Advanced Engineering Physics

Unit 5 : Laser and Fibre Optics

I. Fundamentals of Lasers

1. Introduction and Characteristics of Lasers

- **Basic Definition:** The term laser refers to a device that amplifies light by the stimulated emission of radiation. It is the optical-frequency equivalent of the maser (which amplifies microwaves).
- **Basic Properties of Laser Light:** While the textbook assumes a basic understanding of lasers as sources of coherent radiation, the explicit definitions of **coherence, monochromaticity, directionality, and high intensity** are left to your specific engineering lectures. *(Supplement this section heavily with your class notes).*

2. Physics of Lasing Action

- **Stimulated vs. Spontaneous Emission:**
    - **Core Concept:** If a system is immersed in a radiation field of frequency ω, it can transition between a lower state and an upper state.
    - **Fermi's Golden Rule:** According to a standard result of quantum mechanics known as Fermi's golden rule, the probability P per atom, per unit time, of a stimulated transition between the upper and lower states is mathematically given by:

      $$P = \left(\frac{\mu B_{rf}}{\hbar}\right)^2 \frac{1}{\Delta\omega}$$

      where μ is the magnetic dipole moment, B_{rf} is the amplitude of the radiation field, and $\Delta\omega$ is the combined energy width of the two states.
    - **Net Power Emitted:** The total net energy emitted per unit time ($\mathscr{P}$) by the entire system is the photon energy ($\hbar\omega$) multiplied by the transition rate (P) and the difference in population between the upper (n_u) and lower (n_l) states:

      $$\mathscr{P} = \hbar\omega P(n_u - n_l)$$

- **Einstein Coefficients and their Relations:**
    - **Transition Rates:** In a two-level system exposed to a radiation field with energy density $\rho(\nu)$, the rates of transitions are defined using the Einstein coefficients A (spontaneous) and B (stimulated):
        - **Spontaneous Emission Rate:** $R_{sp} = A_{21}N_2$ (depends only on the population of the upper state, N_2).

    - **Stimulated Emission Rate:** $R_{st} = B_{21} N_2 \rho(\nu)$ (depends on the upper state population and the radiation energy density).
    - **Stimulated Absorption Rate:** $R_{abs} = B_{12} N_1 \rho(\nu)$ (depends on the lower state population, N_1, and the radiation energy density).
  - **Einstein Relations:** By assuming the system is in thermal equilibrium (where upward transitions equal downward transitions: $R_{st} + R_{sp} = R_{abs}$) and substituting Boltzmann's distribution for the populations, the resulting equation for $\rho(\nu)$ is compared to Planck's Radiation Law. This yields the fundamental relations between the coefficients:
    - $B_{12} = B_{21}$ (For non-degenerate states. More generally, $g_1 B_{12} = g_2 B_{21}$ where g represents the degeneracy of the energy levels).
    - $\frac{A_{21}}{B_{21}} = \frac{8\pi h \nu^3}{c^3}$
  - **Physical Significance:** The ratio A_{21}/B_{21} is proportional to ν^3. This implies that at higher frequencies (like optical or UV light), spontaneous emission dominates, making lasers difficult to achieve without strong pumping. At lower frequencies (like microwaves), stimulated emission dominates, which is why masers are comparatively easier to operate. Additionally, the coefficient A_{21} determines the natural lifetime of the excited state ($\tau = 1/A_{21}$).
- **Metastable State & Population Inversion:**
  - **Thermal Equilibrium Limitation:** In normal thermal equilibrium, the population of the upper state is always less than the lower state ($n_u < n_l$). Looking at the power equation above, if $n_u < n_l$, the net power emitted is negative, meaning the system acts as a net *absorber* of light, not an emitter.
  - **Population Inversion:** To achieve laser action, you must force the system into a non-equilibrium state where the upper state population actually exceeds the lower state ($n_u > n_l$). When this happens, stimulated emission dominates, and the radiation field is amplified.
  - **The Metastable State:** To successfully achieve population inversion, the excited electrons must be trapped in a **metastable state**. In the Ruby laser, for example, electrons rapidly decay from high-energy bands into the intermediate ^2E levels. Because photon emission from these ^2E levels to the ground state is relatively slow (about 5×10^{-3} seconds), a massive population of excited electrons can "pile up" here, allowing the upper state population to easily exceed the ground state.
- **Pumping:**
  - **Core Concept:** Pumping is the physical mechanism used to excite the atoms from the ground state into the upper energy states, providing the energy needed for population inversion.
  - **Optical Pumping Mechanism (Ruby Laser Example):** Ruby contains Cr^{3+} ions with two broad upper energy bands ($^4F_1$ and $^4F_2$). Because these bands are extremely broad, they can be pumped highly efficiently by absorbing light from **broadband light sources, such as xenon flash lamps**.

    - **Decay to Lasing Level:** Once pumped into these broad ${}^4F$ bands, the atoms decay very rapidly (in $\sim 10^{-7}$ seconds) via *radiationless processes* (meaning they emit phonons/heat instead of light) down to the metastable ${}^2E$ state, where they wait to participate in the stimulated lasing action.

II. Types of Lasers

1. Solid-State Lasers

- **Ruby Laser:**
    - **Operating Principle:** The ruby laser was the first crystal to exhibit optical maser (laser) action, utilizing the energy levels of Cr^{3+} ions embedded in the host crystal.
    - **Optical Absorption (Pumping):** About $15,000\ \text{cm}^{-1}$ above the ground state lie a pair of states labeled ${}^2E$, and above these lie two broad bands of states labeled ${}^4F_1$ and ${}^4F_2$. Because these ${}^4F$ bands are broad, they can be efficiently populated by absorbing light from broadband sources, such as xenon flash lamps.
    - **Radiationless Decay:** Once atoms are excited into the ${}^4F$ bands, they decay very rapidly (in about $10^{-7}\ \text{s}$) via radiationless processes. During this decay, they emit phonons (lattice vibrations) rather than photons, dropping down into the intermediate ${}^2E$ levels.
    - **Metastable State & Photon Emission:** The ${}^2E$ levels act as metastable states because photon emission from these levels back to the ground state is relatively slow (about $5 \times 10^{-3}\ \text{s}$). This bottleneck allows a large population of excited Cr^{3+} ions to "pile up" in the ${}^2E$ state.
    - **Lasing Action:** For laser action to occur, the population of ions in the ${}^2E$ state must exceed the population in the ground state, achieving a population inversion. When this stored energy is released in a short burst, the ruby laser can emit at a very high power level, with an overall energy conversion efficiency of about one percent.

2. Gas Lasers

- **He-Ne Laser & CO_2 Laser:**
    - **He-Ne Laser (Helium-Neon):**
        - **Construction:** A gas discharge tube containing a mixture of Helium and Neon (typically in a 10:1 ratio). It commonly operates at a wavelength of 632.8 nm (visible red light).
        - **Working Principle & Energy Levels:** An electrical discharge excites Helium atoms to metastable states (2^1S and 2^3S). These states are very close in energy to certain excited states of Neon (the $3s$ and $2s$ levels). Through inelastic collisions, energy is transferred from Helium to Neon, populating Neon's upper energy levels and creating a population inversion relative to Neon's lower $2p$ and $3p$ states. Stimulated emission

        occurs as Neon atoms transition to these lower states. Helium also helps depopulate the lower Neon states via collisions, maintaining the inversion.
  - CO_2 **Laser (Carbon Dioxide):**
    - **Construction:** A gas mixture containing CO_2, Nitrogen (N_2), and Helium (He). It is a molecular gas laser operating in the infrared region (primarily at 10.6 µm).
    - **Working Principle & Energy Levels:** The electrical discharge primarily excites N_2 molecules to their first vibrational state ($v = 1$). Because N_2 is a diatomic molecule, this state is metastable. The vibrational energy of N_2 closely matches the asymmetric stretching vibrational mode (001) of the CO_2 molecule, allowing efficient resonant energy transfer. This creates a population inversion between the (001) upper state and the lower energy bending (010) and symmetric stretching (100) modes of CO_2. Lasing occurs during the transition to these lower states. Helium is added to the mixture to efficiently cool the gas and rapidly depopulate the lower lasing levels, sustaining the population inversion.

3. Semiconductor Diode Lasers

- **Operating Principle:**
  - Stimulated emission of radiation can occur in direct-gap semiconductors (like GaAs) when electrons recombine with holes.
  - Illumination or electrical injection creates electron and hole concentrations that are much larger than their thermal equilibrium values.
  - **Direct vs. Indirect Gaps:** Crystals with direct band gaps are normally required for junction lasers. Indirect gap semiconductors involve competing processes with phonons, meaning carriers recombine less efficiently, and no laser action is observed in them.
- **Quasi-Fermi Levels:**
  - The recombination times for the excess carriers are much longer than the time it takes for electrons to reach thermal equilibrium within the conduction band, or for holes to reach equilibrium within the valence band.
  - This steady-state condition is described by defining separate Fermi levels—called **quasi-Fermi levels**—for the conduction band (μ_c) and the valence band (μ_v).
  - **Requirement for Population Inversion:** To achieve population inversion and laser action, the quasi-Fermi levels must be separated by an amount greater than the band gap (E_g). Mathematically, this is expressed as $\mu_c - \mu_v > E_g$.
- **Double Heterostructure:**
  - While population inversion can be achieved by forward biasing an ordinary $p - n$ junction, almost all practical injection lasers employ a **double heterostructure**.

  - **Mechanism:** The lasing, optically active semiconductor layer is embedded between two wider-gap semiconductor regions of opposite doping. A classic example is a layer of GaAs embedded between layers of (Al,Ga)As.
  - **Quantum Well Confinement:** This structure creates a quantum well that physically confines both electrons and holes. The wide energy gap on the p-type side creates a potential barrier that prevents electrons from escaping, while an opposite barrier on the n-type side prevents holes from escaping.
  - **Electromagnetic Cavity:** The crystal itself acts as the electromagnetic cavity because the flat, polished crystal-air interfaces possess high optical reflectivity.
  - **Efficiency:** Double heterojunction lasers are highly efficient, converting nearly 50% of the input dc electrical energy into light output, with differential efficiencies up to 90%.

4. Laser Applications

- **Bar Code Scanner and LIDAR for Autonomous Vehicles:**
  - **Bar Code Scanner:**
    - **Mechanism:** A laser diode emits a focused beam of light toward a rotating polygonal mirror or an oscillating mirror. This scanning mechanism sweeps the laser beam rapidly across the bar code. The dark bars absorb the light, while the white spaces reflect it back toward a photodetector (photodiode). The photodetector converts the fluctuating intensity of the reflected light into an electrical signal, which a decoder then interprets to identify the specific pattern of the bar code.
  - **LIDAR for Autonomous Vehicles (Light Detection and Ranging):**
    - **Mechanism:** LIDAR systems emit rapid pulses of laser light (typically in the near-infrared spectrum) into the surrounding environment. A highly sensitive sensor measures the exact time it takes for each pulse to hit an object and reflect back to the sensor. By using the Time of Flight (ToF) principle ($Distance = (Speed \times Time)/2$), the system calculates the precise distance to the target. By rapidly firing thousands of these pulses and steering them using rotating mechanical mirrors or solid-state beam-steering technology (like MEMS or phased arrays), the LIDAR generates a dense, highly accurate 3D point cloud of the vehicle's surroundings, allowing the autonomous system to detect obstacles, map road geometry, and navigate safely.

III. Introduction to Fibre Optics

1. Construction and Propagation Principle

- **Construction of an Optical Fibre:**
  - **Core and Cladding:** Physically, optical fibres consist of a very thin core (approximately $10\mu m$ in diameter) composed of high-refractive-index glass.

This core is immediately surrounded by a layer known as the cladding, which possesses a lower refractive index.
    - **Material:** They are typically silica-based lightguides used to carry a high proportion of digital data and information transmitted globally.
- **Propagation Principle:**
    - **Optimal Transmission Window:** The digital data are carried by light waves. The most efficient propagation occurs at wavelengths near $1.55\mu m$ in the infrared region, where the minimum attenuation drops to an astonishingly low $\sim 0.20 \text{ dB km}^{-1}$.
    - **Signal Amplification:** To maintain signal strength over massive distances (e.g., hundreds of kilometers), sections of the fibre are doped with erbium (Er^{3+}) ions. When optically pumped, these ions provide stimulated emission (laser amplification) precisely at the optimal $1.55\mu m$ wavelength.
- **Total Internal Reflection:**
    - **Core Concept:** The fundamental optical principle confining the light within the high-index core as it bounces off the lower-index cladding.
    - **Mathematical Derivation:** Governed by Snell's Law: $n_1 \sin\theta_1 = n_2 \sin\theta_2$, where n_1 is the core index and n_2 is the cladding index ($n_1 > n_2$). As the angle of incidence θ_1 (measured from the normal to the interface) increases, the refracted angle θ_2 approaches 90°. The **critical angle** (θ_c) occurs when $\theta_2 = 90^\circ$, yielding $\sin\theta_c = n_2/n_1$. Any light striking the core-cladding boundary at an angle greater than θ_c undergoes total internal reflection, propagating down the fibre via an evanescent wave decaying exponentially into the cladding.
- **Acceptance Angle & Numerical Aperture:**
    - **Core Concept:** The geometric constraints that determine the maximum angle at which light can enter the fibre face and still be successfully guided down the core without leaking into the cladding.
    - **Formulas:** Applying Snell's law at the fibre entrance (air to core), the maximum acceptance angle θ_a is defined by $\sin\theta_a = n_1 \sin(90^\circ - \theta_c) = n_1 \cos\theta_c$. Using the trigonometric identity $\cos^2\theta_c = 1 - \sin^2\theta_c$ and substituting $\sin\theta_c = n_2/n_1$, we get $\sin\theta_a = \sqrt{n_1^2 - n_2^2}$. This term is defined as the **Numerical Aperture (NA)**: $NA = \sqrt{n_{core}^2 - n_{cladding}^2}$. A higher NA indicates a greater ability to capture light.

2. Classification of Optical Fibres

- **Step-Index vs. Graded-Index Fibres:**
    - **Step-Index Fibre:** The refractive index of the core is uniform (n_1) and drops abruptly to n_2 at the cladding boundary. Light travels in straight zig-zag paths (meridional rays), causing different modes to arrive at the receiver at different times (modal dispersion), which limits bandwidth.
    - **Graded-Index Fibre:** The core's refractive index decreases gradually from the center outwards (usually following a parabolic profile). Light rays follow curved, sinusoidal paths rather than sharp zig-zags. Rays traveling further

from the center move through a lower refractive index (where they travel faster), which equalizes the transit times of different modes, drastically reducing modal dispersion and allowing for higher bandwidth over longer distances.

- **Single-Mode vs. Multi-Mode Fibres:**
  - **Single-Mode Fibre:** Features a very small core diameter (typically ~ 8 to $10\mu m$), restricting light to a single propagation path (the fundamental LP_{01} mode). Because there are no multiple paths, modal dispersion is eliminated entirely. These are used for high-capacity, long-haul telecommunications (e.g., undersea cables).
  - **Multi-Mode Fibre:** Features a larger core diameter (typically $50\mu m$ or $62.5\mu m$), allowing light to propagate via hundreds of distinct paths (modes). Although it has a higher Numerical Aperture (making it easier to couple light into the fibre) and is cheaper to manufacture/use with LED sources, it suffers from modal dispersion. It is strictly used for short-distance communication, such as within data centers, local area networks (LANs), or fiber-to-the-home (FTTH) passive optical networks.

IV. Losses and Applications in Fibre Optics

1. Losses in Optical Fibre (Attenuation)

Core Concept:
The digital data in communication systems are carried by light waves. The most efficient propagation occurs at the "optic window" near $1.55\mu m$ in the infrared region, where the minimum attenuation drops to a remarkably low value of approximately $0.20\ \mathrm{dB\ km}^{-1}$. However, this window is fundamentally bounded by three types of losses:

- **Rayleigh Scattering (Intrinsic Loss):**
  - *Mechanism:* Rayleigh scattering is the dominant intrinsic loss mechanism in the main optic window. It is caused by static, microscopic fluctuations in the local dielectric constant of the inhomogeneous glass. Physically, these are variations in the local refractive index around each group of Si—O bonds.
  - *Frequency Dependence:* The radiant energy scattered from these atomic dipole elements is proportional to the square of their acceleration, meaning the scattered energy goes as the **fourth power of the frequency (ω^4).**
  - *Mathematical Expression:* The attenuation (or extinction) coefficient h dictates that the energy flux decays exponentially over a distance x as $\exp(-hx)$. For a generalized random scattering medium, this coefficient is given by $h \propto \frac{1}{\lambda^4 N}\langle(\Delta n)^2\rangle$, confirming that higher frequencies (shorter wavelengths) scatter much more severely than infrared wavelengths.
- **Impurity Absorption (Extrinsic Loss):**
  - *Mechanism:* Serious signal loss can originate from specific chemical impurities trapped within the silica core.

  - *The "Water Line":* The most prominent impurity absorption is caused by OH^- ions that inevitably accompany SiO_2 during manufacturing. This creates a massive spike in attenuation known as the "water line," which is the second harmonic of an OH absorption line natively sitting at $2.7\mu m$.
- **Electronic Absorption:**
  - *Mechanism:* At the high-frequency (short-wavelength) boundary of the transmission window, moving toward the ultraviolet, light absorption is ultimately dominated by electronic transitions (where photons have enough energy to excite electrons to higher energy bands).

2. Applications of Optical Fibres

- **Communication Systems:**
  - *Data Transfer:* Optical fibers form the backbone of modern global communication, carrying a massive proportion of data using the $1.55\mu m$ transmission window.
  - *Signal Amplification (Er^{3+} Doping):* Even with extremely low attenuation, a signal traveling 100 km will lose about 20 dB of power. To boost the signal for long-distance data transfer, sections of the optic fiber are doped with **Erbium (Er^{3+}) ions**.
  - *Pumping:* These Er^{3+} ions are optically "pumped" to an excited state. As the weakened data signal passes through, it triggers stimulated emission from the Erbium ions, which act as a laser amplifier perfectly tuned to boost the signal directly at the $1.55\mu m$ wavelength.
- **Sensors for Structural Health Monitoring:**
  - **Fiber Bragg Gratings (FBGs):** A Fiber Bragg Grating is created by exposing a short segment of the fiber core to a periodic pattern of intense ultraviolet (UV) laser light. This permanently induces a periodic variation in the core's refractive index, effectively creating a wavelength-selective mirror.
  - **Operating Principle (Bragg Condition):** When a broadband light source travels through the fiber, the grating reflects a very specific wavelength of light—known as the Bragg wavelength (λ_B)—while transmitting all others. This is governed by the condition $\lambda_B = 2n_{eff}\Lambda$, where n_{eff} is the effective refractive index of the core mode, and Λ is the physical period (spacing) of the grating.
  - **Sensing Mechanism (Strain and Temperature):** If the fiber is stretched by mechanical strain, the grating period Λ physically increases. If the fiber's temperature changes, both Λ (via thermal expansion) and n_{eff} (via the thermo-optic effect) change. Both physical strain and thermal shifts cause a measurable shift ($\Delta\lambda_B$) in the reflected peak wavelength.
  - **Structural Application:** By embedding FBG sensors into concrete structures (like bridges or dams) or bonding them to aerospace components (like aircraft wings or composite materials), engineers can monitor the reflected wavelength in real-time. A shift in the wavelength directly correlates to

mechanical stress, microscopic cracking, or thermal anomalies, allowing for early failure detection and continuous structural health monitoring without adding significant weight or altering the host material's integrity.