Laser in Medicine

Introduction

Light and Laser in Medicine

Light is a form of electromagnetic radiation that travels in waves and spans a broad spectrum of wavelengths, from infrared to ultraviolet. In medicine, light has long been used for illumination, diagnosis, and therapy—such as in endoscopy, imaging, and phototherapy.

However, ordinary light (like from bulbs or the sun) is polychromatic, incoherent, and divergent, which limits its precision and intensity in medical applications.

This led to the invention of the laser (Light Amplification by Stimulated Emission of Radiation) in 1960 by Theodore Maiman. Unlike normal light, laser light is highly monochromatic (single wavelength), coherent (in-phase), and collimated (parallel beams), making it exceptionally focused and powerful.

These properties make lasers ideal tools in medicine for:

- **Surgical precision**
- **Targeted therapy**
- **Non-invasive diagnostics**

The development of laser technology has revolutionized many medical fields, including dermatology, ophthalmology, oncology, and regenerative medicine.

Laser light is unique because it emits a narrow beam of a **single wavelength (monochromatic light)** that is **coherent** (each wave is in phase with the others) and

collimated (low divergence). These properties make the laser a highly efficient energy source.

The number and variety of applications of lasers in **biology and medicine** have increased significantly. The laser operates based on **Einstein's "Theory of Stimulated Emission of Radiation"**, which states that when an electrical source excites the optical cavity of a laser, the active medium absorbs the thermal, electrical, or optical energy, leading to photon emission.

Principles of Laser Operation

When an electrical or optical source is directed into the **laser optical cavity**, the excitation medium absorbs energy, causing electrons to become excited and store an exact quantum of energy. However, atoms in this excited state are unstable and **spontaneously emit energy** in the form of light. This emitted energy follows these steps:

1. **Spontaneous Emission** – Excited atoms release energy randomly.
2. **Stimulated Emission** – A photon interacts with an excited atom, causing it to emit another photon of the same wavelength, phase, and direction.

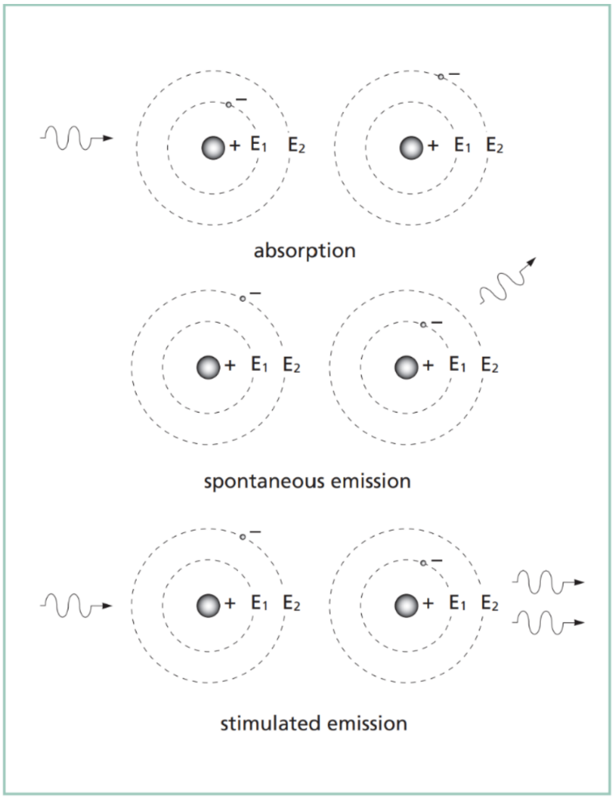
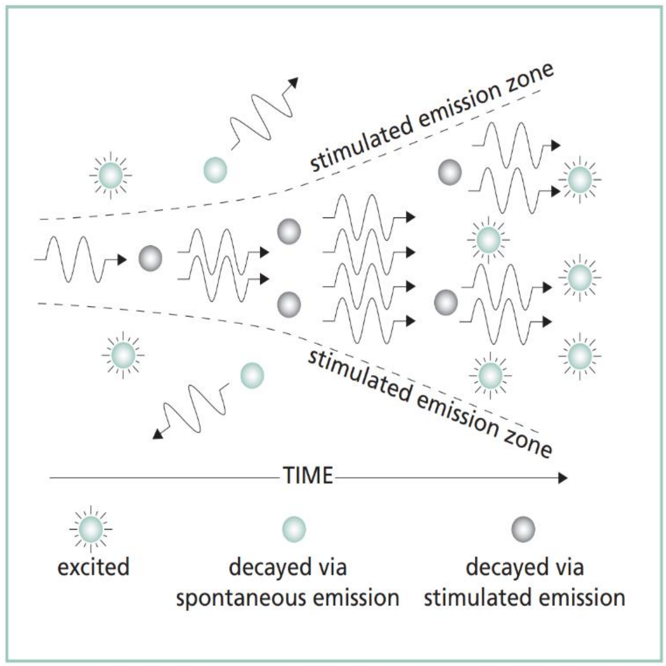


Figure 1 - Spontaneous and stimulated emission.

3. **Amplification** – The intensity of the laser beam increases as the emitted photons interact with other excited atoms, producing more photons.

Figure 2 - Amplification by stimulated emission.



4. **Optical Cavity Reflection** – Parallel mirrors in the cavity increase the **intracavity intensity**, allowing only a small portion (1% to 20%) of the light to escape through a **partially transparent front mirror** (output coupler).

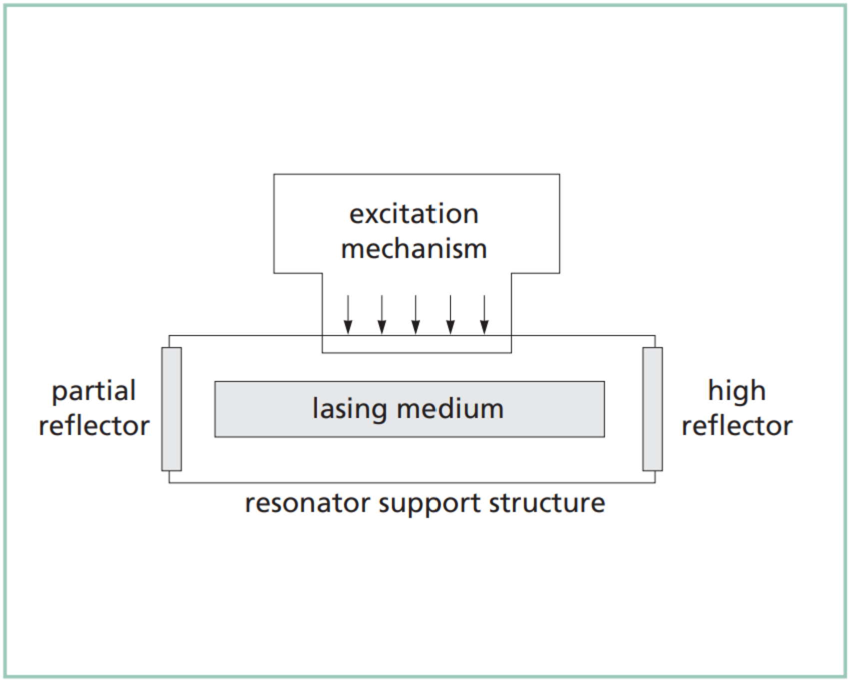


Figure 3 - Schematic diagram of a basic laser

Laser Properties

Laser light differs significantly from ordinary light due to its distinct properties:

- **Monochromaticity** – A laser emits a single wavelength of light, allowing for targeted medical applications.
- **Coherence** – The emitted light waves are in phase, enhancing precision.
- **Collimation** – Laser beams travel in a highly directed manner, with low divergence.
- **High Intensity** – Laser beams can concentrate energy on very small areas.

Types of Medical Lasers

Lasers used in medicine differ based on their excitation medium and output wavelength.

Laser Type	Wavelength	Medical Applications
CO_2 Laser	10.6 µm (Infrared)	Soft tissue surgery, dermatology
Nd:YAG Laser	1064 nm (Near IR)	Deep tissue penetration, oncology
Excimer Laser	193 nm (UV)	LASIK eye surgery, corneal reshaping
Argon Laser	488–514 nm (Visible)	Retinal treatments, vascular lesions
Diode Laser	810-980 nm	Dentistry, dermatology, hair removal

Understanding Laser Light and Normal Light in Medical Applications

1. **Monochromaticity (Single Wavelength vs. Multiple Wavelengths)**
    - **Laser Light:** A laser emits light of a **single specific wavelength**, which makes it highly useful for precise medical applications, such as cutting tissues or targeting specific chromophores (e.g., melanin in hair removal lasers).
    - **Normal Light:** Ordinary light sources (sunlight, bulbs, LEDs) emit a **broad spectrum of wavelengths**, which means they cannot selectively target specific tissues in medical applications.
2. **Coherence (Ordered Waves vs. Random Waves)**
    - **Laser Light:** The light waves in a laser beam are **in phase**, meaning they move together in a perfectly synchronized manner. This **coherence** allows laser beams to be **highly focused and powerful**.

- **Normal Light:** The waves are **out of phase** (incoherent), meaning they move randomly and interfere with each other, leading to **scattered and unfocused light**.

3. **Directionality (Straight Beam vs. Scattered Emission)**
    - **Laser Light:** Highly directional due to the **stimulated emission process** within the laser cavity. This property allows laser beams to be **precisely aimed**, making them useful for surgeries and eye treatments.
    - **Normal Light:** Spreads out in **all directions**. For example, a **light bulb** emits light in all directions, making it ineffective for precise applications.
4. **Collimation (Parallel Beam vs. Diverging Beam)**
    - **Laser Light:** Forms a **parallel beam with minimal divergence**. A laser beam can travel long distances without losing intensity, making it ideal for applications like **laser surgery and laser communication**.
    - **Normal Light:** Light waves spread apart as they move further from the source. For instance, at 1 meter from a filament lamp, the eye receives about **one-millionth** of the total emitted light, while a laser beam **remains strong even at long distances**.
5. **Intensity (High Power Density vs. Low Power Density)**
    - **Laser Light:** Concentrated energy allows **precise cutting, burning, and medical treatments**. For example, a **CO_2 laser** can cut through soft tissue with minimal bleeding.

- **Normal Light:** Lower intensity due to spreading, which makes it unsuitable for surgical applications.

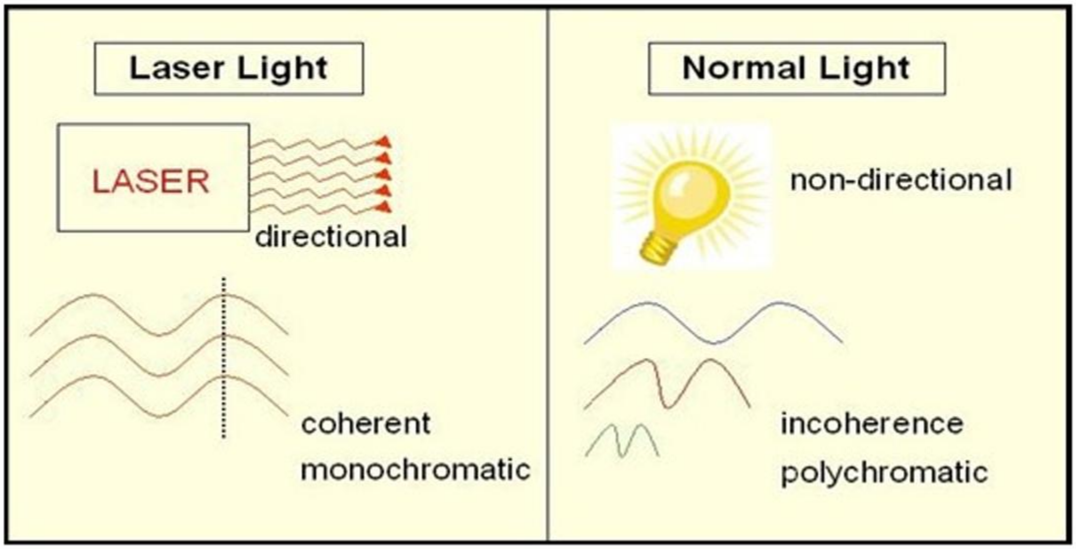


Figure 4: The difference between laser light and normal light.

Laser-Tissue Interactions

When a laser beam strikes biological tissue, several interactions occur:

1. **Reflection** – Some laser energy is reflected off the surface, affecting efficiency.
2. **Absorption** – Tissue absorbs laser energy, leading to heating, coagulation, or vaporization.
3. **Scattering** – The beam spreads within tissue, impacting penetration depth.
4. **Transmission** – Light passes through tissue with minimal interaction, useful for **endoscopic** applications.

Effects of Laser on Biological Tissues

The response of biological tissues to laser exposure depends on the wavelength, intensity, and duration of exposure:

- **Photothermal Effect** – Heat generation leads to tissue coagulation, vaporization, or incision (e.g., CO_2 laser surgery).
- **Photochemical Effect** – Laser energy triggers chemical reactions (e.g., **Photodynamic Therapy (PDT)** for cancer treatment).
- **Photoablation** – High-energy laser disrupts molecular bonds, removing tissue layers (e.g., **Excimer lasers** for LASIK surgery).

Laser Power, Irradiation Dose, and Energy Density in Medicine

In medical applications, the effectiveness and safety of laser procedures depend greatly on controlling the amount of energy delivered to the tissue. This is why understanding laser power, dose, and energy density is essential for clinicians.

- **Laser Power (P)**

Power is the rate at which energy is delivered by the laser, measured in watts (W). Higher power means more energy is delivered per second.

Formula: Energy (Joules) = Power (Watts) × Time (Seconds)

- **Energy Density / Fluence**

Also known as laser dose, this is the amount of energy per unit area delivered to the tissue, measured in J/cm^2.

Formula: Dose (J/cm^2) = Power Density (W/cm^2) × Time (s)

Or: Dose = Energy (J) / Area (cm^2)

Higher dose focused on a small area results in stronger tissue effects.

- **Power Density (Irradiance)**

Refers to power per unit area, measured in W/cm². It affects how quickly the laser interacts with the tissue.

- **High power density:** fast cutting or ablation.
- **Low power density:** gentle stimulation or heating.

Why These Parameters Are Important

Each treatment requires a specific dose to be effective and safe. Too much energy can burn or scar tissue. Too little energy might be ineffective.

Practical Example

Procedure	Target Tissue	Typical Dose (J/cm²)	Purpose
Tattoo removal	Ink pigment	1–5	Break pigment particles
Skin resurfacing	Epidermis	5–10	Ablate superficial layers
Hair removal	Hair follicle	10–40	Destroy follicle with heat
Photobiomodulation	Muscle/nerve	1–8	Reduce pain, stimulate repair

Medical Applications of Lasers

1. Laser Surgery

- **CO_2 Lasers** – Used in ENT surgery, dermatology, gynecology, and general surgery.
- **Nd:YAG Lasers** – Penetrate deep into tissues, useful in **prostate surgery and endoscopic tumor removal**.
- **Advantages of Laser Surgery:**
  - Minimally invasive
  - Reduced bleeding
  - Faster healing and recovery

2. Dermatology Applications

- **Hair Removal** – Lasers target melanin in hair follicles (Alexandrite, Diode, Nd:YAG lasers).
- **Tattoo Removal** – Q-switched lasers break down tattoo pigments.
- **Skin Resurfacing** – Fractional lasers reduce scars and wrinkles.

3. Ophthalmology Applications

- **Photocoagulation** – Seals leaking blood vessels in diabetic retinopathy.
- **LASIK & PRK** – Excimer lasers reshape the cornea to correct vision.
- **Femtosecond Lasers** – Used in **cataract surgery** for precision incisions.

4. Oncology (Cancer Treatment)

- **Photodynamic Therapy (PDT)** – Uses laser-activated drugs to destroy cancer cells.

- **Tumor Ablation** – High-power lasers eliminate cancerous tissue.

5. Laser-Based Diagnostics

- **Optical Coherence Tomography (OCT)** – High-resolution imaging for the retina and blood vessels.
- **Laser Doppler Imaging** – Measures blood flow in tissues.
- **Raman Spectroscopy** – Detects early cancer by analyzing molecular changes in tissues.

Future Trends in Laser Medicine

- **AI-Driven Laser Applications** – Artificial intelligence enhances robotic surgery and precision treatments.
- **Nanoparticle-Assisted Laser Therapy** – Nanoparticles improve targeting of cancer cells.
- **Laser-Based Regenerative Medicine** – Potential applications in tissue engineering.

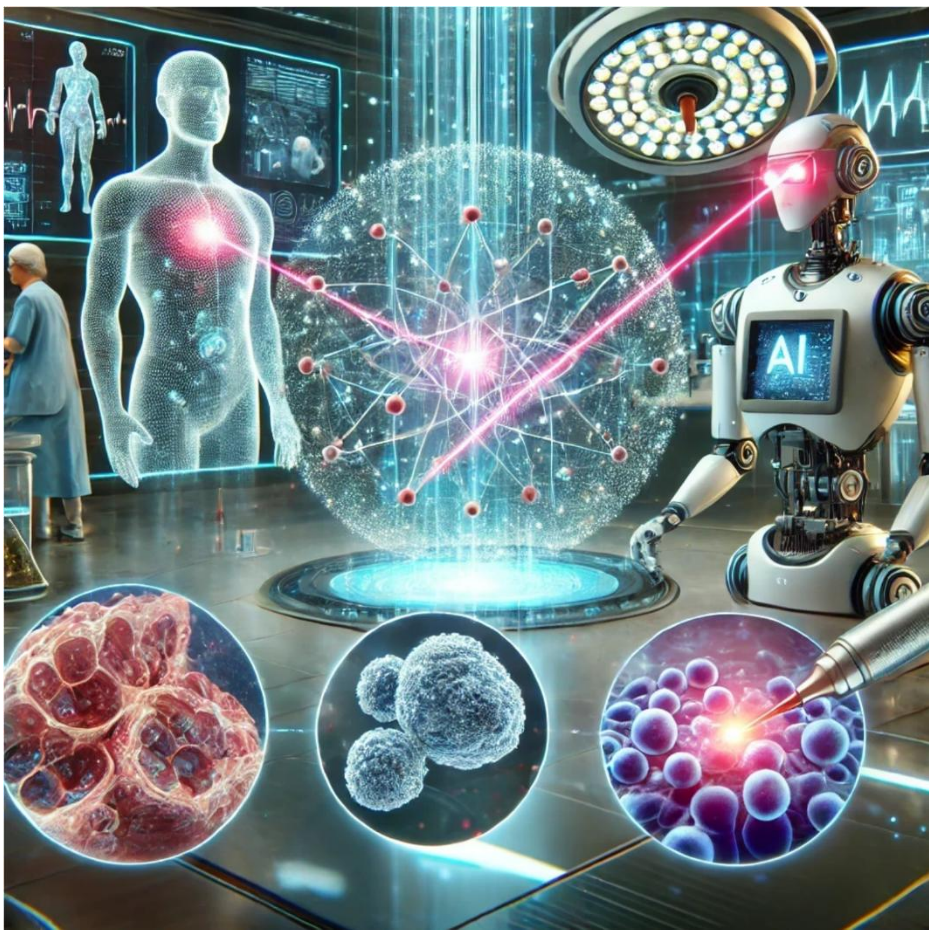


Figure 5 - Future Trends in Laser Medicine