of 1.4. Calculate the refractive index of the cladding. (Ans: n_2 = 1.3077).

6.3. An optical glass fiber of refractive index 1.5 is to be clad with another glass to ensure internal reflection that will contain light travelling within 5° of the fiber axis. What maximum refractive index is allowed for the cladding? (Ans: n_2 = 1.4943).

6.4. The angle of acceptance of an optical fiber is 30° when kept in air. Find the angle of acceptance when it is in a medium of refractive index 1.33. (Ans: θ_0 = 22.08°)

6.5. The numerical aperture of an optical fiber is 0.2 when surrounded by air. Determine the refractive index of its core given the refractive index of cladding as 1.59. Also find the acceptance angle when it is in medium of refractive index 1.33.

6.6. Calculate the numerical aperture and hance the acceptance angle for an optical fiber whose core and cladding have refractive index of 1.59 and 1.40, respectively. (Ans: NA = 0.7537, θ_0 = 48.91°)

6.7.2 Optical Fiber Parameters

Optical fiber parameters are physical, geometrical, and performance characteristics that define the behavior and performance of an optical fiber. These parameters influence light propagation, signal transmission efficiency, and overall fiber performance.

Table 6.3. A comprehensive summary of optical fiber parameters.

Parameter	Definition	Typical Values
Core Diameter (d_{core})	Diameter of the central light-propagating region	8–10 µm (single-mode), 50–62.5 µm (multimode)
Cladding Diameter	Diameter of the outer layer	125 µm
Numerical Aperture (NA)	Light-gathering ability	0.1 (single-mode), 0.2–0.3 (multimode)
Mode Field Diameter (MFD)	Effective light distribution width	~9–10 µm at 1550 nm
Refractive Index Profile	Core-to-cladding refractive index distribution	Step index, Graded index
Cutoff Wavelength (λ_c)	Wavelength above which only one mode propagates	~1260 nm
Attenuation (α)	Optical power loss per unit length	~0.2 dB/km (single-mode), ~3 dB/km (multimode)

Dispersion	Spreading of light pulses	~17 ps/nm·km (chromatic dispersion at 1550 nm)
Bandwidth	Data-carrying capacity	~4700 MHz·km (OM4 multimode), unlimited (single-mode)
Bending Loss	Loss due to fiber bending	Critical radius: 10–30 mm
Operating Wavelengths	Optimal transmission wavelengths	850 nm, 1310 nm, 1550 nm
Tensile Strength	Maximum stress without breaking	~100–200 kpsi

6.8 Types of Optical Fiber

Optical fibers are classified based on their:

- mode of propagation
- refractive index profile
- material composition

1. Based on Mode of Propagation

a. Single-Mode Fiber (SMF)

- Description: Allows only one mode of light to propagate.
- Core Diameter: ~8–10 µm.
- Applications: Long-distance communication, high-speed data transmission.
- Advantages:
  - Minimal modal dispersion, enabling longer transmission distances.
  - Higher bandwidth compared to multimode fibers.
- Examples: Used in telecom networks and submarine cables.

b. Multimode Fiber (MMF)

- Description: Allows multiple modes of light to propagate simultaneously.
- Core Diameter: 50 µm or 62.5 µm.

- Applications: Short-distance communication, LANs, and data centers.
- Advantages:
  - Easier to couple light into the core due to a larger diameter.
  - Lower cost compared to single-mode fibers.
- Examples: Used in Ethernet and high-performance computing.

2. Based on Refractive Index Profile

a. Step-Index Fiber

- Description: The refractive index of the core is uniform and sharply decreases at the core-cladding boundary.
- Types:
  - Single-mode step-index fiber.
  - Multimode step-index fiber.
- Applications: Short-distance communication, sensing.
- Advantages:
  - Simpler design and manufacturing.
  - Cost-effective for specific applications.

b. Graded-Index Fiber

- Description: The refractive index of the core decreases gradually from the center to the cladding.
- Applications: Multimode applications like high-speed data transmission.
- Advantages:
  - Reduces modal dispersion, allowing for higher bandwidth.
  - More efficient for medium-range communication.

3. Based on Material Composition

a. Glass Fiber

- Core and Cladding Material: Made of silica glass.
- Applications: High-performance communication systems, sensors.
- Advantages:
  - Low attenuation and high bandwidth.
  - Operates over a wide range of wavelengths.

- Examples: Telecommunications and medical imaging.

b. Plastic Fiber

- Core and Cladding Material: Made of polymer (e.g., PMMA - Polymethyl Methacrylate).
- Applications: Short-distance communication, automotive networks.
- Advantages:
    - Flexible and easy to handle.
    - Low cost compared to glass fibers.
- Examples: Used in home networks and decorative lighting.

4. Based on Special Properties

a. Polarization-Maintaining Fiber (PMF)

- Description: Maintains the polarization state of light during transmission.
- Applications: Fiber-optic gyroscopes, sensors, and scientific research.
- Advantages:
    - High stability for applications requiring specific polarization states.

b. Photonic Crystal Fiber (PCF)

- Description: Contains air holes arranged in a specific pattern, guiding light based on the photonic bandgap effect.
- Applications: Nonlinear optics, high-power transmission, sensing.
- Advantages:
    - Customizable dispersion and single-mode operation over a wide range of wavelengths.

c. Plastic Optical Fiber (POF)

- Description: Made entirely of plastic materials.
- Applications: Low-cost, short-distance communication like automotive and industrial networks.
- Advantages:
    - High flexibility and larger core diameter for easier light coupling.

Table 6.4. A comprehensive summary of types of optical fibers.

Type	Core Diameter	Refractive Index Profile	Material	Applications	Advantages
Single-Mode Fiber (SMF)	8–10 µm	Step-Index	Glass	Long-distance communication	High bandwidth, minimal dispersion
Multimode Fiber (MMF)	50 µm, 62.5 µm	Step or Graded-Index	Glass/Plastic	Short-distance communication	Cost-effective, easy light coupling
Step-Index Fiber	Varies	Uniform	Glass/Plastic	Short-distance, sensing	Simple design, low cost
Graded-Index Fiber	Varies	Gradual decrease	Glass	High-speed data transmission	Reduced modal dispersion
Glass Fiber	8–10 µm, 50 µm	Step or Graded-Index	Silica Glass	Telecom, medical imaging	Low attenuation, wide wavelength use
Plastic Fiber	>200 µm	Step-Index	Plastic	Home networks, lighting	Flexible, low cost

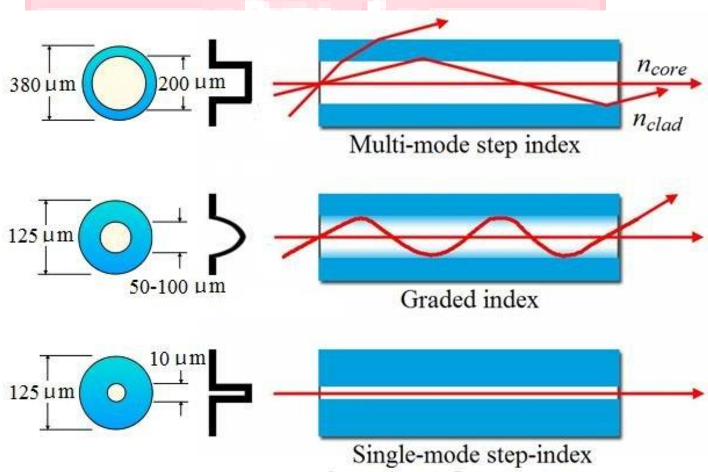

Figure 6.15. Types of optical fiber.[6]

6.9. Advantages of Optical Fiber Communication over Conventional

Optical fiber communication has revolutionized the field of telecommunications, offering significant advantages over conventional methods such as copper wires and wireless communication.

1. Higher Bandwidth

- **Explanation:** Optical fibers can carry much higher data rates compared to copper cables or wireless systems.
- **Quantitative Value:** Single-mode fibers can achieve bandwidths exceeding **100 Tbps** over long distances.
- **Example:** Used in internet backbones to handle high-speed data transfers and video streaming services.

2. Lower Signal Attenuation

- **Explanation:** Optical fibers have lower power loss compared to electrical cables, enabling long-distance communication without significant signal degradation.
- **Quantitative Value:** Signal attenuation in optical fibers is as low as **0.2 dB/km** at 1550 nm, compared to **8–10 dB/km** for copper cables.
- **Example:** Transcontinental and submarine cables rely on optical fibers for transmitting signals over thousands of kilometers.

3. Immunity to Electromagnetic Interference (EMI)

- **Explanation:** Optical fibers are immune to electromagnetic interference, ensuring stable and distortion-free signal transmission.
- **Advantage:** Ideal for use in environments with high electrical noise, such as industrial settings and power stations.
- **Example:** Optical fibers are used in aircraft communication systems to avoid interference from electronic devices.

4. Enhanced Security

- **Explanation:** Optical fibers are difficult to tap into without being detected, providing secure data transmission.
- **Advantage:** Critical for military, banking, and government applications.

- **Example:** Encrypted communication networks use optical fibers for secure information exchange.

5. Lightweight and Compact Design

- **Explanation:** Optical fibers are significantly lighter and thinner than copper cables, making them easier to install and handle.
- **Quantitative Value:** Optical fibers weigh **1/4th** as much as copper cables for the same length.
- **Example:** Used in aerospace and marine industries where weight is a critical factor.

6. High Signal Capacity

- **Explanation:** Optical fibers support multiplexing techniques, such as Wavelength Division Multiplexing (WDM), allowing multiple signals to be transmitted simultaneously on a single fiber.
- **Advantage:** Increases the data-carrying capacity without additional physical fibers.
- **Example:** Deployed in fiber-to-the-home (FTTH) networks for high-speed internet access.

7. Long-Distance Communication

- **Explanation:** Due to low attenuation and advanced amplification techniques (e.g., erbium-doped fiber amplifiers, EDFA), optical fibers can transmit signals over long distances without requiring frequent repeaters.
- **Quantitative Value:** Repeater spacing can exceed **50–100 km**, compared to **5–10 km** for copper cables.
- **Example:** Used in submarine cables for transoceanic communication.

8. Immunity to Environmental Factors

- **Explanation:** Optical fibers are resistant to environmental factors such as temperature fluctuations, moisture, and corrosion.
- **Advantage:** Ensures reliability and durability in harsh conditions.
- **Example:** Optical fibers are preferred in outdoor and underwater installations.

9. Cost-Effective in the Long Run

- **Explanation:** Although the initial installation cost of optical fibers is higher, their long lifespan, minimal maintenance, and higher data capacity make them cost-effective over time.

- **Example:** Telecommunications companies rely on optical fibers to meet growing data demands efficiently.

10. Support for Emerging Technologies

- **Explanation:** Optical fibers are compatible with cutting-edge technologies such as 5G networks, IoT, and AI-driven communication systems.
- **Advantage:** Enables the adoption of advanced applications that require high data rates and low latency.
- **Example:** Used in smart city infrastructures and autonomous vehicle communication.

Table 6.5. A comprehensive summary of advantages of optical fiber communication over conventional method.

Feature	Optical Fiber	Copper Wire	Wireless
Bandwidth	Up to 100 Tbps	Limited to Mbps	Limited to Gbps
Attenuation	~0.2 dB/km (1550 nm)	~8–10 dB/km	Signal loss over distance
EMI Resistance	Immune	Susceptible	Susceptible
Security	High	Moderate	Low
Weight	Lightweight	Heavy	N/A
Environmental Durability	High	Low	Moderate
Distance	Long-distance (50–100 km)	Short-distance (5–10 km)	Variable

6.10. Application of Optical Fiber in Medical Field: Endoscopy

Endoscopy is a medical procedure that uses optical fibers to visually examine the interior of organs and cavities within the human body without the need for major surgery.

Optical fibers in endoscopy work on the principle of total internal reflection, which enables the transmission of light and images through flexible or rigid fiber bundles. The fiber bundle is divided into two types:

1. Illumination Fibers: Transmit light into the body to illuminate the area of interest.
2. Imaging Fibers: Transmit the reflected light (image) from the illuminated area back to the eyepiece or camera.

Components of an Optical Fiber Endoscope

1. Light Source: Provides intense light (often from LED or xenon lamps) for illumination.
2. Optical Fiber Bundle: Transmits light into the body and returns images for observation.
3. Lens System: Focuses the image for clear visualization.
4. Eyepiece or Camera: Allows the medical professional to view or record the images.
5. Control System: Helps steer the endoscope for precise movement and positioning.

Applications of Optical Fiber in Endoscopy

1. Gastrointestinal Endoscopy:
    - Examines the esophagus, stomach, and intestines to detect ulcers, tumors, or infections.
    - Example: Gastroscopy to diagnose and treat stomach disorders.
2. Bronchoscopy:
    - Examines the respiratory tract, including the lungs and bronchi, to detect abnormalities like tumors or blockages.
    - Example: Used to perform biopsies or remove foreign objects.
3. Laparoscopy:
    - Visualizes the abdominal cavity for diagnostic or surgical purposes.
    - Example: Used in gallbladder removal or hernia repair.
4. Arthroscopy:
    - Examines joints to diagnose or treat conditions such as arthritis or ligament damage.
    - Example: Used in minimally invasive surgeries for knee or shoulder repair.
5. Otoscopy:
    - Examines the ear canal and eardrum to detect infections or blockages.
    - Example: Diagnosing middle-ear infections.
6. Cystoscopy:
    - Examines the bladder and urinary tract for abnormalities.
    - Example: Detecting bladder tumors or stones.

7. Colonoscopy:
   - Examines the colon and rectum to detect polyps, cancers, or inflammation.
   - Example: Screening for colorectal cancer.

Advantages of Optical Fiber Endoscopy

1. Minimally Invasive: Requires only small incisions or natural orifices for access.
2. Real-Time Visualization: Provides live images for immediate diagnosis and intervention.
3. High Precision: Allows for targeted biopsies and precise surgical procedures.
4. Flexibility and Maneuverability: The flexible fiber bundle enables access to hard-to-reach areas.
5. Reduced Recovery Time: Patients experience less trauma and faster recovery compared to open surgeries.
6. Lightweight and Compact: Optical fiber endoscopes are easy to handle and transport.

Types of Lasers Used in Fiber Optic Endoscopy

1. Diode Lasers: Provide light for illumination and are compact and efficient.
2. Nd:YAG Lasers: Used for therapeutic procedures like removing tumors or coagulating tissues.
3. Argon Lasers: Useful in treating retinal and vascular conditions during endoscopic procedures.

Questions:

1. Define numerical aperture of an optical fiber. Derive an expression for it.
2. Explain the terms acceptance angle and acceptance cone.
3. Obtain expression for acceptance cone.
4. Discuss TIR in optical fiber.
5. Describe the two main components of an optical fiber.
6. Discuss the application of optical fiber in endoscopy.
7. Discuss the types of an optical fiber.

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