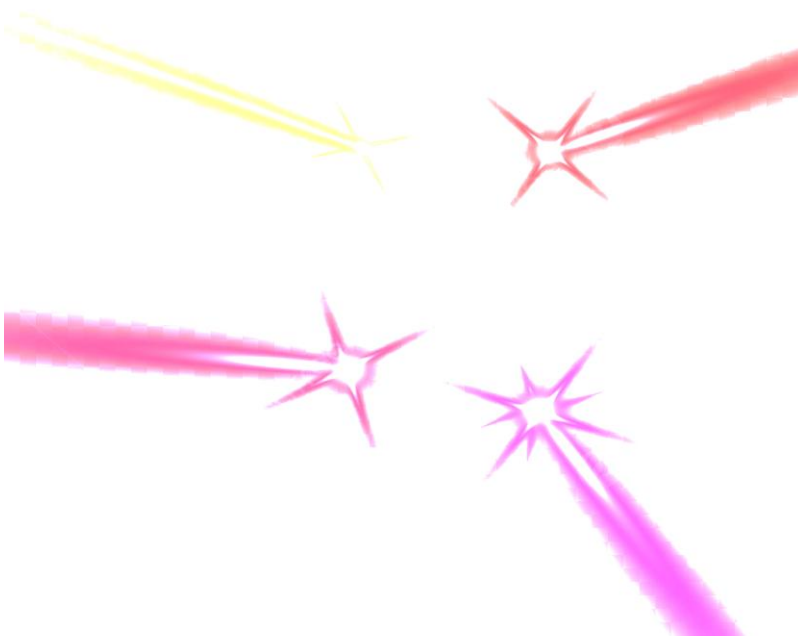
Lecture 3 / Part 1
Types of Lasers



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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.

First: Solid-state lasers

A **Solid-State (SS) Laser** uses a solid crystalline or glass material as its lasing medium and is typically optically pumped. It should not be confused with semiconductor (diode) lasers, which are also solid-state devices but are usually electrically pumped though, in principle, optical pumping can be possible in some cases.

In **optical pumping**, the active medium is excited by illumination from an external electromagnetic source. The photons from this source are absorbed by the atoms or ions within the lasing material, transferring energy and creating the population inversion required for laser action.

There are two main types of electromagnetic sources used for optical pumping:

1. **Broadband sources** – such as flash lamps, incandescent lamps, or arc lamps.
2. **Narrowband sources** – such as another laser.

There are various types of solid-state lasers, depending on the materials and pumping methods used. In the following sections, we will examine some of these types.

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1- Ruby laser

A **ruby laser** is a type of **solid-state laser** that uses a **synthetic ruby crystal (Al_2O_3: Cr^{3+})** as its lasing medium. It was the **first operational laser**, successfully demonstrated by Theodore H. Maiman in 1960. The ruby laser emits a **deep red beam** with a **wavelength of 694.3 nm**, which lies in the **visible region** of the electromagnetic spectrum. It is one of the few solid-state lasers that produce visible light.

Construction of the Ruby Laser

A ruby laser consists of three main components:

1. **Laser (Gain) Medium**
2. **Pump Source**
3. **Optical Resonator**

1. Laser Medium

The active medium in a ruby laser is a cylindrical rod of synthetic ruby, composed of **aluminum oxide (Al_2O_3)** doped with approximately **0.05% chromium ions (Cr^{3+})**. The chromium ions are responsible for the laser action, as they provide the necessary energy levels for stimulated emission. The sapphire host (Al_2O_3) offers excellent mechanical and thermal stability, making it suitable for high-intensity optical pumping.

2. Pump Source

The pump source provides the external energy needed to excite the chromium ions in the ruby crystal. In most ruby lasers, a **helical flashlamp (xenon flashtube)** is wrapped around the ruby rod. When the flashlamp is triggered, it emits intense pulses of white light that are absorbed by the Cr^{3+} ions. This process raises electrons from the ground state (E_1) to the higher energy level (E_3), creating a population inversion necessary for laser operation. The ruby laser uses **optical pumping**, a method in which light energy is used to excite electrons rather than electrical current.

3. Optical Resonator

The ruby rod is placed between **two parallel mirrors** forming an optical resonator:

- One mirror is **fully reflective**, to reflect all incident light back into the medium.
- The other is **partially reflective**, allowing a small portion of the amplified light to escape as the output laser beam.

These mirrors cause the emitted photons to oscillate back and forth through the medium, stimulating further emission and amplifying the coherent light.

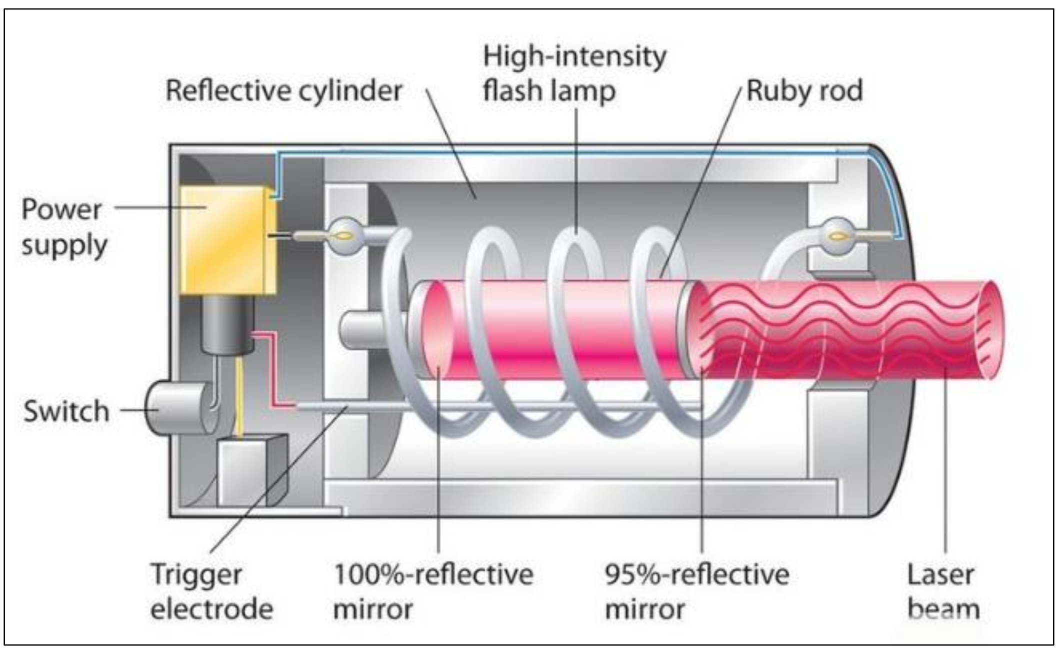

Fig. (1) Component of the first ruby laser.

Working Principle of Ruby Laser

The ruby laser operates as a three-level solid-state laser system, involving three energy levels of the Cr^{3+} ions:

- E_1: Ground state (lowest energy level)
- E_2: Metastable state (intermediate level)
- E_3: Pump level (highest energy level)

1. Optical Pumping: The flashlamp excites Cr^{3+} ions from the ground state (E_1) to the higher energy level (E_3).
2. Non-Radiative Transition: Excited electrons quickly drop from E_3 to the metastable level (E_2), releasing heat.
3. Population Inversion: Because E_2 has a longer lifetime, more electrons accumulate there, creating population inversion.
4. Stimulated Emission: Photons from excited ions at E_2 trigger more emissions, producing coherent red light at 694.3 nm.
5. Laser Output: The amplified light reflects between mirrors, and part of it escapes through the partially reflective mirror as the laser beam.

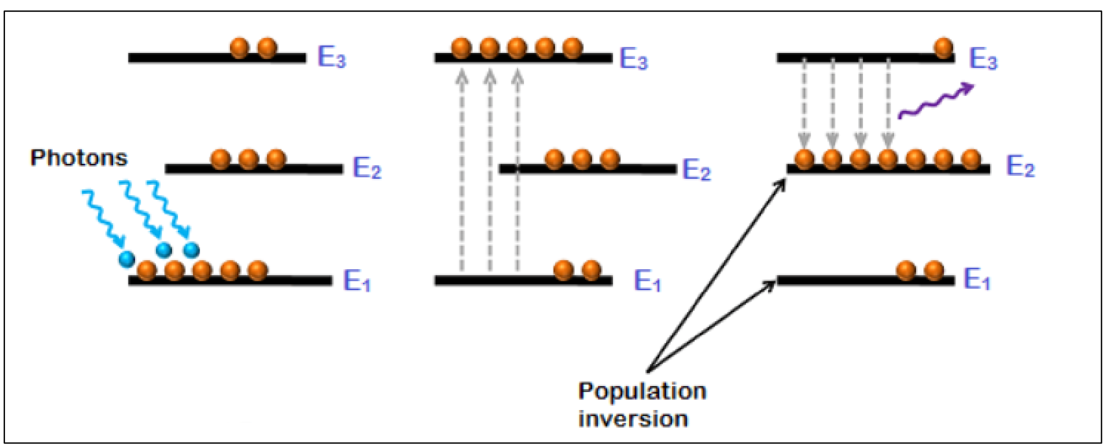

Fig. (2) Working Principle of Ruby Laser.

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Characteristics of Ruby Laser

- Type: Three-level solid-state laser
- Wavelength: 694.3 nm (deep red)
- Pumping Method: Optical (flashlamp)
- Efficiency: Relatively low (≈0.1–1%)
- Mode of Operation: Pulsed, not continuous (due to optical pumping requirements)

Applications

- Holography and optical research
- Range finding and target designation
- Medical surgery and dermatology
- Education and demonstration purposes

2- Nd:YAG Laser (Neodymium-doped Yttrium Aluminum Garnet Laser)

The Nd:YAG laser (Neodymium-doped Yttrium Aluminum Garnet) is a type of solid-state laser where neodymium ions (Nd^{3+}) are doped into a Yttrium Aluminum Garnet ($Y_3Al_5O_{12}$) crystal. It is one of the most widely used and versatile lasers in both industrial and medical fields. The laser typically emits light at a wavelength of 1064 nm, which lies in the near-infrared region of the electromagnetic spectrum.

Working Principle

1. **Pumping:** The Nd: YAG crystal is optically pumped using **laser diodes** or **flash lamps**. These pump sources emit light around **808 nm**, which is strongly absorbed by the Nd^{3+} ions inside the crystal.
2. **Excitation:** The absorbed energy excites the neodymium ions to a higher energy level.

3. **Spontaneous Emission:** Some ions drop to a slightly lower energy level, releasing photons spontaneously.
4. **Stimulated Emission:** These photons stimulate other excited ions to emit photons of the same wavelength and phase, creating a **coherent beam** of light.
5. **Resonator:** Mirrors placed at both ends of the laser cavity reflect the light back and forth, amplifying it through multiple passes before a portion exits through a **partially reflective mirror**, forming the laser beam.

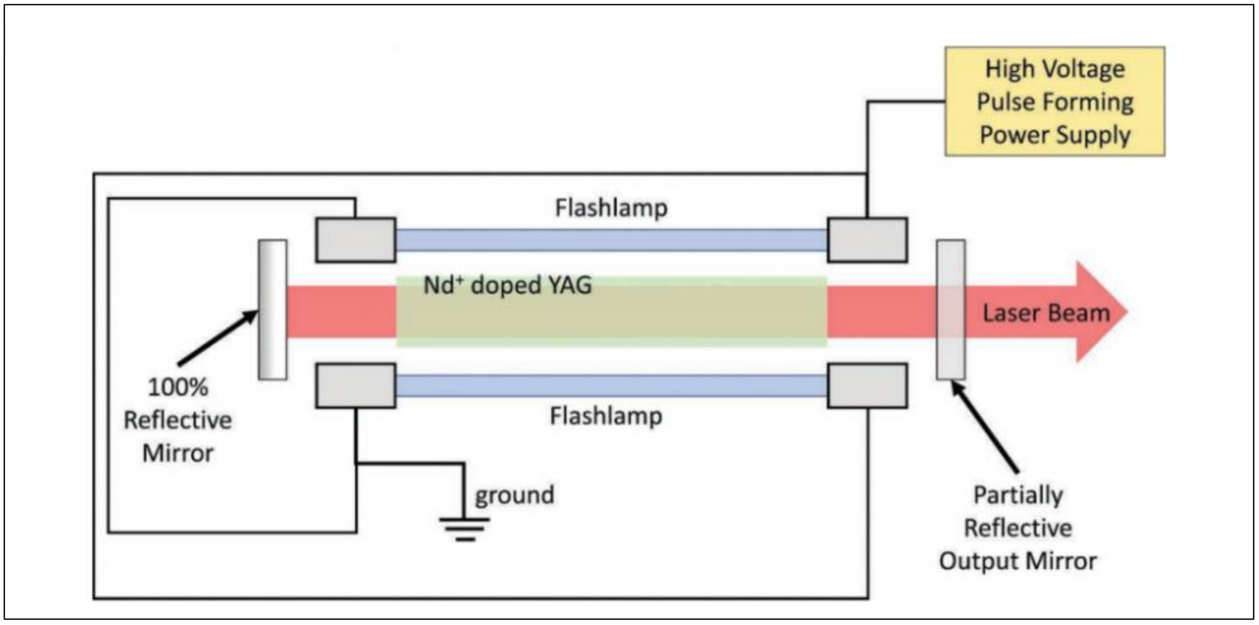

Fig. (3) Nd: YAG Laser.

Properties

- **Active Medium:** Nd^{3+} ions doped into $Y_3Al_5O_{12}$ crystal
- **Wavelength:** 1064 nm (infrared region)
- **Laser Type:** Four-level system (low lasing threshold)
- **Cooling:** Can operate at **room temperature** with efficient heat removal
- **Efficiency:** High optical-to-optical conversion efficiency

- **Durability:** Mechanically strong and thermally stable crystal

Applications

- **Medical Field:**
  - Laser surgery (ophthalmology, dermatology, dentistry)
  - Tattoo and hair removal
  - Treatment of vascular lesions
- **Industrial Applications:**
  - Cutting, welding, drilling, and engraving of metals and ceramics
  - Micromachining and marking
- **Military and Defense:**
  - Target designation and range finding
  - LIDAR (Light Detection and Ranging) systems

3- Nd:YLF Laser

Neodymium-doped lithium yttrium fluoride (Nd:YLF) has several advantages compared to Nd:YAG. The emission wavelength is nearly the same as that of Nd:YAG—**1053 nm or 1047 nm**, depending on the polarization direction. However, Nd:YLF has a fluorescence lifetime of approximately 480 μs, which is more than double that of Nd:YAG. This theoretically reduces the required pump power by about half.

The stimulated emission cross section of Nd:YLF is roughly half that of Nd:YAG, which decreases the optical gain but also minimizes parasitic effects such as amplified spontaneous emission (ASE). Unfortunately, Nd:YLF exhibits

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significantly lower thermal conductivity, which prevents its use in high-average-power laser systems.

Another drawback is the inferior mechanical strength of YLF crystals, making it considerably more difficult to fabricate large, high-optical-quality crystals compared to Nd:YAG. Despite these limitations, Nd:YLF shares nearly identical absorption characteristics with Nd:YAG and can be efficiently diode-pumped using similar methods.

In addition, Nd:YLF is a naturally birefringent material, meaning it produces linearly polarized laser output without the need for additional optical components. This property is highly beneficial for applications that require stable polarization. Typical applications of Nd:YLF lasers include Q-switched and mode-locked laser systems, scientific research, medical instrumentation, LIDAR, and precision spectroscopy. While it is not ideal for high-power continuous-wave operation due to thermal limitations, Nd:YLF remains an excellent choice for pulsed and polarization-sensitive laser systems that demand high beam quality and energy efficiency.