LASER

Light Amplification by Stimulated Emission of Radiation

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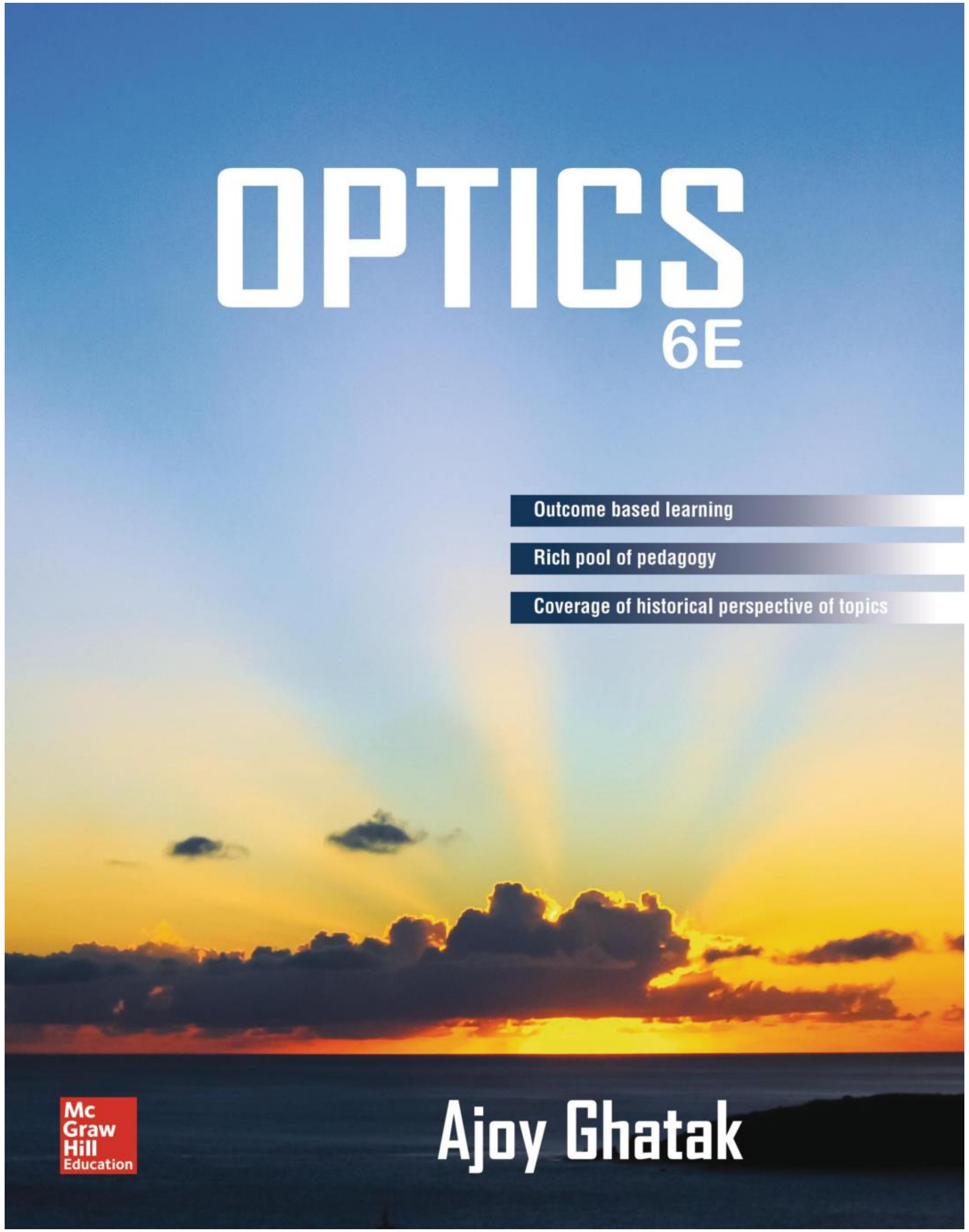
Reference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Lasers: an introduction

Chapter Twenty-Six

LASER

LASER stands for **Light Amplification by Stimulated Emission of Radiation**. It is a device that emits light through a process of **optical amplification** based on the principles of **stimulated emission** of electromagnetic radiation.

Key Features of Laser Light:

- **Monochromatic** – Laser emits light of a single wavelength (or a very narrow range of wavelengths).
- **Coherent** – The emitted photons are in phase, leading to a highly organized wavefront.
- **Highly Directional** – Laser beams are very narrow and do not spread out like ordinary light.
- **High Intensity** – Due to coherence and minimal divergence, lasers can be extremely powerful.

Applications of Lasers:

- **Industrial** – Cutting, welding, engraving, and marking.
- **Medical** – Laser surgery, eye treatments (LASIK), and cancer therapy.
- **Communication** – Fiber-optic communication and data transmission.
- **Scientific Research** – Spectroscopy, holography, and quantum mechanics experiments.
- **Military & Defense** – Laser-guided weapons and rangefinders.
- **Textile Industry** – Fabric cutting, engraving, and patterning.

Spontaneous and Stimulated Emissions

1. Spontaneous emission. Atoms in the energy state E_2 can make a (spontaneous) transition to the energy state E_1 with the emission of radiation of frequency

$$\omega = \frac{E_2 - E_1}{\hbar} \qquad \textbf{(1)}$$

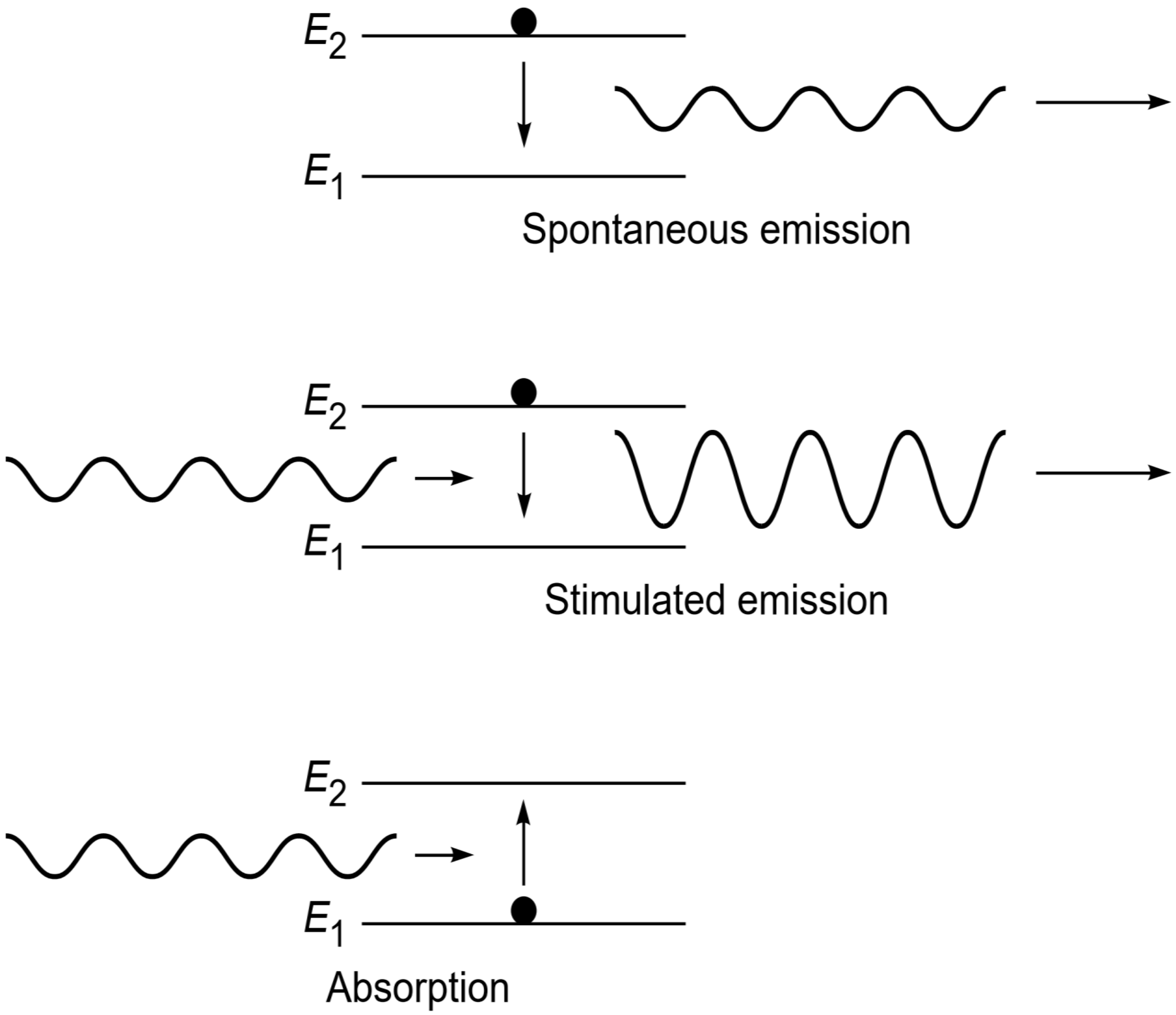
where

$$\hbar = \frac{h}{2\pi} \approx 1.0546 \times 10^{-34}\ \text{J s}$$

and h ($\approx 6.626 \times 10^{-34}$ J s) is known as Planck's constant. Since this process can occur even in the absence of any radiation, this is called spontaneous emission [see Fig. 26.1(a)]. The rate of spontaneous emission is proportional to the number of atoms in the excited state.

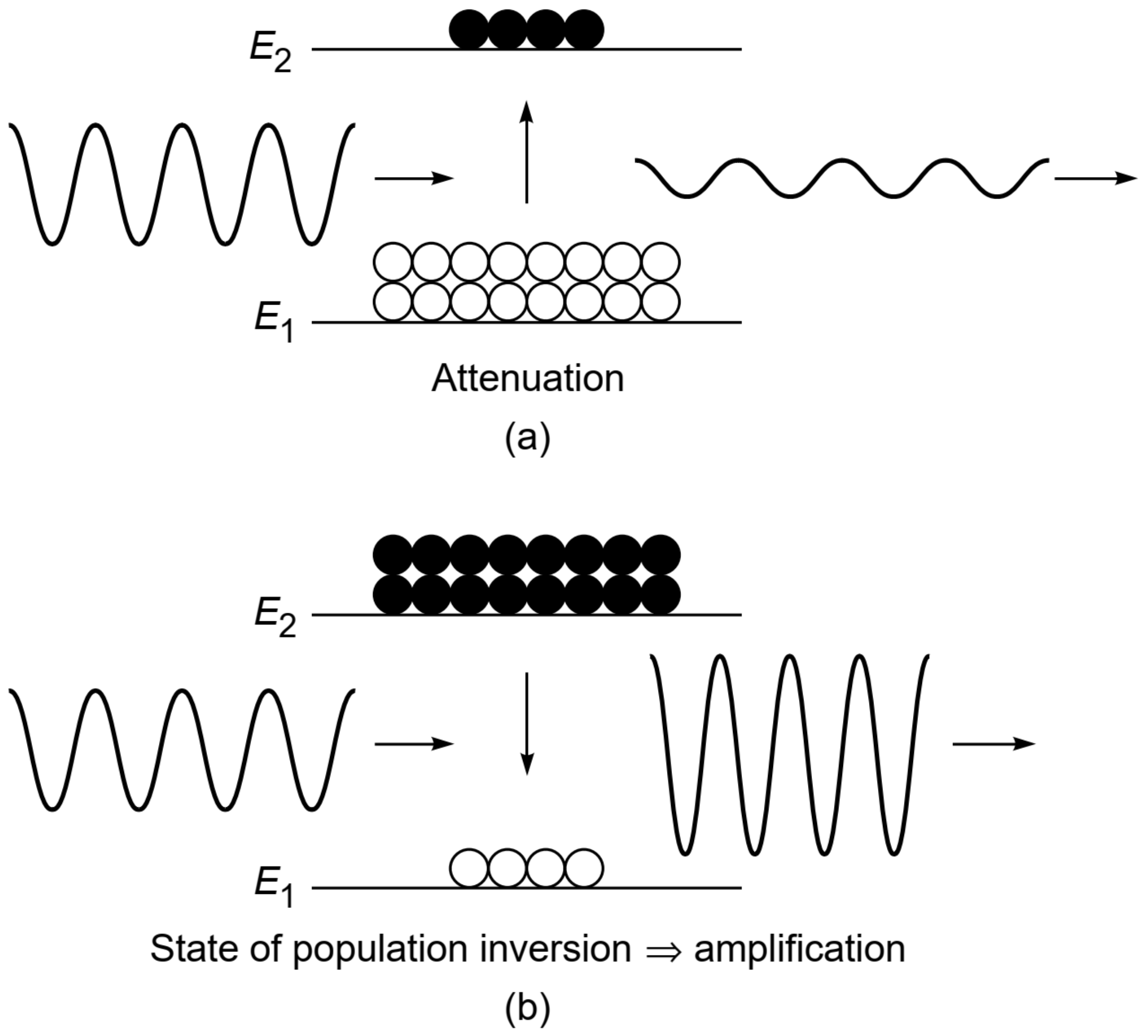
2. Stimulated emission. As put forward by Einstein, when an atom is in the excited state, it can also make a transition to a lower energy state through what is known as stimulated emission, in which an incident signal of appropriate frequency triggers an atom in an excited state to emit radiation—this results in the amplification of the incident beam [see Fig. 26.1(b)]. The rate of stimulated emission depends on both the intensity of the external field and the number of atoms in the excited state.

3. Stimulated absorption. Stimulated absorption (or simply absorption) is the process in which the electromagnetic radiation of an appropriate frequency (corresponding to the energy difference of the two atomic levels) can pump the atom to its excited state [see Fig. 26.1(c)]. The rate of stimulated absorption depends both on the intensity of the external field and on the number of atoms in the lower energy state.



Basic Working Principle of a Laser

Fig. 26.2 (a) A larger number of atoms in the lower state result in the attenuation of the beam. (b) A larger number of atoms in the upper state (which is known as population inversion) result in the amplification of the beam.



Basic Working Principle of a Laser

- **Absorption** – Electrons in an atom absorb energy and move to a higher energy level.
- **Spontaneous Emission** – The excited electrons return to a lower energy level by emitting photons.
- **Stimulated Emission** – An incoming photon induces an excited electron to release another photon of the same phase, frequency, and direction. This process leads to **light amplification**.
- **Population Inversion** – More electrons are in an excited state than in the ground state, which is necessary for laser action.
- **Optical Feedback** – The emitted photons are reflected back and forth in an **optical cavity** to enhance amplification before exiting as a laser beam.

Main Components of the Laser

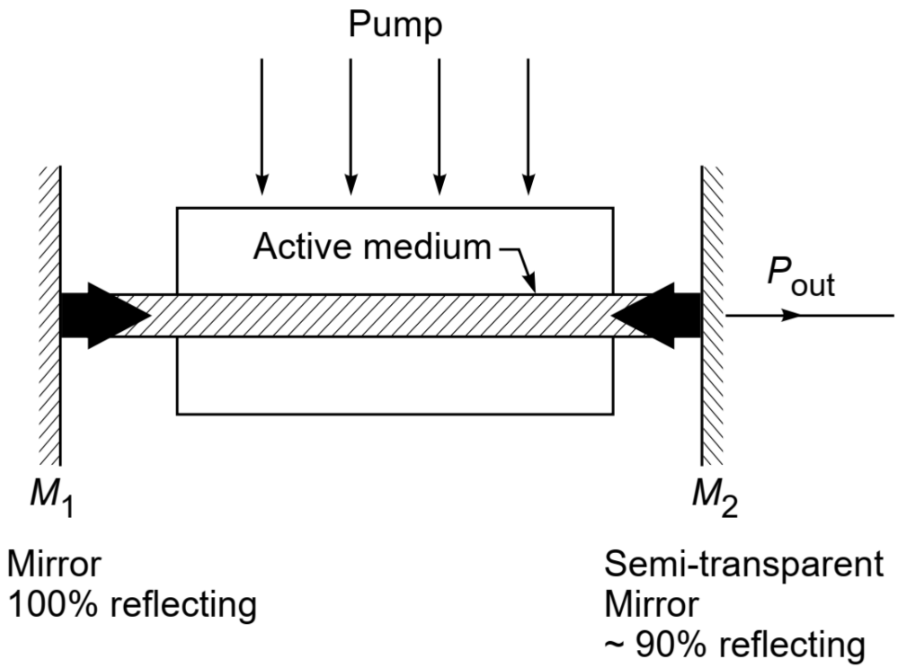


Fig. 26.3 The three basic components of a laser are (1) the active medium (which provides amplification), (2) the optical resonator (which provides frequency selection and optical feedback), and (3) the pump (which supplies power to the active medium to achieve population inversion).

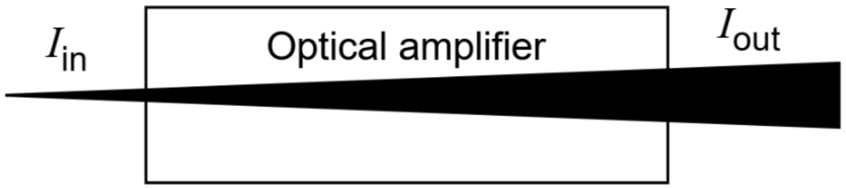


Fig. 26.4 The active medium essentially consists of a collection of atoms in a state of population inversion which can amplify the input light beam (or spontaneously emitted light) by stimulated emission. This is known as optical amplification.

Main Components of the Laser

1. Active medium. The active medium consists of a collection of atoms, molecules, or ions (in solid, liquid, or gaseous form) which is capable of amplifying light waves. Under normal circumstances, there are always a larger number of atoms in the lower energy state than in the excited energy state. An electromagnetic wave passing through such a collection of atoms is attenuated; this is discussed in detail in Sec. 26.6. To have optical amplification, the medium has to be kept in a state of *population inversion*, i.e., in a state in which the number of atoms in the upper energy level is greater than that in the lower energy level—this is achieved by means of the pump.

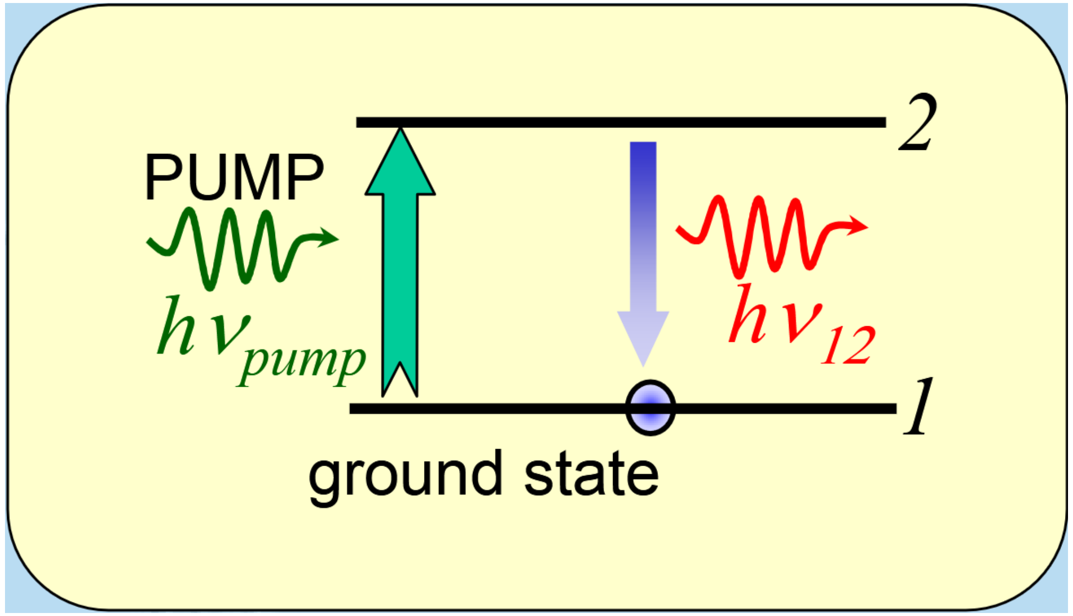
2. Pumping source. The pump enables us to obtain such a state of population inversion between a pair of energy levels of the atomic system. When we have a state of population inversion, the input light beam can get amplified by stimulated emission (see Fig. 26.4).

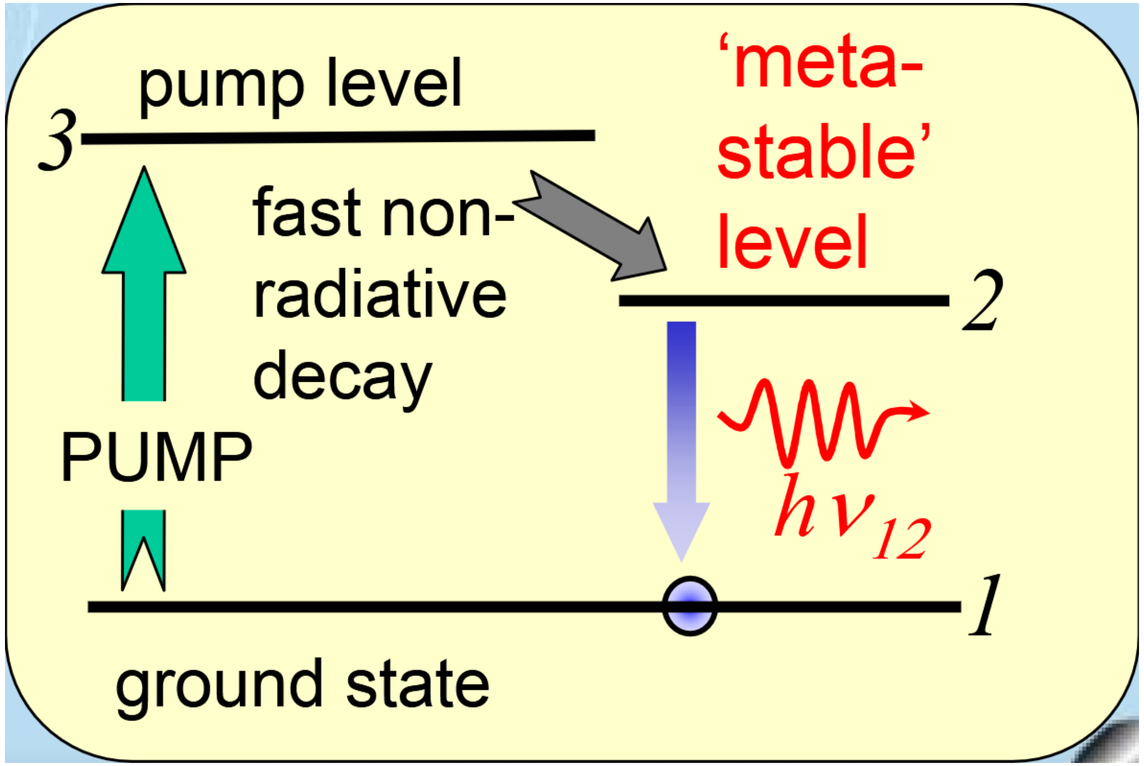
3. Optical resonator. A medium with population inversion is capable of amplification; however, for it to act as an oscillator, a part of the output energy must be fed back into the system.[2] Such feedback is brought about by placing the active medium in a resonator; the resonator could be just a pair of mirrors facing each other.

The properties of a laser beam

1. **Monochromaticity** – A laser emits light of a single wavelength (or a very narrow range of wavelengths), making it highly monochromatic compared to ordinary light sources.
2. **Coherence** – Laser light exhibits both temporal and spatial coherence, meaning that the wavefronts are well-ordered and maintain a fixed phase relationship over time and distance.
3. **Collimation** – A laser beam is highly collimated, meaning it has very little divergence and can travel long distances with minimal spreading.
4. **High Intensity** – Due to the coherent superposition of light waves, a laser beam can achieve extremely high intensity compared to conventional light sources.
5. **Polarization** – Laser light is typically polarized, meaning the electric field oscillates in a specific direction, which can be controlled and utilized in applications requiring polarized light.
6. **Directionality** – A laser emits light in a very specific and narrow direction, unlike conventional sources that emit in multiple directions.

Three-level laser system

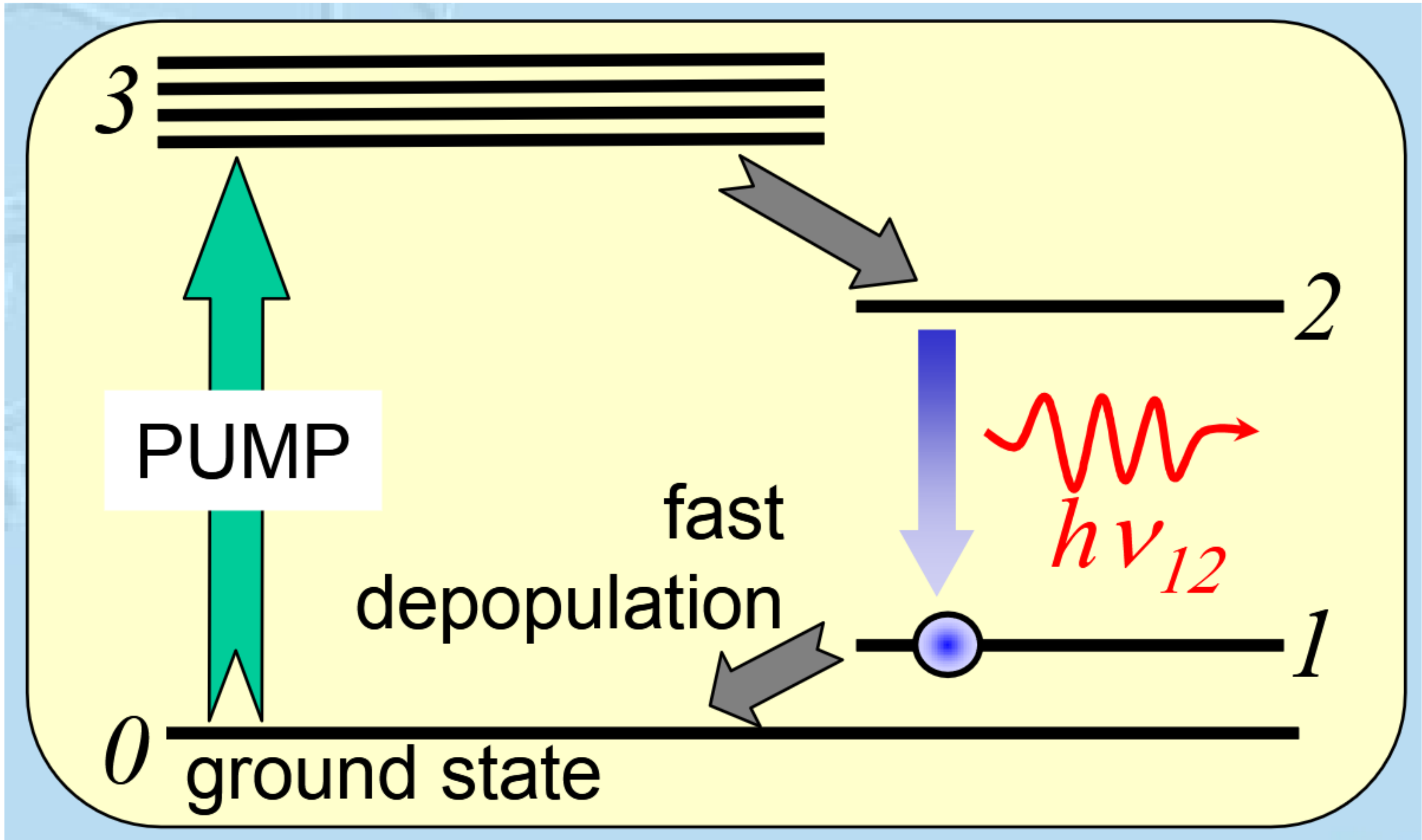




Three-level laser system

- Molecules are **pumped from the ground state** to an upper state.
- The upper state **quickly decays** to an **intermediate state** (longer lifetime) via **nonradiative processes**.
- **Stimulated emission** occurs between this intermediate state and the ground state.
- A major issue is the **high population of the ground state**, requiring intense pumping to achieve **population inversion**.
- If population inversion is not achieved, **absorption dominates** instead of stimulated emission.

Four-level laser system



Four-level laser system

- The laser transition occurs between an **upper state** and a **lower state slightly above the ground state**.
- **Faster decay** from the lower state to the ground state ensures a **low population** in the lower lasing state.
- This **reduces competition from absorption** and allows for **easier population inversion**.
- Requires **less intense pumping** compared to three-level lasers.

Four-level lasers are more efficient and easier to operate than three-level lasers due to the better separation of energy levels and lower competition from absorption.

Examples of Three-Level and Four-Level Laser Systems

Feature	Ruby Laser (Three-Level)	He-Ne Laser (Four-Level)
Active Medium	Cr^{3+}-doped Al_2O_3	Helium-Neon gas
Pumping	Optical (flash lamp)	Electrical discharge
Wavelength	694.3 nm (red)	632.8 nm (red)
Efficiency	Lower (requires intense pumping)	Higher (easier population inversion)
Applications	Holography, dermatology, range-finding	Metrology, barcode scanners, alignment

Laser in garment manufacturing

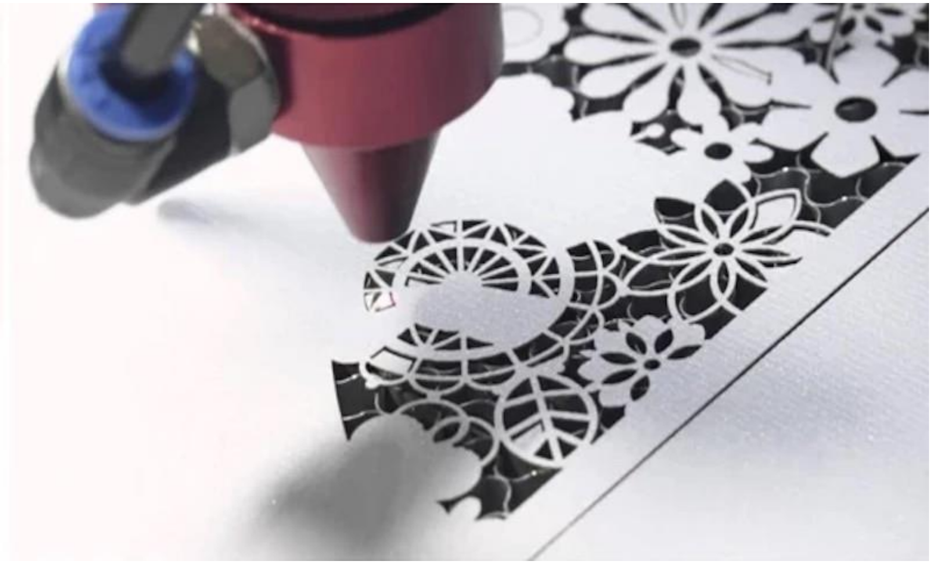


Fig. 5 Laser engraving items: **a** engraving machine, **b** denim, **c** garment, **d** buttons, **e** leather and **f** embroidery

Applications of Laser in Fabric Marking and Patterning

A. Fabric Marking

- **Tailoring & Garment Manufacturing** – Marks fabric for precision cutting and stitching.
- **Sewing & Embroidery Guides** – Assists in alignment without chalk or ink.
- **Barcode & QR Code Marking** – Useful for tracking in textile production.

B. Fabric Patterning & Engraving

- **Laser Etching & Engraving** – Burns patterns into fabric for decorative effects.
- **Denim Fading & Distressing** – Creates faded or worn-out looks in fashion.
- **Lace & Intricate Cutwork** – Cuts delicate patterns with precision, preventing fraying.

C. Laser Cutting for Fabric Design

- **Appliqué & Layered Designs** – Used in embroidery and decorative textiles.
- **Perforation & Ventilation Patterns** – Creates breathable patterns in sportswear.
- **Synthetic & Composite Fabric Cutting** – Ideal for polyester, nylon, and technical fabrics.