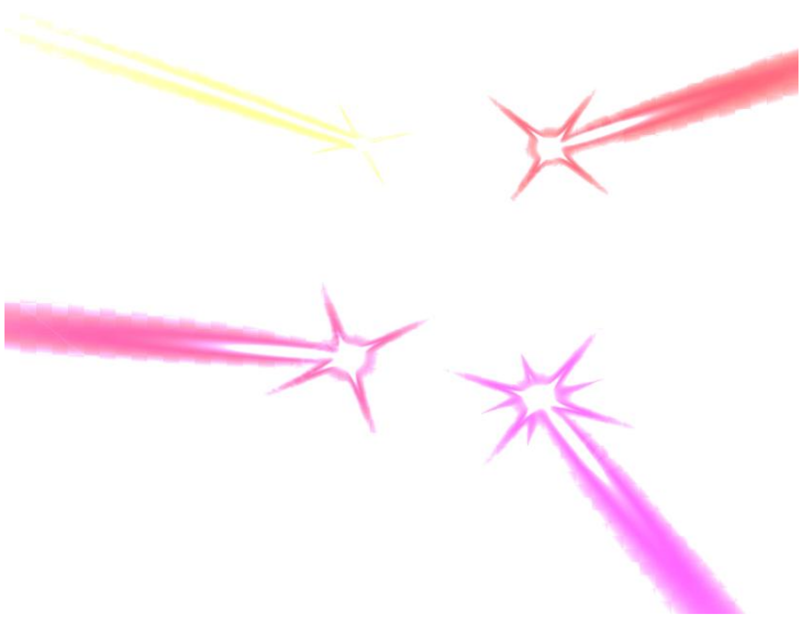
Al-Mustaqbal University / College of Engineering & Technology
Department of Medical Instrumentation Techniques Engineering
Class: 4th
Subject: Medical Laser Systems
Lecturer: MSc. Huda Wasfi Hassoon
1st term – Lecture No. 1 & Lecture Name :Introduction to Light & Laser Generation

Lecture 1
Introduction to Light & Laser Generation



Lecturer:
MSc. Huda Wasfi Hassoon

Email (: huda.wasfi@uomus.edu.iq)

Light is one of the most fundamental phenomena in physics. It is essential not only for vision and daily life, but also for understanding modern technologies such as lasers. To fully understand how lasers work, we must first study the nature of light itself, its properties, and how it interacts with matter.

The Nature of Light

Light is a form of **electromagnetic radiation**, which means it is a wave that can travel through space carrying energy. Unlike sound, which needs air or another medium to propagate, light does not require any material medium. It can move through a complete vacuum at the constant speed of about $3.0 \times 10^8\ m/s$.

An electromagnetic wave consists of two parts: an **electric field** and a **magnetic field**. These fields are oscillating and always oriented at right angles to each other. Moreover, both fields are also perpendicular to the direction in which the wave travels. For example, if the wave is moving forward along the x-axis, the electric field might oscillate vertically along the y-axis, while the magnetic field oscillates horizontally along the z-axis. This arrangement is fundamental and is shown in most diagrams of electromagnetic waves.

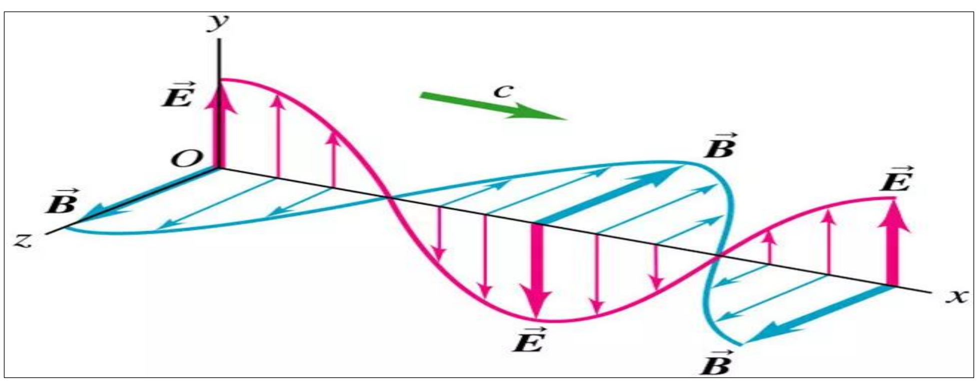


Fig. (1) Electromagnetic wave propagation.

The Electromagnetic Spectrum

Light visible to the human eye is only a tiny part of a much larger range called the **electromagnetic spectrum**. This spectrum includes all types of electromagnetic waves, ordered by their wavelength and frequency. At the low-energy, long-wavelength end, we have **radio waves**, used in broadcasting and communication. Next come **microwaves**, used in radar and cooking. After that is the **infrared region**, which we often feel as heat.

In the middle of the spectrum is the **visible light region** (about 400–700 nm), which includes all the colors that the human eye can detect—from red at longer wavelengths to violet at shorter wavelengths. Beyond the visible region lies **ultraviolet (UV) radiation**, which has shorter wavelengths and can cause sunburn. Then we move to **X-rays**, widely used in medical imaging, and finally **gamma rays**, which have the shortest wavelengths and the highest energies, often produced in nuclear reactions. Thus, the visible part of the spectrum is only a small window in a very broad range of electromagnetic waves.

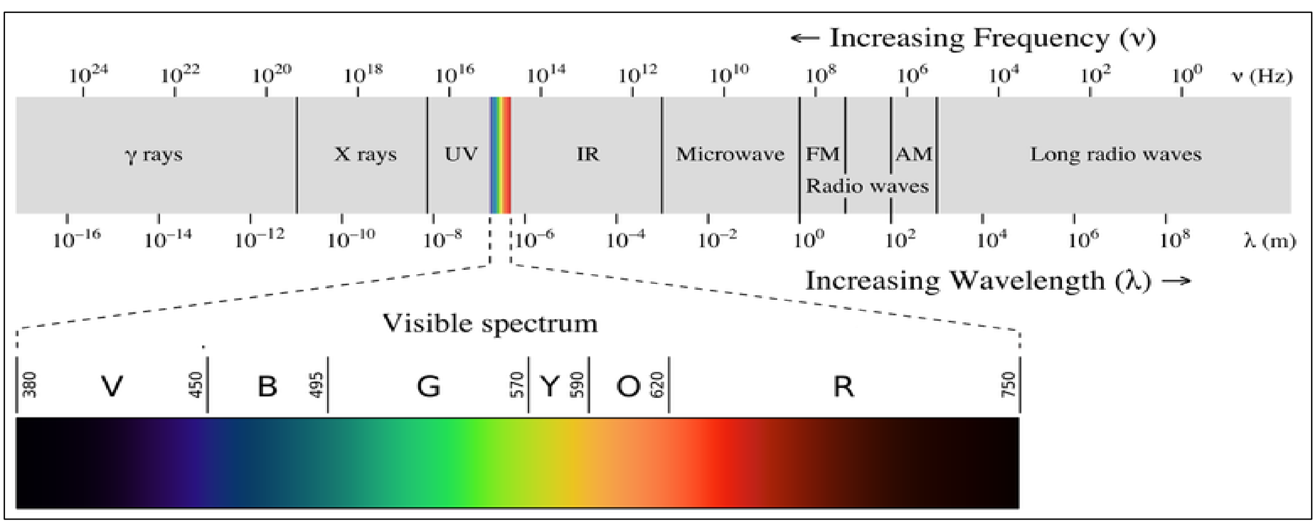


Fig. (2) The electromagnetic spectrum.

Email (: huda.wasfi@uomus.edu.iq)

Basic Properties of Light Waves

Like all waves, light is characterized by three main quantities: wavelength, frequency, and amplitude.

- The **wavelength (λ)** is the distance between two consecutive peaks of the wave.
- The **frequency (ν)** is the number of oscillations that pass a point per second.
- The **period (T)** is the time required for one complete cycle, and it is related to frequency by $T = 1/\nu$.

The wavelength and frequency are connected by a simple relation:

$$\nu = \frac{c}{\lambda}$$

where c is the speed of light in vacuum. This means that waves with higher frequencies always have shorter wavelengths, while waves with lower frequencies have longer wavelengths.

The **amplitude** of the wave, which is the maximum strength of the electric field, determines the **intensity** of light. The intensity is proportional to the square of the amplitude. In simple terms, the brighter the light, the larger the electric field associated with it.

Photons and the Particle Nature of Light

Although light is a wave, it also shows particle-like behavior. The particle form of light is called a **photon**. Each photon carries a specific amount of energy, which depends only on the frequency of the light:

$$E = h\nu$$

Here, h is Planck's constant.

Email (: huda.wasfi@uomus.edu.iq)

This concept explains why ultraviolet light, which has a high frequency, carries much more energy per photon than radio waves, which have very low frequency. The brightness of a light beam is therefore connected not only to the electric field amplitude, but also to the number of photons it contains.

This dual nature of light—sometimes behaving like a wave and sometimes like a particle—is called **wave–particle duality**, and it is crucial in modern physics.

Interaction of Light with Matter

In 1916, Albert Einstein introduced three important processes that describe how light interacts with matter: **absorption, spontaneous emission, and stimulated emission**.

- Electrons in atoms can only occupy specific energy levels. Normally, they stay in the lowest level, called the ground state. When a photon with the right energy is **absorbed,** the electron moves to a higher, excited state.
- Excited states are unstable. After a short time (the lifetime), the electron falls back to a lower level, releasing a photon. This is called **spontaneous emission**. The emitted photon has random direction and phase, which is why ordinary light is incoherent.
- The most important process is **stimulated emission**. If a photon passes near an excited atom, it can trigger the release of another photon. This new photon is identical to the first—same energy, frequency, phase, and direction.

Email (: huda.wasfi@uomus.edu.iq)

This property of stimulated emission is the fundamental principle of the laser. For a laser to work, stimulated emission must dominate over absorption and spontaneous emission.

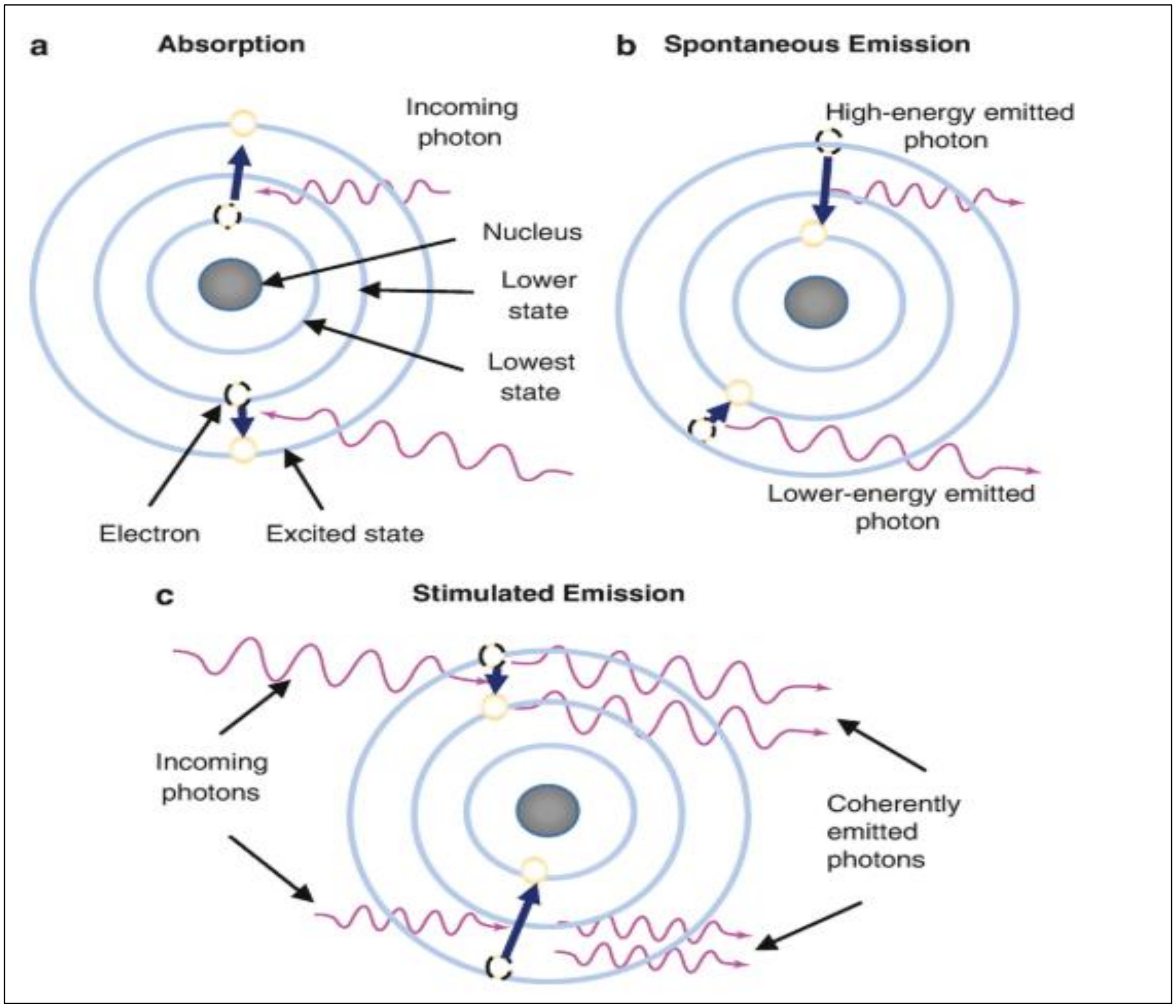


Fig. (3) Schematic of (a) absorption, (b) spontaneous emission, and (c) stimulated emission.

Introduction to Lasers

The term "laser" is an acronym for **Light Amplification by Stimulated Emission of Radiation**. A laser is an optical system that generates a highly special form of light. Unlike ordinary light (such as from a light bulb), which is incoherent and spreads in all directions, laser light is distinguished by three key properties:

1. **Coherence:** The light waves are in phase with each other, both in time and space.
2. **Monochromaticity:** The light consists of essentially a single pure color, meaning a very narrow wavelength range.
3. **Directionality:** The beam is highly collimated and diverges very little, allowing it to travel long distances without spreading.

This unique combination of properties makes lasers invaluable in countless applications, from surgery and barcode scanners to telecommunications and industrial cutting.

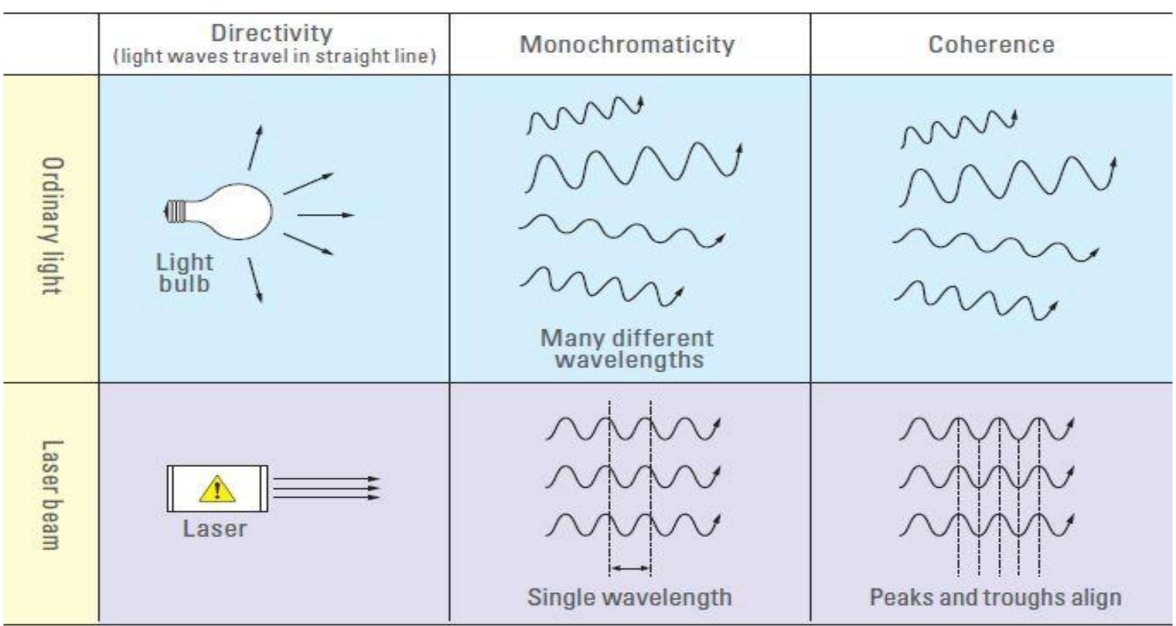


Fig. (4) The difference between Laser and Light.

Email (: huda.wasfi@uomus.edu.iq)

Population inversion

Normally, most atoms in a material reside in their lowest energy level (ground state). This is the natural order. **Population Inversion** is the fundamental process that makes a laser work. It is the deliberate creation of an "upside-down" state where more atoms are pushed into a higher energy level than a lower one. This inversion is crucial because it allows light to be **amplified** instead of absorbed. Without it, stimulated emission cannot dominate, and lasing is impossible. It is the non-negotiable prerequisite for any laser.

1- Three-Level Laser

In a three-level laser, the atoms in the gain medium exist in three main energy states:

1. **Ground State (E_1):** The lowest energy level where most atoms reside initially.
2. **Excited State (E_3):** A high-energy level that atoms are pumped into.
3. **Metastable State (E_2):** A semi-stable, intermediate energy level with a relatively long lifetime.

How it Works:

1. **Pumping:** Energy (e.g., light or electrical discharge) is used to "pump" atoms from the ground state (E_1) to the high-energy excited state (E_3).
2. **Rapid Decay:** Atoms in E_3 quickly decay (non-radiatively) to the metastable state (E_2).

3. **Population Inversion:** For lasing to occur, more atoms must be in the metastable state (E_2) than in the ground state (E_1). This is called **population inversion**.
4. **Stimulated Emission:** When a photon with the correct energy (E_2 - E_1) passes by, it stimulates an atom in E_2 to drop to E_1, emitting an identical photon. This creates the laser light.
5. The atom returns to E_1, ready to be pumped again.

Achieving population inversion is very difficult. Because the laser transition ends at the ground state (E_1), you must pump more than half of the total atoms from E_1 to E_2 to have more atoms in E_2 than in E_1. This requires **very high pumping power**, making three-level lasers inefficient.

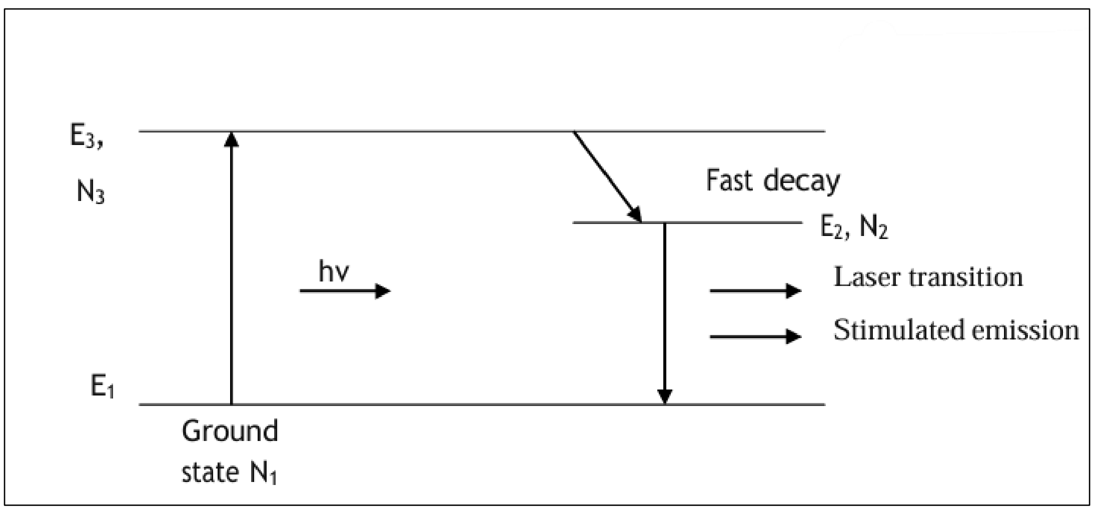


Fig. (5) Schematic diagram of three-level laser.

2- Four-Level Laser

A four-level laser uses a more efficient system with four main energy states:

1. **Ground State (E_1)**
2. **Excited State (E_4)**
3. **Upper Laser Level (E_3):** A metastable state.
4. **Lower Laser Level (E_2):** A short-lived intermediate state.

How it Works:

1. **Pumping:** Atoms are pumped from the ground state (E_1) to the high-energy excited state (E_4).
2. **Rapid Decay:** Atoms in E_4 quickly decay to the upper laser level (E_3).
3. **Population Inversion:** It is much easier to achieve population inversion between E_3 and E_2 because the lower laser level (E_2) is normally almost empty (unlike the ground state in a three-level system).
4. **Stimulated Emission:** A photon triggers an atom to drop from E_3 to E_2, emitting laser light.
5. **Rapid Emptying:** Atoms in the lower laser level (E_2) decay very rapidly back to the ground state (E_1), keeping E_2 empty and maintaining the population inversion.

Since the lower laser level (E_2) is not the ground state and empties quickly, it is very easy to maintain a population inversion. This makes four-level lasers **highly efficient** and allows them to operate with **much lower pumping power**. Most common modern lasers are four-level lasers.

Email (: huda.wasfi@uomus.edu.iq)

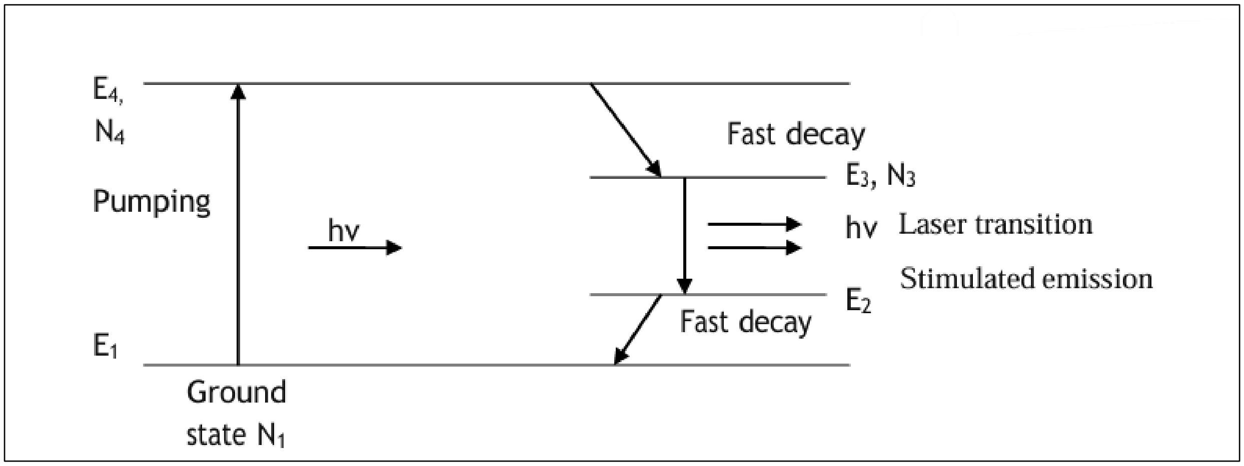


Fig. (6) Schematic diagram of four-level laser.

The Optical Components of a Laser System

A laser works on the principle of light amplification by stimulated emission of radiation. To achieve this, it requires specific optical components to generate, contain, and control the light. Every laser consists of four fundamental parts:

1. The Gain Medium (The Heart of the Laser)

- **What it is:** This is the core material where light amplification actually occurs. It can be a solid, liquid, gas, or semiconductor.
- **Function:** Its atoms or molecules are "pumped" to an excited energy state. When light passes through it, these excited atoms are stimulated to emit new photons that are identical to the incoming ones, leading to **optical amplification**.
- **Examples:**
    - **Solid-State:** crystal.
    - **Gas:** Helium-Neon (HeNe), Carbon Dioxide (CO_2).

- **Liquid:** Organic dye solutions.
- **Semiconductor:** Gallium Arsenide (GaAs) in laser diodes.

2. The Pump Source (The Engine)

- **What it is:** This is the device that provides energy to the gain medium.
- **Function:** Its "pumps" the atoms in the gain medium from their ground state to a higher, excited energy state. This is essential for creating the **population inversion** required for lasing.

3. The Optical Resonator (The Amplifying Cavity)

- **What it is:** This is a set of two mirrors placed on either side of the gain medium, forming a cavity where light can bounce back and forth.
- **Function:** It traps the light photons, making them pass through the gain medium repeatedly. Each pass results in further amplification through stimulated emission. It also helps to create a highly **collimated** and **coherent** beam.
- **Key Components:**
  - **Full Reflector (High Reflector Mirror):** One mirror is ~100% reflective, reflecting almost all light back into the cavity.
  - **Output Coupler (Partial Reflector):** The second mirror is partially transparent (e.g., 95% reflective, 5% transmitting). It allows a portion of the highly amplified light inside the cavity to escape as the **useful laser beam**.

4. The Output Laser Beam (The Result)

- **What it is:** The intense, highly organized beam of light that exits through the output coupler.
- **Defining Properties:** This is what distinguishes laser light from ordinary light:
  - **Coherence:** The light waves are in phase with each other.
  - **Monochromaticity:** The light consists of a very pure color (a narrow range of wavelengths).
  - **Collimation:** The beam is highly directional and spreads out very little over long distances.

The Lasing Cycle

1. **Pumping:** The pump source energizes the atoms in the gain medium.
2. **Population Inversion:** A population inversion is achieved in the gain medium.
3. **Spontaneous Emission:** Some excited atoms decay randomly, emitting photons in all directions.
4. **Stimulated Emission & Amplification:** Photons traveling along the cavity's axis bounce between the mirrors. As they pass through the gain medium, they **stimulate** excited atoms to emit more identical photons, creating a chain reaction and a rapid build-up of light intensity.
5. **Output:** When the amplified light inside the cavity is powerful enough, a portion passes through the output coupler, forming the **coherent, highly concentrated laser beam**.

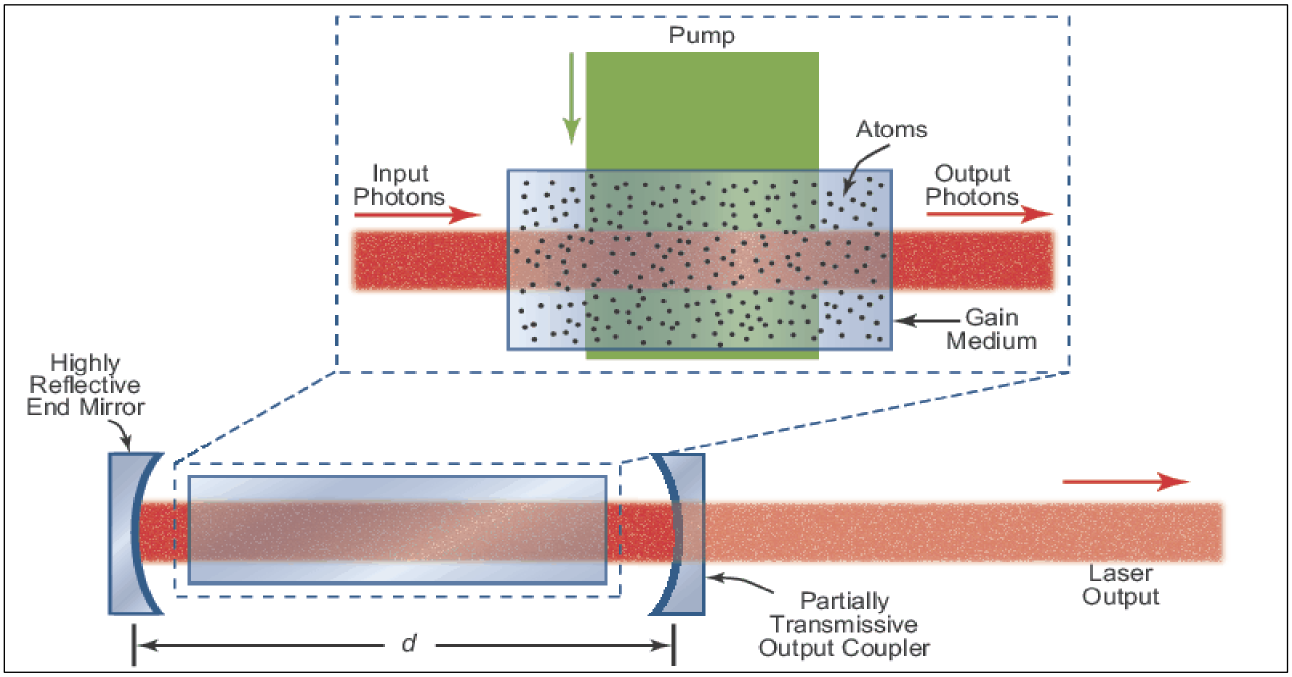


Fig. (6) Physical components of a laser system.

Q1: Is laser light always part of the visible region of the electromagnetic spectrum?

Solution:

Q2: What is the main part inside a laser that generates the light?

Solution:

Q3: What is the most important property that makes laser light different from light from a normal lamp?

Solution: