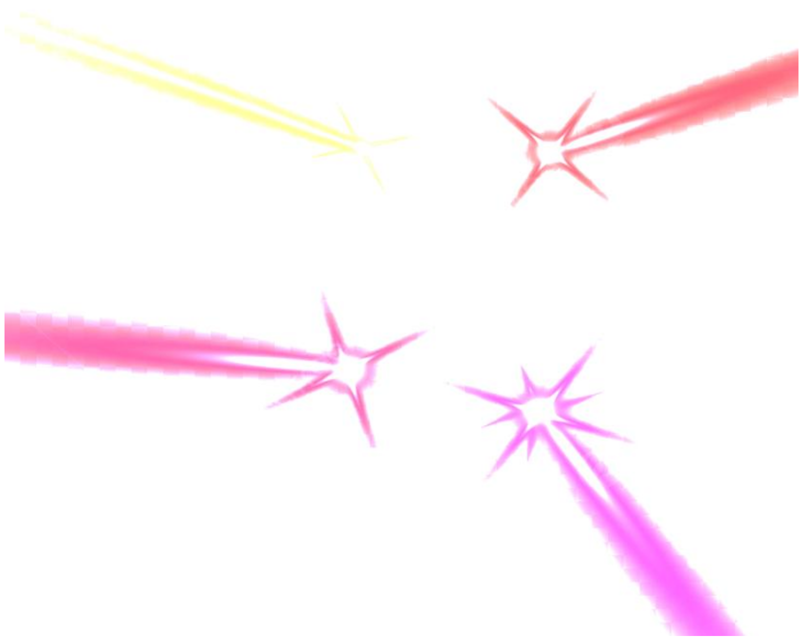
Lecture 5 / Part 3
Types of Lasers



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Lasers are commonly categorized according to their gain medium—the material responsible for amplifying light through stimulated emission. Depending on the radiating species involved, lasers can operate using atoms or molecules in a dilute gas, organic dyes dissolved in liquid solutions, semiconductor materials, or dielectric solids and glasses doped with specific ions. Based on these media, lasers are broadly classified into four main types: gas lasers, liquid (or dye) lasers, semiconductor lasers, and solid-state lasers.

Third: Semiconductor Laser

A semiconductor laser, also known as a diode laser, is a specially fabricated p-n junction diode that emits coherent and monochromatic light when forward-biased. It operates based on the principle of stimulated emission within a direct band gap semiconductor material, typically gallium arsenide (GaAs). Because of its compact size, efficiency, and direct electrical excitation, it is one of the most widely used types of lasers today.

Construction and Components of a Semiconductor Laser

A semiconductor laser, also known as a laser diode, is primarily made of a **p-n junction** fabricated from a **direct band gap semiconductor** such as gallium arsenide (GaAs). The device is designed in a way that allows efficient recombination of charge carriers (electrons and holes) in a small active region, producing coherent light. The main components are as follows:

1. **P-type Region:** This region is doped with *acceptor impurities* to create an abundance of positive charge carriers known as holes. It forms one side of the p-n junction and supplies holes to the active region when the device is forward-biased.

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2. **N-type Region:** This region is doped with *donor impurities* to produce a large number of free electrons as the majority carriers. It provides electrons to the active region during forward bias.
3. **Active Region (Junction Region):** This is the thin layer located at the interface between the p-type and n-type regions. It is the heart of the laser, where electrons and holes recombine to produce photons through spontaneous and stimulated emission. The active region is typically only a few micrometers thick. In modern lasers, this region is optically and electronically confined using heterojunction structures to enhance efficiency.
4. **Electrodes (Contacts):** Metallic contacts are placed on the top (p-side) and bottom (n-side) surfaces of the diode to provide a path for the electric current. When a forward voltage is applied across these contacts, it injects carriers into the active region.
5. **Optical Cavity / Reflective End Faces:** The two opposite end faces of the semiconductor crystal are polished and parallel to each other. They act as mirrors, forming an optical resonator. One mirror is fully reflective, while the other is partially reflective to allow part of the light to exit as a laser beam.
6. **Substrate (Base Layer):** The substrate provides mechanical support to the device and serves as a foundation on which the layers of the semiconductor are grown. It also helps in conducting heat away from the active region during operation.
7. **Heat Sink:** Because semiconductor lasers generate heat during operation, a metal heat sink is attached to dissipate thermal energy efficiently, ensuring stable performance and preventing damage.

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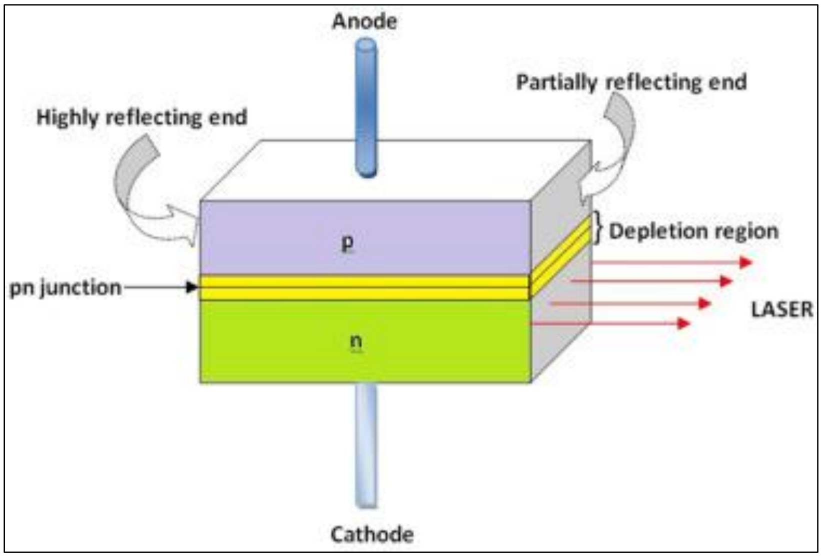

Fig. (1) Construction and Components of a Semiconductor Laser.

Working Principle of Semiconductor Laser

The working principle of a semiconductor laser is based on the interaction between electrons and holes in a p-n junction under forward bias, resulting in stimulated emission of radiation. This process can be understood in several key stages:

1. Forward Bias and Carrier Injection

When the p-n junction is forward-biased, electrons from the n-region and holes from the p-region are injected into the active region (the junction area). This increases the concentration of both electrons and holes in the same region, leading to a high carrier density. In a normal diode, this recombination produces **spontaneous emission**, giving off weak light. However, in a semiconductor laser, the injected current is made sufficiently large to achieve **population inversion**.

2. Population Inversion

Population inversion occurs when the number of electrons in the excited state (conduction band) becomes greater than the number of electrons in the ground state (valence band). This condition is necessary for laser action.

In a semiconductor with a direct band gap (such as GaAs), electrons can easily drop from the conduction band to the valence band, releasing photons (light) directly. When population inversion is achieved, stimulated emission becomes dominant.

3. Spontaneous and Stimulated Emission

Initially, some electrons recombine spontaneously with holes, emitting photons in random directions (spontaneous emission). These emitted photons then collide with other excited electrons in the conduction band, stimulating them to recombine with holes and release additional photons.

Each new photon has:

- The **same energy** (thus the same wavelength),
- The **same direction**, and
- The **same phase** as the stimulating photon.

This process is known as stimulated emission, and it results in the amplification of coherent light.

4. Optical Resonator and Feedback

The semiconductor crystal is designed with two polished parallel end faces that act as mirrors, forming an optical resonator or cavity. The photons generated by stimulated emission travel back and forth between these faces, getting amplified with every pass.

One of the faces is made partially transparent, allowing a portion of the amplified light to escape as a coherent laser beam, while the rest of the light continues to reflect and maintain the lasing process.

5. Threshold Current

The threshold current is the minimum forward current required to achieve population inversion and start the laser action. Below this current, the device behaves as a normal LED (light-emitting diode), emitting weak spontaneous light. Above this threshold, stimulated emission dominates, and laser light is produced.

6. Output Light and Wavelength

The emitted laser light has:

- **Wavelength** determined by the semiconductor's band gap energy E_g:

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

where $h$is Planck's constant and $c$is the speed of light.

- For **GaAs**, $E_g \approx 1.43\ eV$, giving a wavelength around **840 nm** (infrared).
- The output is **highly coherent**, **directional**, and **monochromatic**.

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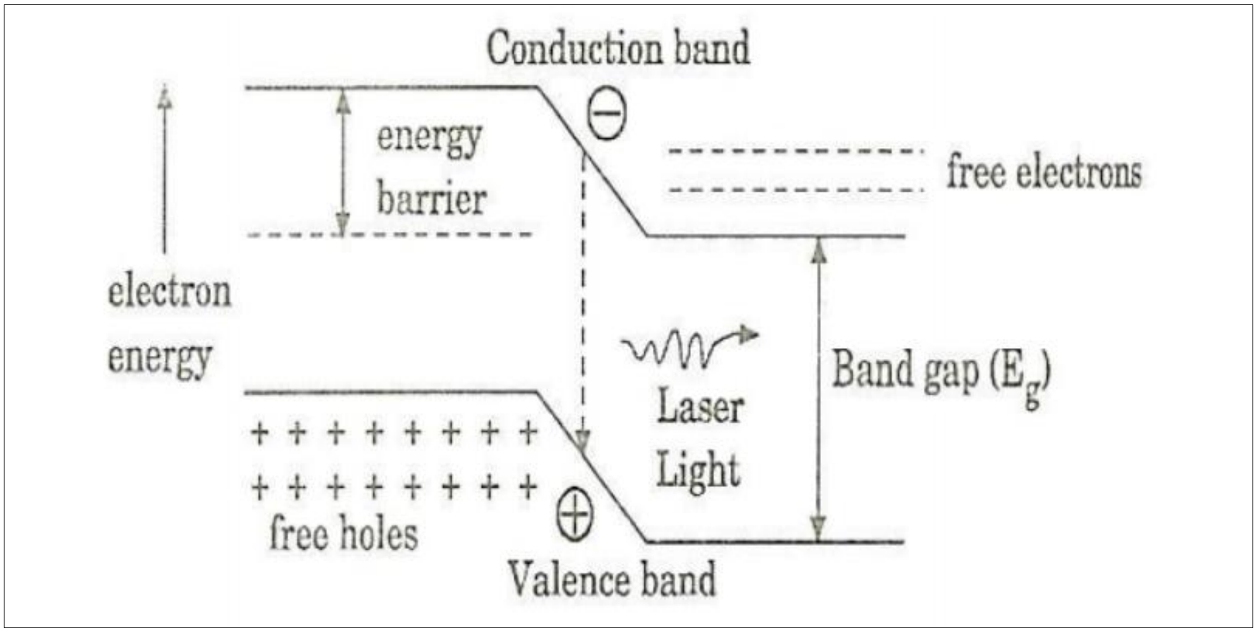

Fig. (2) Working Principle of Semiconductor Laser.

Characteristics

1. **Active medium:** p-n junction made from GaAs or similar compounds (e.g., InGaAs, AlGaAs).
2. **Pumping method:** Direct electrical pumping (via forward bias current).
3. **Power output:** Typically, around 1mW for low-power devices; higher powers available in modern designs.
4. **Nature of output:** Continuous wave (CW) or pulsed.
5. **Wavelength:** Typically, between 830 nm and 850 nm (infrared region).
6. **Beam divergence:** Large (about 10°–20°) due to the small size of the active region.
7. **Efficiency:** High electrical-to-optical conversion efficiency.
8. **Size:** Very compact (less than a millimeter).

Applications

- Optical fiber communication systems
- Laser printers and barcode scanners
- Laser pointers
- Medical instruments (e.g., eye surgery, dental treatments)
- Military and industrial ranging systems

Fourth: Liquid Lasers/Dye Lasers

A dye laser is a type of liquid laser that uses an organic dye dissolved in a liquid solvent (commonly alcohol) as the active medium. Dye molecules are organic compounds containing carbon that exhibit strong fluorescence when excited by visible light. Because of this property, they can serve as excellent gain media capable of amplifying light and producing laser emission.

The dye laser was first developed in the 1960s and remains widely used due to its broad tunability and high spectral purity.

Components of a Dye Laser

A typical dye laser consists of the following main components:

1. Active Medium: A liquid solution of an organic fluorescent dye (such as *Rhodamine 6G*) dissolved in an alcohol solvent (e.g., methanol or ethanol).
2. Optical Pumping Source: Provides the excitation energy required to raise dye molecules to higher energy levels. The pump is usually another laser such as a nitrogen laser, frequency-doubled Nd:YAG laser, or argon ion laser.

3. Optical Cavity (Resonator): Formed by three mirrors:
   - Two high-reflectance curved mirrors that focus the light within the dye jet.
   - One partially transmitting output coupler (typically 10–20% transmission) that allows part of the light to exit as the laser beam.
4. Dye Circulation System: Ensures continuous flow of the dye solution through a nozzle (jet) for cooling and maintaining optical quality by constantly refreshing the active medium.
5. Tuning Element: A diffraction grating or prism is placed in the cavity to select and tune the laser wavelength precisely.

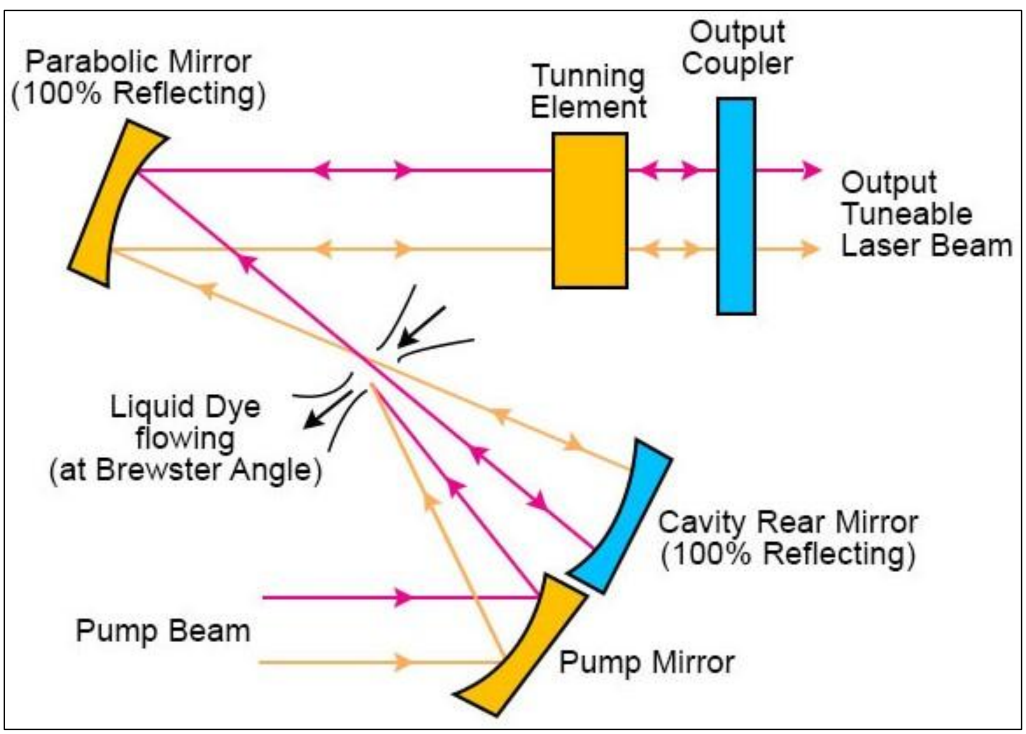

Fig. (3) Schematic Diagram of a Tunable Dye Laser.

Principle of Operation

The dye laser operates based on **optical pumping** and **stimulated emission** within a **four-level energy system**:

1. **Excitation:** Pump light (photons) is absorbed by dye molecules, raising electrons from the ground state to higher electronic energy levels.
2. **Internal Conversion:** Within picoseconds, excited molecules lose some vibrational energy (non-radiative decay) and settle to the lowest vibrational level of the excited electronic state.
3. **Stimulated Emission:** The molecules then return to various vibrational levels of the ground state, emitting photons in the process. Because transitions can occur over a range of vibrational levels, the **emission spectrum is broad**, allowing for wavelength tunability.
4. **Population Inversion:** Continuous optical pumping maintains more molecules in the excited state than in the ground state, ensuring sustained laser emission.

Wavelength Range and Tunability

Organic dyes possess **broad fluorescence bands** (typically 50–100 nm wide). By using a **tuning element**—a prism or diffraction grating—inside the laser cavity, a narrow spectral region can be selected and continuously adjusted.

Common dyes and their emission ranges:

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- **Rhodamine 6G:** 560–650 nm (orange-red region)
- **Coumarin:** 420–500 nm (blue-green region)
- **Stilbene:** 350–420 nm (ultraviolet region)

Thus, dye lasers can cover almost the entire visible spectrum and parts of the UV and near-infrared regions.

Modes of Operation

Dye lasers can operate in two distinct modes:

1. **Pulsed Mode:**
    - Achieved using **pulsed pumping sources** such as nitrogen lasers or flash lamps.
    - Produces **short, high-intensity pulses** of laser light.
2. **Continuous-Wave (CW) Mode:**
    - Requires a **continuous pump source**, usually a CW argon ion laser.
    - Provides **steady, continuous output** ideal for spectroscopy.

Characteristics of Dye Lasers

- **Tunable:** Wide wavelength range (50–100 nm per dye).
- **Narrow Linewidth:** Capable of very high spectral resolution.
- **Short Pulse Duration:** Can achieve picosecond to nanosecond pulses.
- **High Coherence:** Produces spatially and temporally coherent light.
- **Efficient Cooling:** Flowing liquid medium efficiently removes heat.

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- **Homogeneous Active Medium:** Liquids have uniform optical properties without crystal defects.

Advantages

- **Broad Tunability:** Allows selection of any wavelength within a wide spectral range.
- **Simple Cooling Mechanism:** The liquid dye carries heat away, maintaining stability.
- **Ease of Wavelength Change:** Changing the dye or solvent alters the emission range.
- **High Spectral Purity:** Very narrow emission linewidths.
- **Applicable in Many Fields:** Used in spectroscopy, holography, medical diagnostics, isotope separation, and laser-induced fluorescence studies.

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