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PHYSICS OF SEMICONDUCTORS
(SUBJECT CODE: 03019201BS01)

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UNIT- 2
Optoelectronics

Introduction

- **What is optoelectronics devices ?**

Optoelectronic devices are specialized electronic components that either **emit, detect, or control light**—typically using semiconductor materials. They form a bridge between optics (the study of light) and electronics, enabling conversion between electrical and optical signals. These devices play a crucial role in modern technologies, including communications, displays, sensing, and energy generation.

Types of Optoelectronics devices

Device Category	Function
Emitters	**LED, Laser Diode**
Detectors	**Photodiode, Phototransistor**
Transducers	**Solar Cells (photovoltaic conversion)**
Modulators	Electro-optic modulators
Sensors	Photoresistors (LDR), Imaging devices

Introduction

What is Light !!!

Sources of Ordinary Light !!!

Introduction

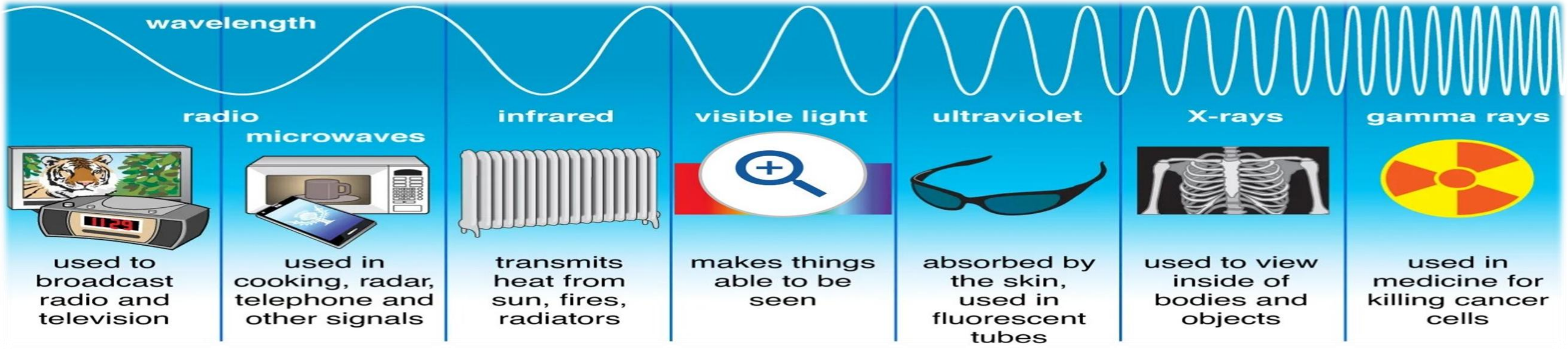
What is Light !!!

- Light is a form of electromagnetic radiation that is visible to the human eye.
- It is a type of energy that travels in the form of waves, and it is part of a broader spectrum of electromagnetic radiation.
- The electromagnetic spectrum encompasses a wide range of frequencies and wavelengths, with light falling within a specific region of this spectrum.

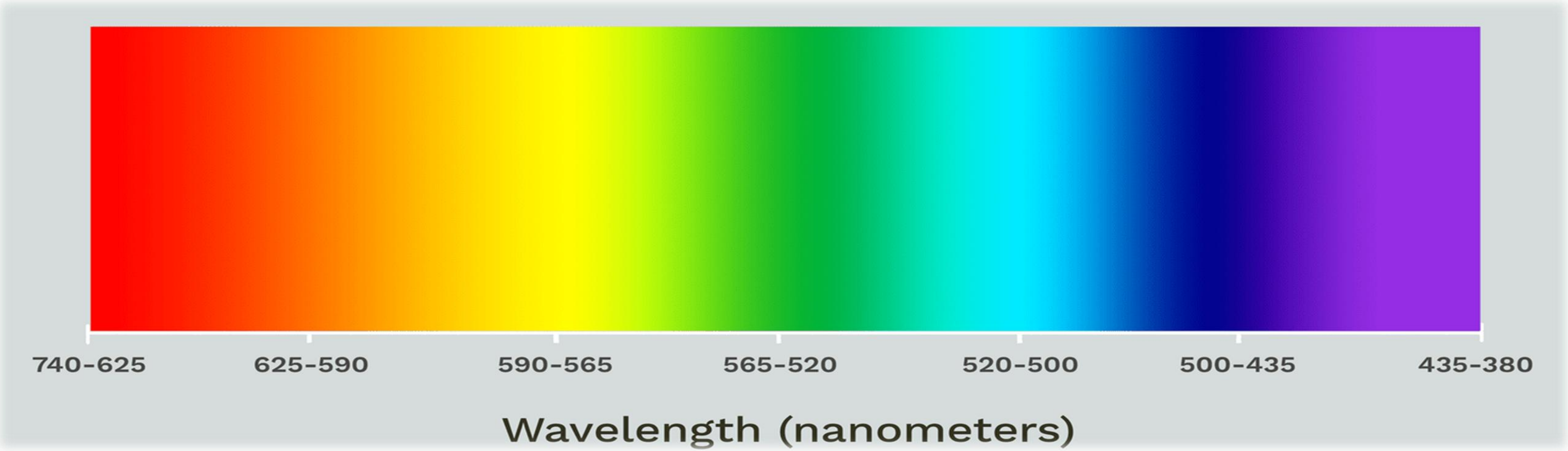
Electromagnetic Spectrum

SPEED: In a vacuum, light travels at a constant speed **(3.00×10^8 m/s)**, denoted as c. This speed is one of the fundamental constants in physics.

ELECTROMAGNETIC SPECTRUM: Light is just one portion of the electromagnetic spectrum, which includes various types of electromagnetic radiation such as **radio waves, microwaves, infrared radiation, visible, ultraviolet radiation, X-rays, and gamma rays.** Each type of electromagnetic radiation has a specific range of wavelengths and frequencies.



Visible Spectrum



WAVELENGTH AND COLOR: The different colours of light are associated with different wavelengths. In the visible spectrum, shorter wavelengths correspond to colours like violet and blue, while longer wavelengths correspond to colours like red and orange.

ENERGY: The energy of a light wave is directly proportional to its frequency. This relationship is described by the equation **$E=h\nu$**, where **E** is the energy, **h** is Planck's constant, and **ν** is the frequency of the light wave.

Photo Emitter Device - LESER

LASER –

Light Amplification by Stimulated Emission of Radiation

A device that stimulates atoms or molecules to emit light at particular wavelength and amplifies that light producing a **1) High Degree Of Coherency**

(2) Highly Monochromatic

(3) Highly Directional

(4) Highly Intense.

History of LASER

1916

- Albert Einstein gave the theoretical prediction of "**Stimulated Emission**" which is fundamental to the operation of all lasers.

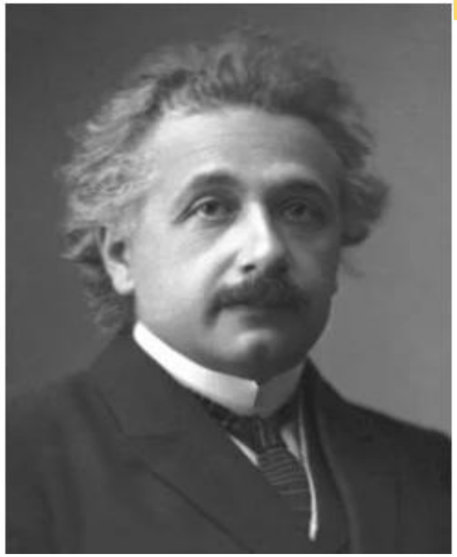
1958

- C.H. Townes and his co-workers constructed first MASER (Microwave Amplification By Stimulated Emission Of Radiation) using ammonia based on the prediction of Einstein.
- Townes and Schawlow proposed a method of extending MASER principle to visible light.

1960

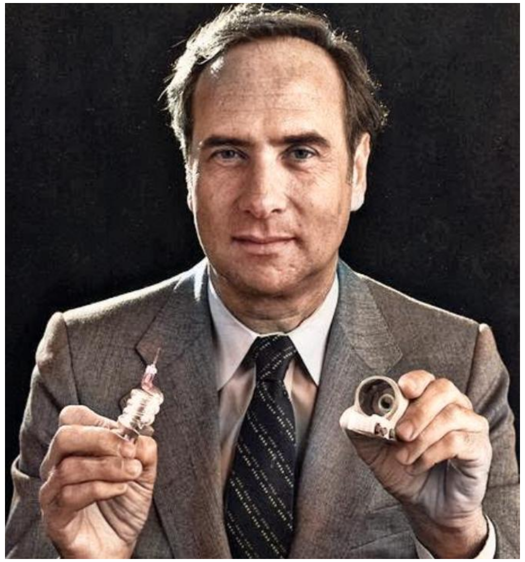
- T. Maiman built the first **LASER (RUBY LASER).**
- Laser is also called **Optical MASER.**

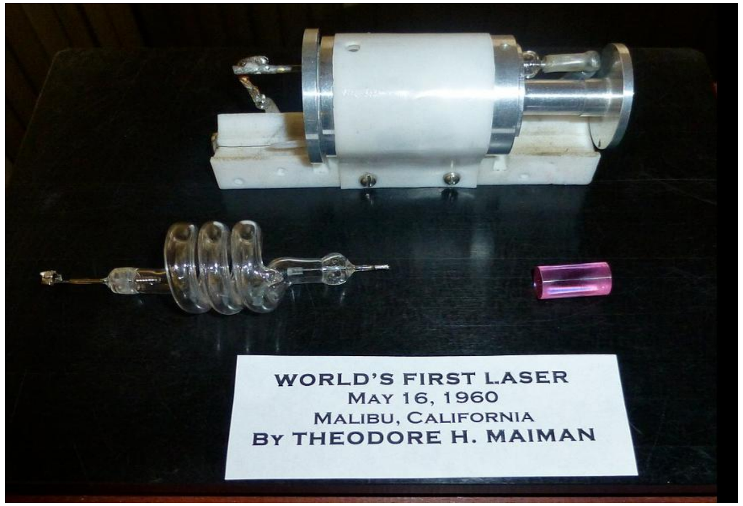
History of LASER



Albert Einstein gave the theoretical prediction of “**Stimulated Emission in 1916**

T. Maiman with his laser in July 1960



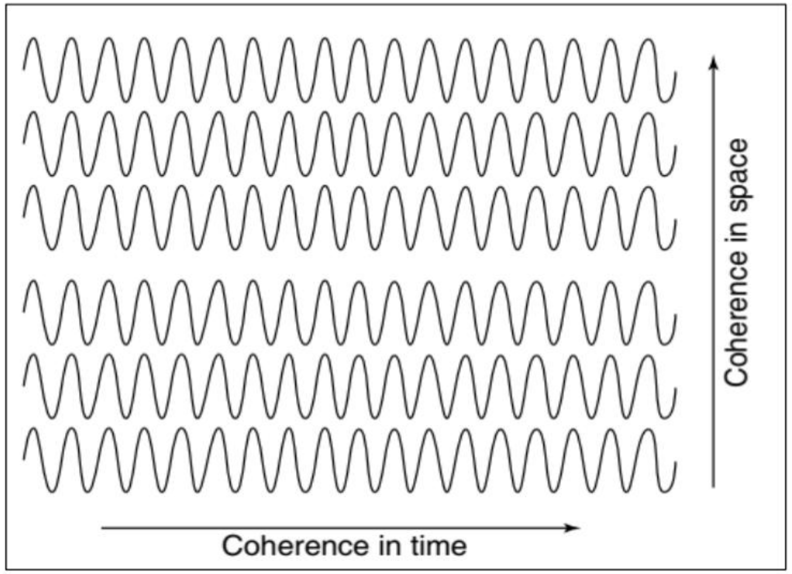


Characteristics/Properties of LASER light

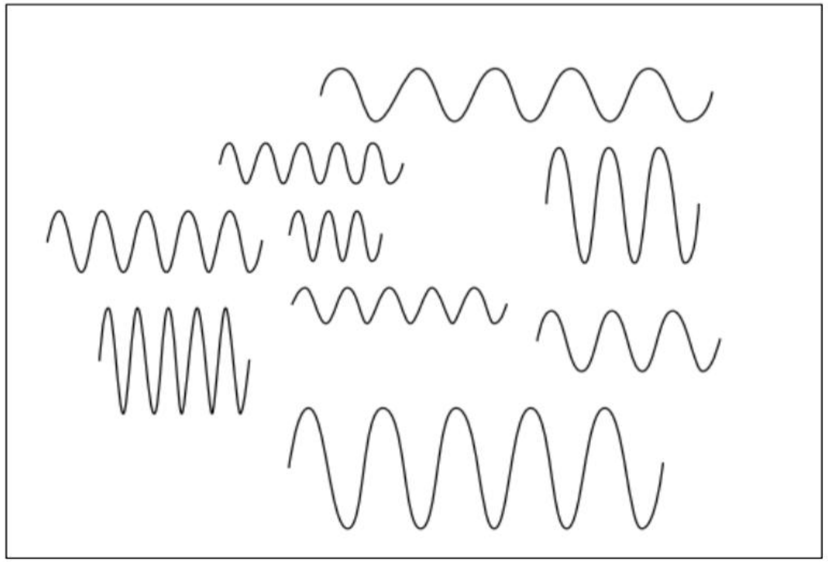
LASER encompasses interaction between atoms and molecules of matter and electromagnetic field.
The beam emitted by laser can have following features:
(1) High Degree Of Coherency (2) Highly Monochromatic (3) Highly Directional (4) Highly Intense

1. **Laser is highly coherent.**
2. **Laser is highly monochromatic** unlike ordinary light which means that all laser rays have same wavelength and frequency when they are emitted from same source.
3. **Laser can be directed to a distant object and travel as a parallel beam** with only negligible spreading due to diffraction effect. Hence its highly directional unlike ordinary light which emits light in all directions and is highly divergent. In LASER, divergence is in some mm.
4. **Laser emits light** in the form of narrow beam with energy concentrated in a small region of space. So, the **beam intensity is tremendously large and stays constant with distance** unlike ordinary light.

COHERENT (LASER) and INCOHERENT (ORDINARY) Light



Group of coherent photons



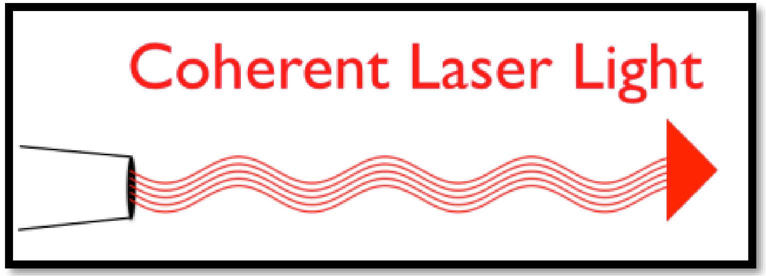
Group of incoherent photons

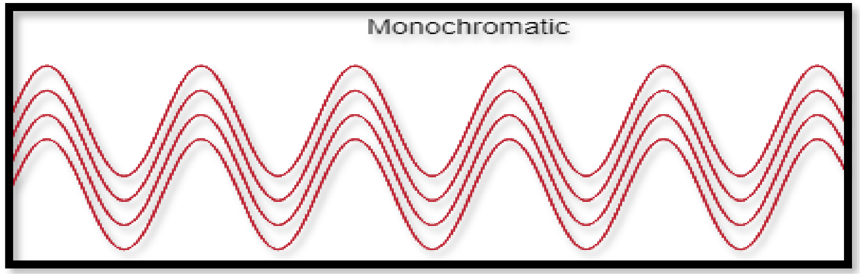
Coherence is related to zero or constant/definite phase relationship at different points of time and space. For a source to be coherent, it must emit radiation of single frequency or frequency spread must be small. Laser is highly coherent but ordinary light is incoherent in nature as they emit light waves with no constant phase difference with each other, they comes from independent atoms which emit on time scale of 10^{-8} s.

Characteristics/Properties of LASER light

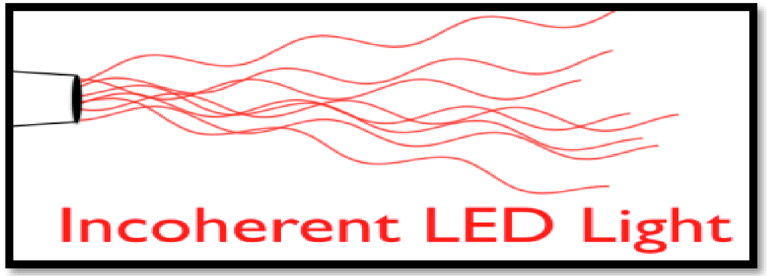
•**High coherence**: Photons are in phase spatially and temporally, resulting in highly ordered waves.

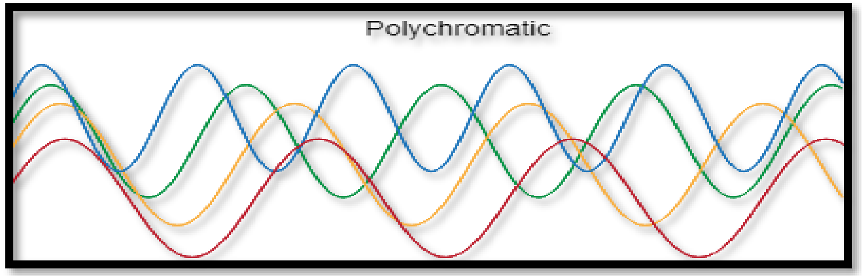
LASER LIGHT





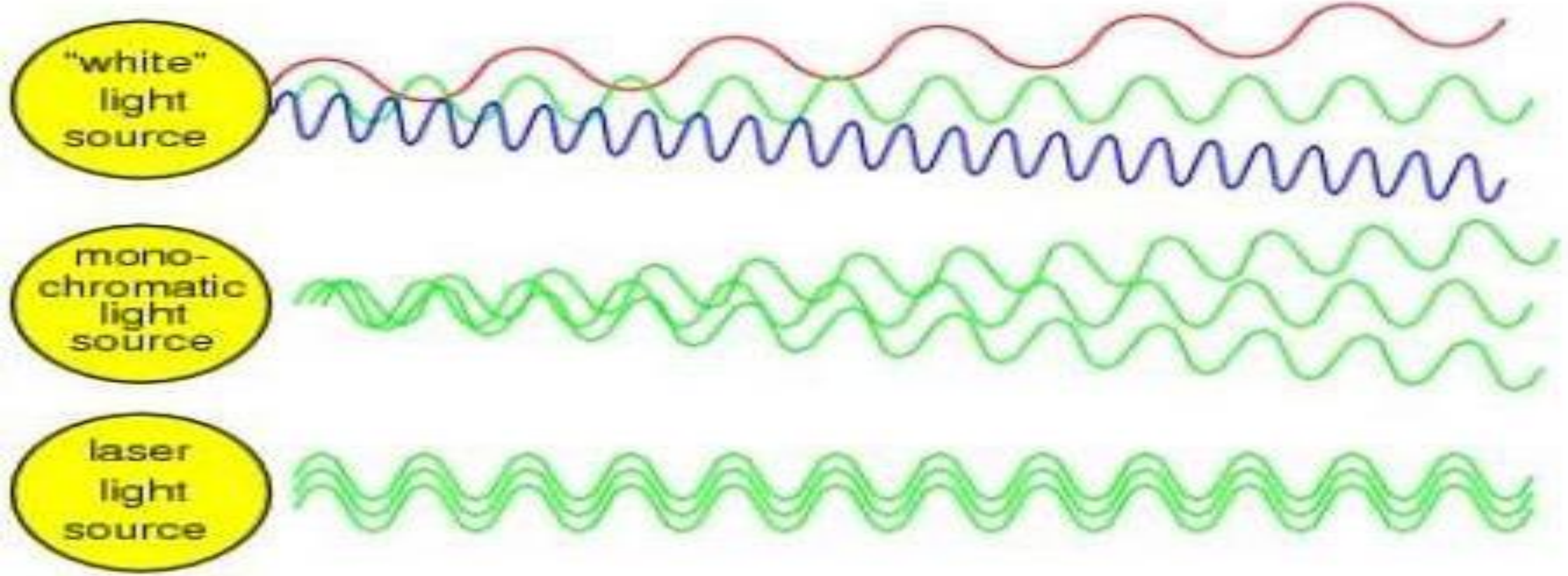
ORDINARY LIGHT





Characteristics/Properties of LASER light

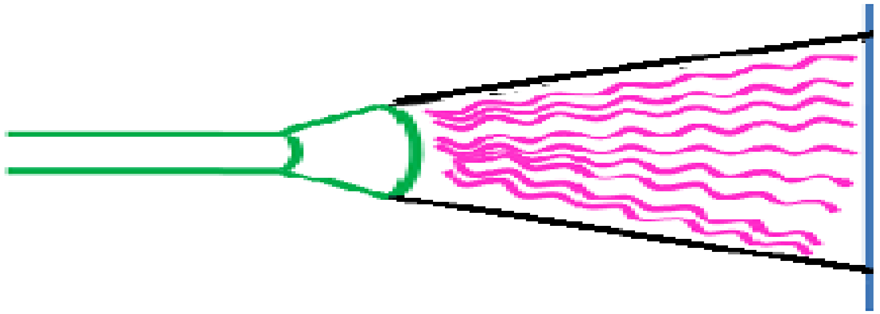
- **Monochromaticity**: Laser light is of a single wavelength (color). **light wave has same frequency**



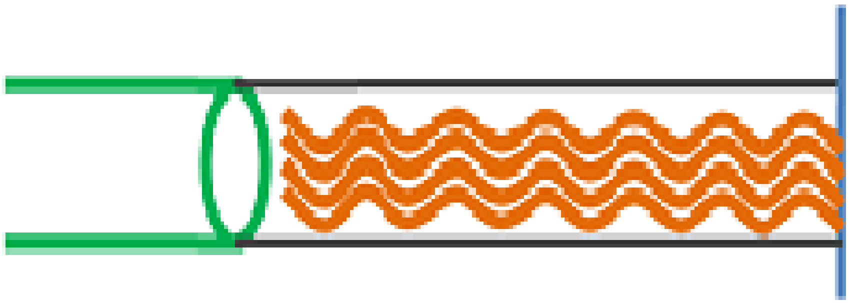
Characteristics/Properties of LASER light

- **High directionality:** The laser beam is extremely narrow and can travel long distances with minimal spread.

- **High intensity:** Laser light is vastly more intense than ordinary sources due to the concentration of energy.



Ordinary light

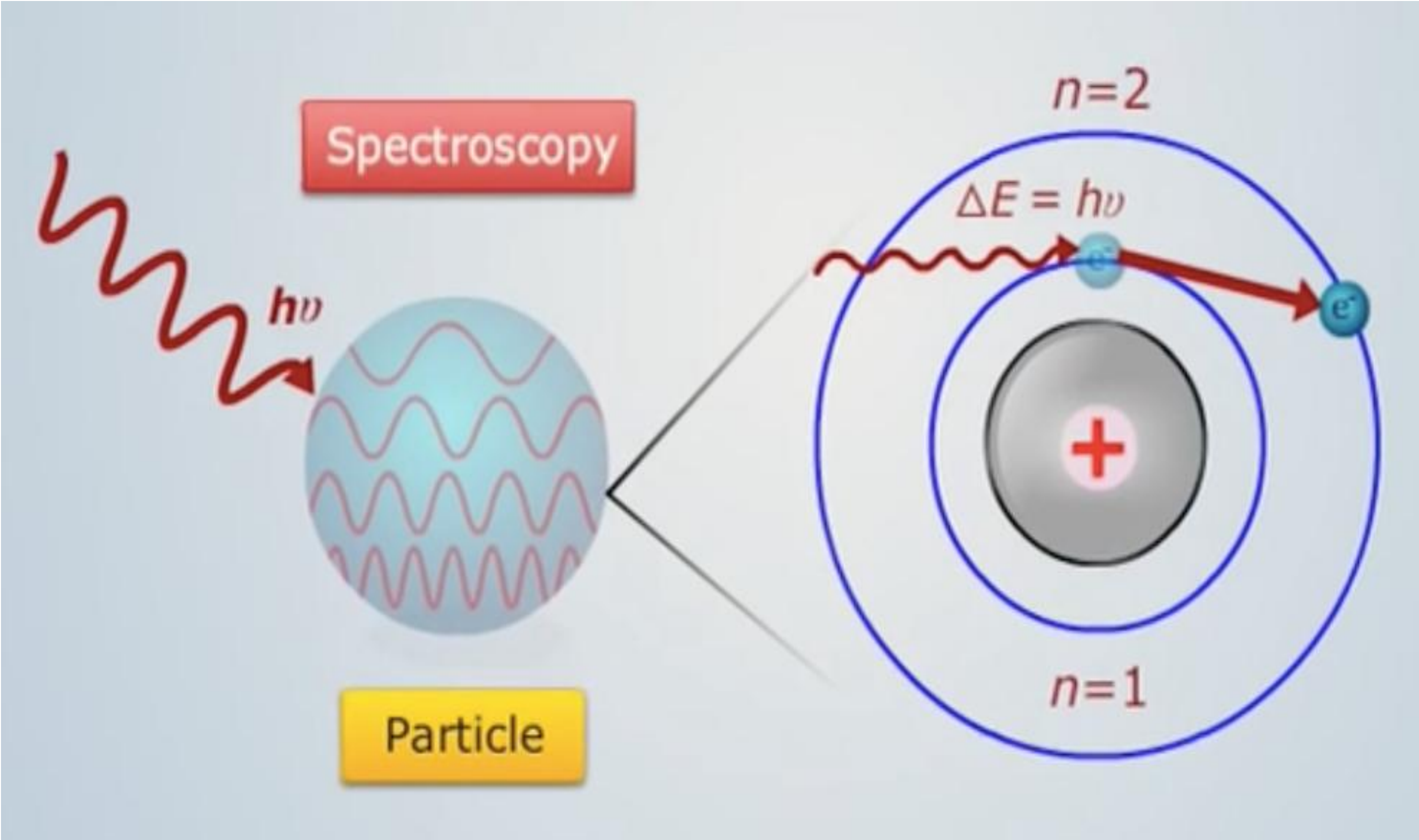


LASER Light

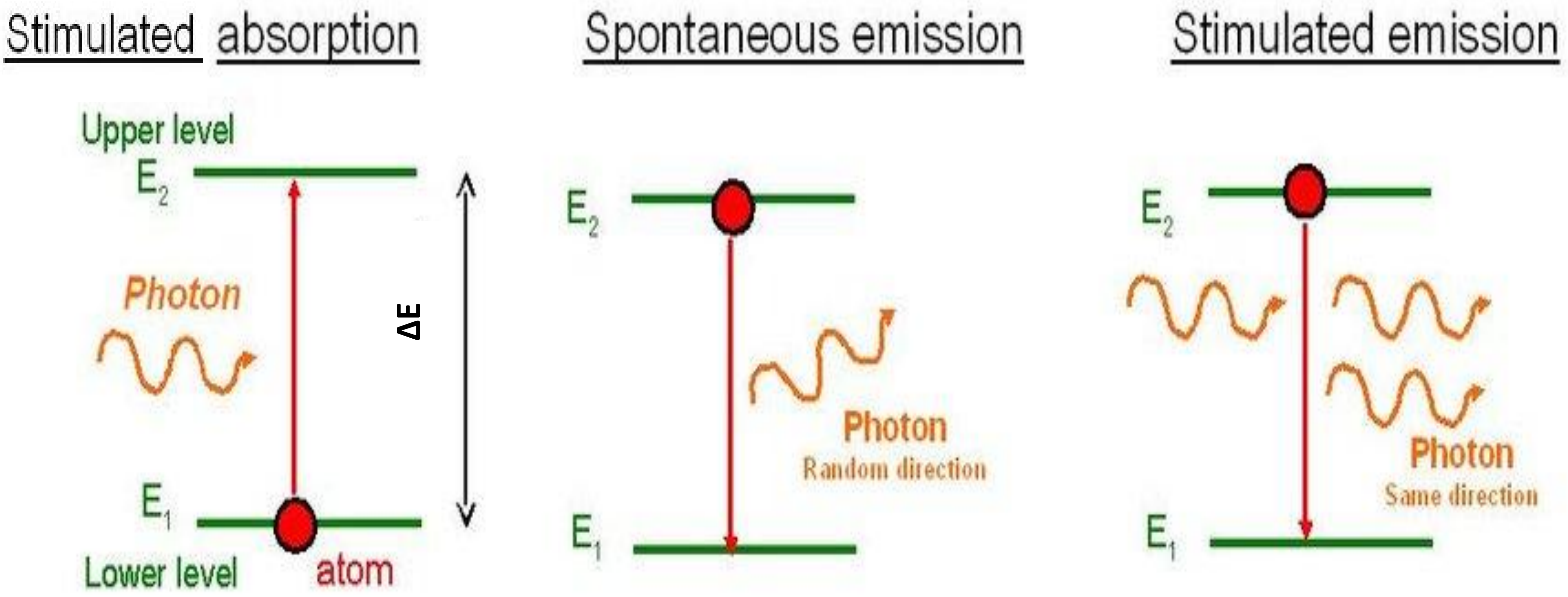
Interaction of radiation (light) with Matter

Radiation, especially in the form of photons (light), interacts with matter primarily through three main mechanisms:

1. Stimulated Absorption
2. Spontaneous Emission
3. Stimulated Emission



Interaction of radiation (light) with Matter



Interaction of radiation (light) with Matter

- **Stimulated Absorption**: A photon's energy is taken up by an electron in an atom. This excites the electron to a higher energy state, commonly observed in photoelectric absorption, crucial for devices like **photodiodes.**

- **Spontaneous Emission:** An excited electron returns to a lower energy state without external prompting, emitting a photon with random phase and direction. **(E.g. LED)**

Stimulated emission (key to lasers): If an electron in an excited state is struck by a photon of suitable energy, it emits a second, identical photon. This leads to coherent, monochromatic, and directional light—the defining qualities of **lasers**.

Einstein's theory of matter-radiation interaction

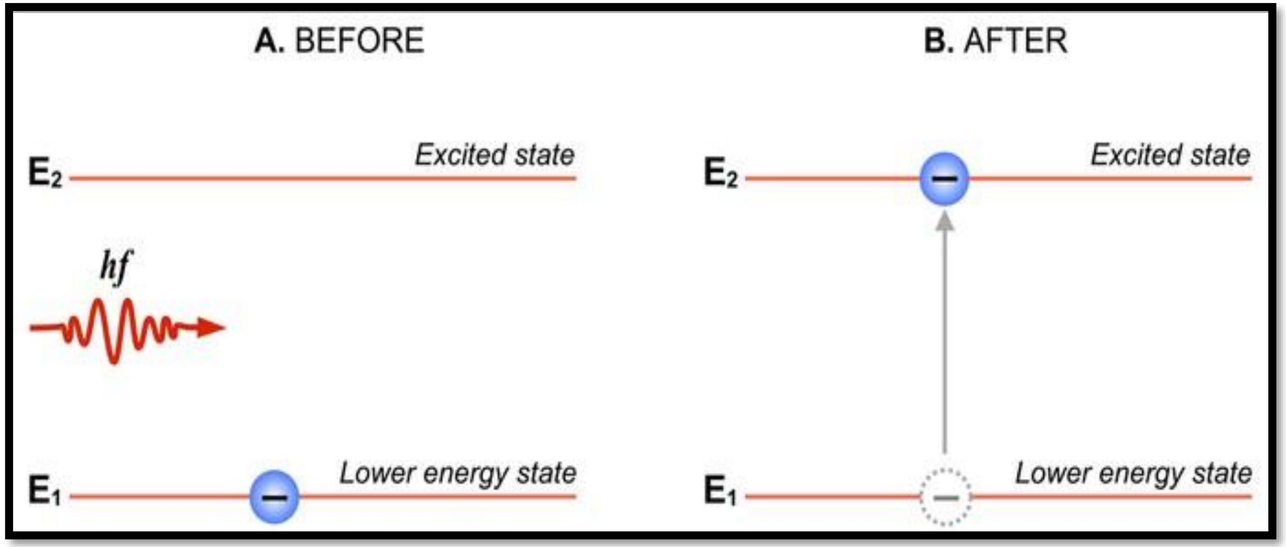
- Bohr's theory of an atom states that an electron revolving in orbits around the nucleus can only have certain (discrete) values of energies. These are referred to as the atom's energy levels.

- Bohr proposed that light emission takes place when the atom makes a transition from an excited state (of energy E_2 state to a relaxation (of energy E_1 state.

$$h\nu = E_2 - E_1 \qquad \text{..........(i)}$$

Interaction of matter with radiation: Stimulated Absorption

- Consider an atom is initially in lower energy state (E_1).
- A photon of energy **$h\nu$ (= E_2 - E_1)** when incident on the atom in (E_1), it is absorbed by the atom.
- On absorbing the energy, the atom transits to its higher energy state (E_2).
- This phenomenon in which the atom transits to the higher energy state with the help of external agent (radiation energy) is called **STIMULATED Absorption.**



Interaction of matter with radiation: Stimulated Absorption

- An absorption process is represented by
- $E_2 = E_1 + h\nu$

  $\Rightarrow E_2 - E_1 = \Delta E = h\nu$

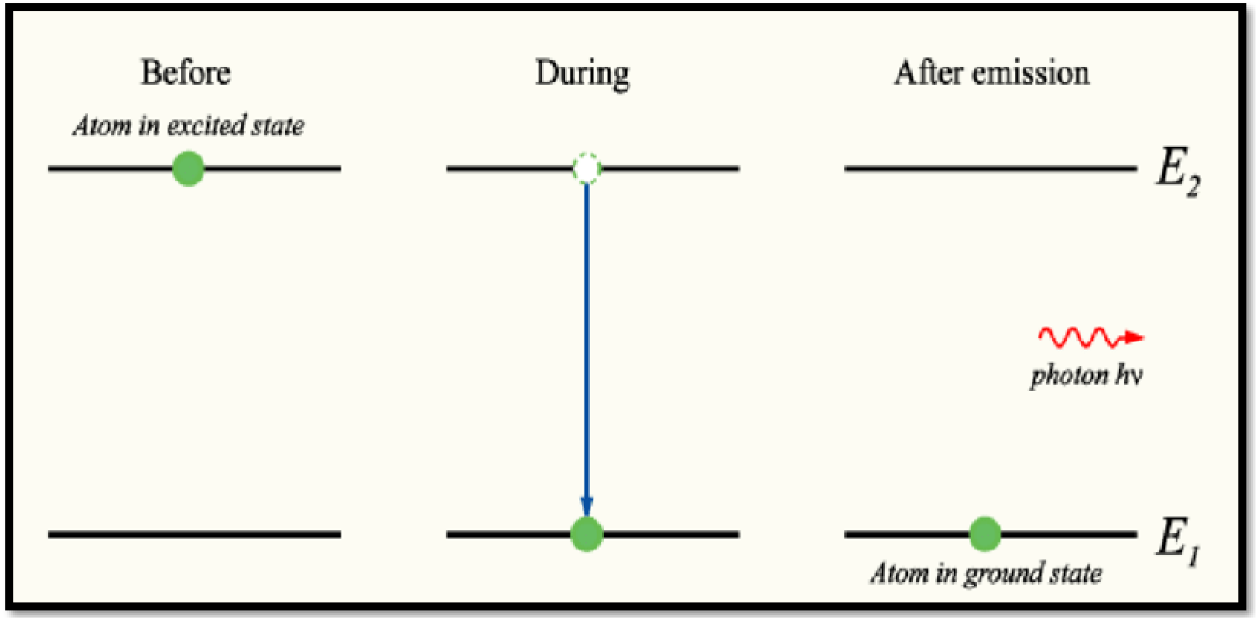
- The probability of occurrence of this absorption from state 1 to state 2 is directly proportional to the energy density of the radiation

$$P_{12} = B_{12}\ \rho(\nu) \qquad \ldots\ldots\ldots\ldots\text{(ii)}$$

Where the proportionality constant B_{12} is known as the Einstein's coefficient of absorption of radiation.

Interaction of matter with radiation: Spontaneous Emission

- Lifetime of upper energy state is very short.
- Consider an atom is initially in excited state (E_2).
- It can come down to the ground state E_1 by emitting a photon of energy **hv (= E_2 - E_1)** on its own after 10^{-8} s (**without any external agent).**
- This process is called **SPONTANEOUS Emission.**



Interaction of matter with radiation: Spontaneous Emission

- The probability of occurrence of this spontaneous emission transition from state 2 to state 1 depends only on the properties of states 2 and 1 and is given by
- $P'_{21} = A_{21}$ …………(iii)

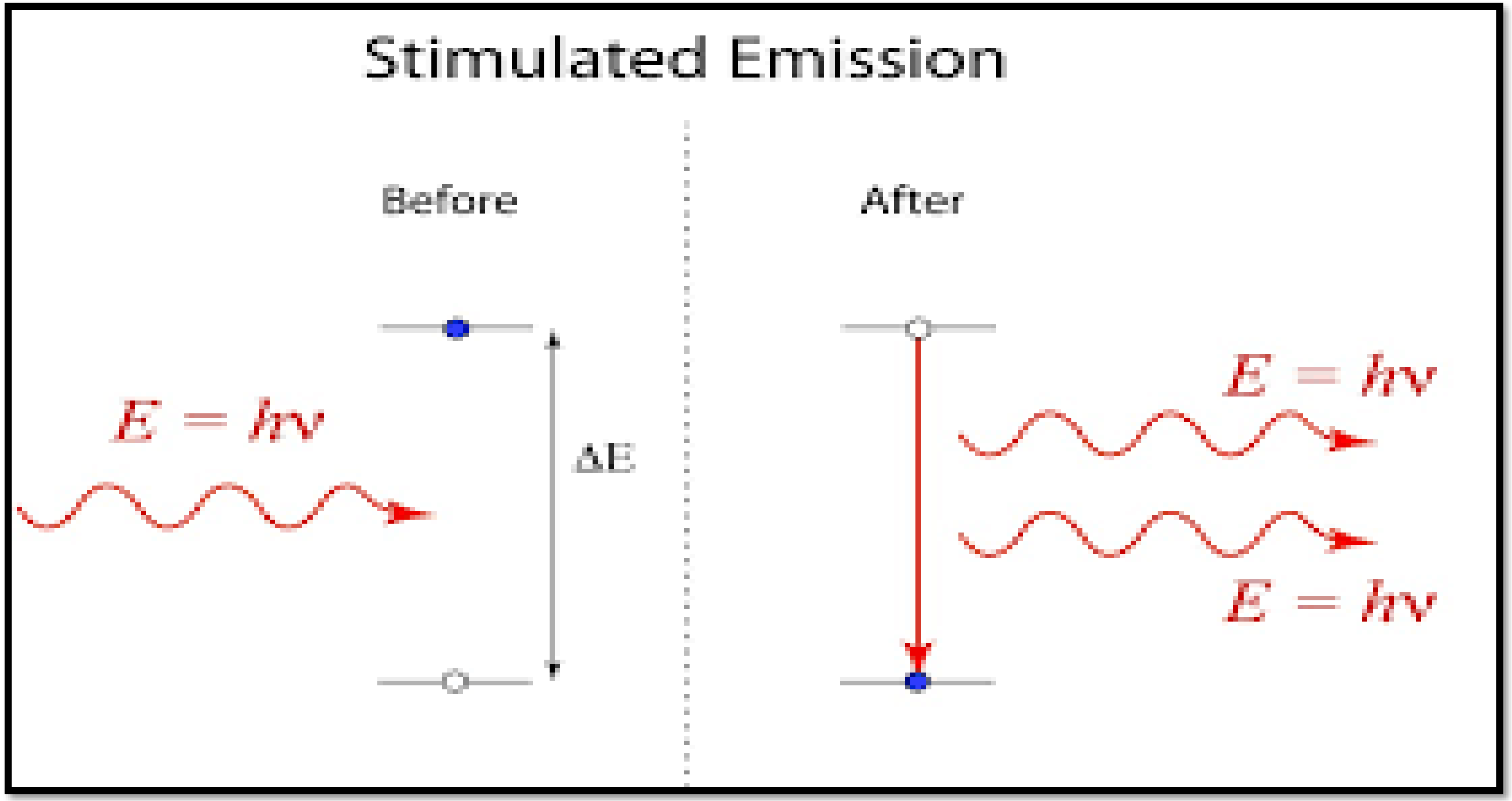
Where A_{21} is known as the

Einstein's coefficient of spontaneous emission of radiation.

Interaction of matter with radiation: Stimulated Emission

- Stimulated emission is induced emission, in which an incident photon of energy $h\nu$ causes an emission from upper state E_2 to the lower state E_1, which is represented by
- $h\nu = \Delta E = E2 - E1$
- The probability of occurrence of stimulated emission transition from the upper level 2 to the lower level 1 is proportional to the energy density $\rho(\nu)$ of the radiation and is expressed as
- $P''_{21} = B_{21}\,\rho(\nu)$ .... (iv)

Interaction of matter with radiation: Stimulated Emission



Relation between Einstein's Coefficients

Let us consider an assembly of independent atoms which can exists only in 2 levels, 1 and 2 with energies E_1 and E_2. Let N_1 and N_2 be the number of atoms per unit volume in the states 1 and 2 respectively. These numbers are called Population of respective levels.
At thermal equilibrium, the no of atoms present in a particular energy is determined by Maxwell's-Boltzmann Statistics, i.e.

$$\boxed{N_2 = N_1 \exp\{-(E_2 - E_1)/KT\}}$$

Where,
K= Boltzmann's constant = 1.38×10^{-23} J/K
T= Absolute Temperature in Kelvin
We have these following equations:

Here,
B_{12}= Einstein Coefficient Stimulated Absorption
B_{21}=Einstein Coefficient of Stimulated Emission
A_{21}=Einstein Coefficient of Spontaneous Emission

The Rate of Stimulated Absorption (R_1) transition is given by:

$$\boxed{R_1(\text{St. Absorption}) = B_{12}\,\rho(\nu)\,N_1} \quad \text{-----}\ (1)$$

The Rate of Spontaneous Emission **(R_2)** is given by:

$$\boxed{R_2\ (\text{Sp. Emission}) = A_{21}\,N_2} \quad \text{--------}\ (2)$$

The Rate of Stimulated Emission **(R_3)** is given by:

$$\boxed{R_3\ (\text{St. Emission}) = B_{21}\,\rho(\nu)\,N_2} \quad \text{------}\ (3)$$

Relation between Einstein's Co-

Solving the equations, we get,

$$\frac{A_{21}}{B_{21}} = \frac{8\pi h\nu^3}{c^3} \quad \text{and} \quad B_{12} = B_{21}$$

Where c = speed of light

These relations are known as Einstein's Relations.

Let's discuss the physical significance of these relations:

1. We have $B_{12} = B_{21}$, which states that the probability of stimulated emission is numerically equal to the probability of stimulated absorption. So stimulated emission is an reverse process of stimulated absorption, but their rates are not same because stimulated emission is proportional to the no of atoms per unit volume in E_2 excited state, i.e N_2 while stimulated absorption is proportional to the no of atoms per unit volume in E_1 ground state, i.e N_1.

2. Again, we have ,

$$A_{21} / B_{21} = 8\pi h\nu^3 / c^3,$$

Therefore, $B_{21} = (A_{21} \cdot c^3) / 8\pi h\nu^3$

Which implies that the co-efficient of Stimulated Emission B_{21} is inversely proportional to the third power of frequency of radiation.

PHYSICAL SIGNIFICANCE

R' = Rate of Stimulated Emission / Rate of Stimulated Absorption

$$R' = [B_{21} N_2 \rho(\nu)] / [B_{12} N_1 \rho(\nu)] = N_2 / N_1$$

This shows, at thermal equilibrium, the number of atoms per unit volume N_1 in ground state is very large in comparison to number of atoms in excited state , i.e. $N_1 >> N_2$.

But to achieve higher rate of stimulated emission we should have $N_2 >> N_1$.

Conditions for achieving Light amplification

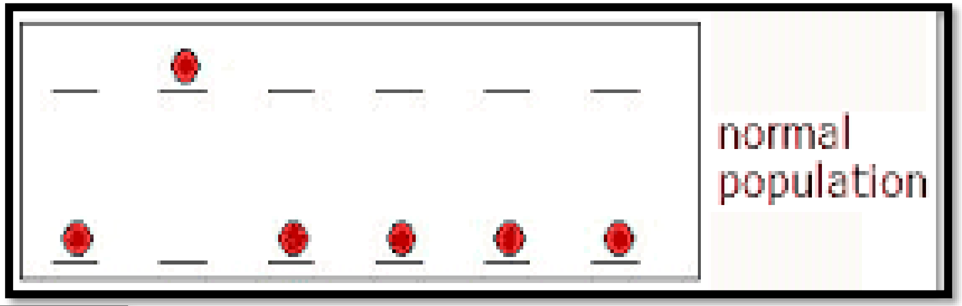
In practice, absorption and spontaneous emission always occurs together with stimulated emission. The laser operation is achieved when simulated emission exceeds in a large way than the other two processes.
A light amplification only occurs when these **3 conditions** **are fulfilled, they are as follows:**

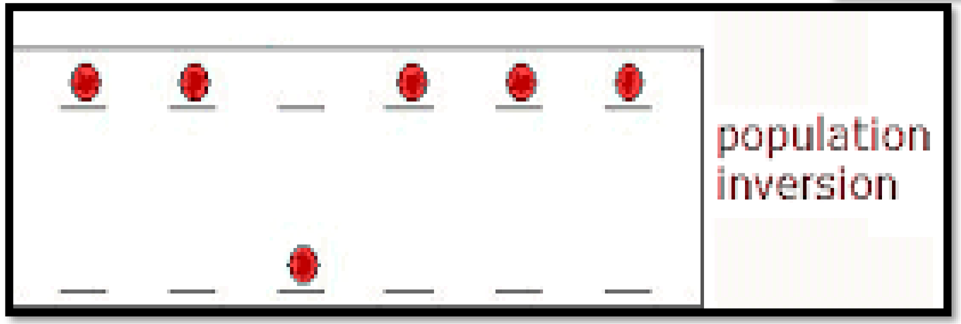
1. Population at the excited level should be large than that of lower energy level ($N_2 >> N_1$). Artificial situation known as **Population Inversion** is to be created in the medium.

2. The ratio of B_{21}/A_{21} should be very large and this can be achieved by choosing a **metastable state** at the higher level..

3. The energy density of radiation $\rho(\nu)$ should be very large. Large number of photons in the active medium are required. It is made larger by enclosing the emitted radiation in the optical resonant cavity formed by 2 parallel mirrors. The radiation is reflected many times till the photon density reaches to a very high value and stimulated emissions are triggered on a large scale.

Population Inversion

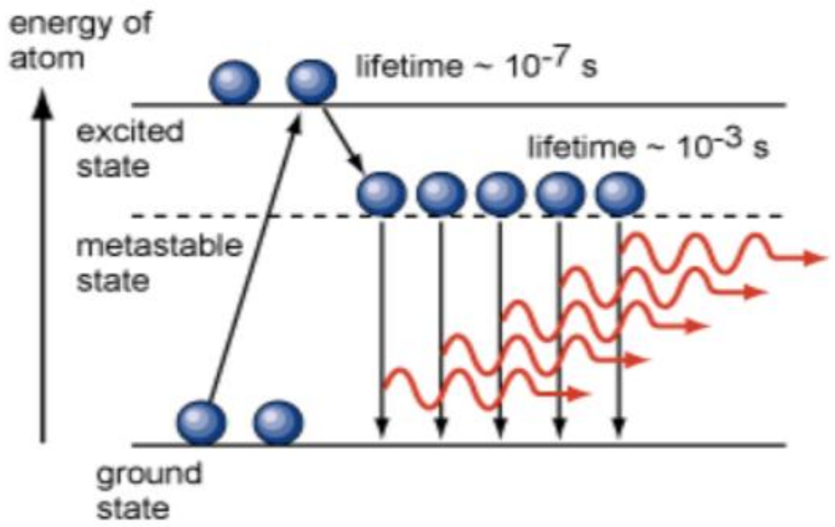




Definition : **Population Inversion is an artificial non-equilibrium process/condition of the material that is established by generation of large numbers of atoms in the higher energy state than ground state (N2>>N1).This is achieved by pumping.**

[At ordinary conditions N1 > N2, i.e., the population in the ground or lower state is always greater than the population in the excited or higher states.]

Metastable States



Metastable states are excited states which have relatively longer lifetime due to slow radiative or non-radiative decay.

Population inversion can be established if the lifetime of the excited states (metastable) is 10^{-6} to 10^{-3} s which is considerably more than the lifetime of the ordinary excited state levels.

Metastable state can be obtained in a crystal system containing impurities. These levels lie in the forbidden band gap of the host crystal.

Spontaneous Emission Vs. Stimulated Emission

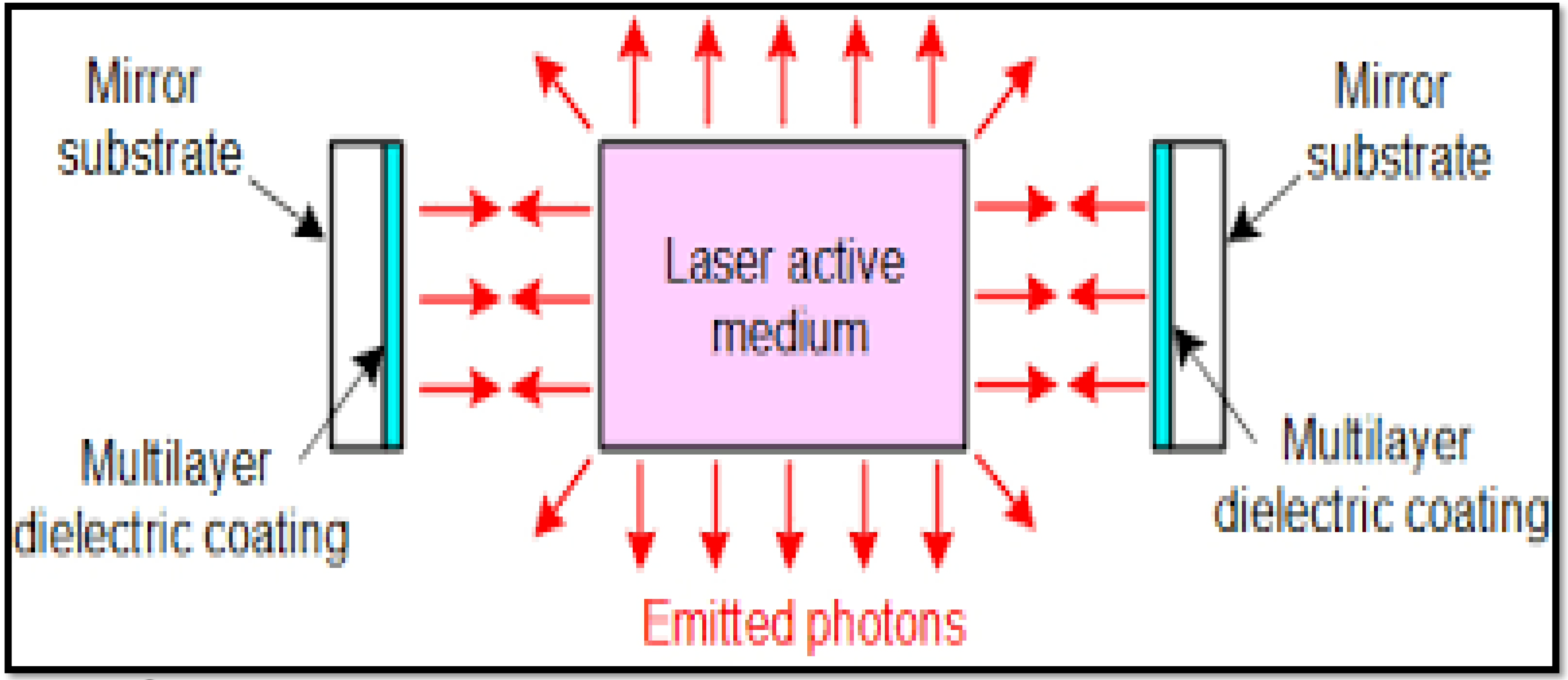
NO:	Spontaneous emission	Stimulated emission
1.	The spontaneous emission was postulated by Bohr	The stimulated emission was postulated by Einstein
2.	Additional photons are not required in spontaneous emission	Additional photons are required in stimulated emission
3.	One photon is emitted in spontaneous emission	Two photons are emitted in stimulated emission
4.	The emitted radiation is polychromatic	The emitted radiation is monochromatic
5.	The emitted radiation is incoherent	The emitted radiation is coherent
6.	The emitted radiation is less intense.	The emitted radiation is highly intense
7.	The emitted radiation have less directionality Example: light from sodium or mercury lamp	The emitted radiation have high directionality Example: light from laser source.

Components of Laser

Laser requires three Components: **1) Active Medium/Gain Medium**

2) Pumping scheme

3) Optical Cavity/Resonator



Components of Laser: Active Medium

1) Active Medium:

- The fundamental component of laser is material medium which is known as an Active/Gain Medium.
- This active medium can be solid, liquid or gaseous in nature. After the invention of ruby laser (solid state laser), other active media such as glasses, plastics, liquids, gases and even plasma were used.
- In Active Medium, only a small fraction of the atoms are responsible for the light amplification known as **ACTIVE CENTRES**. The rest part of the medium behaves as a Host and supports the active centres in the bulk.
- An active medium should possess good mechanical, thermal and optical properties as well as transparency to stimulated radiation and laser output.

Types:

Solid (e.g., Ruby, Nd:YAG crystals)

Liquid (e.g., dye solutions)

Gas (e.g., He-Ne, CO_2)

Semiconductor (e.g., GaAs in laser diodes)

The choice of active medium determines the laser's wavelength (color) and properties.

Components of Laser

2) **Pumping scheme :** Supplies external energy to excite the atoms of the active medium, creating a population inversion (more atoms in an excited state than in the ground state).

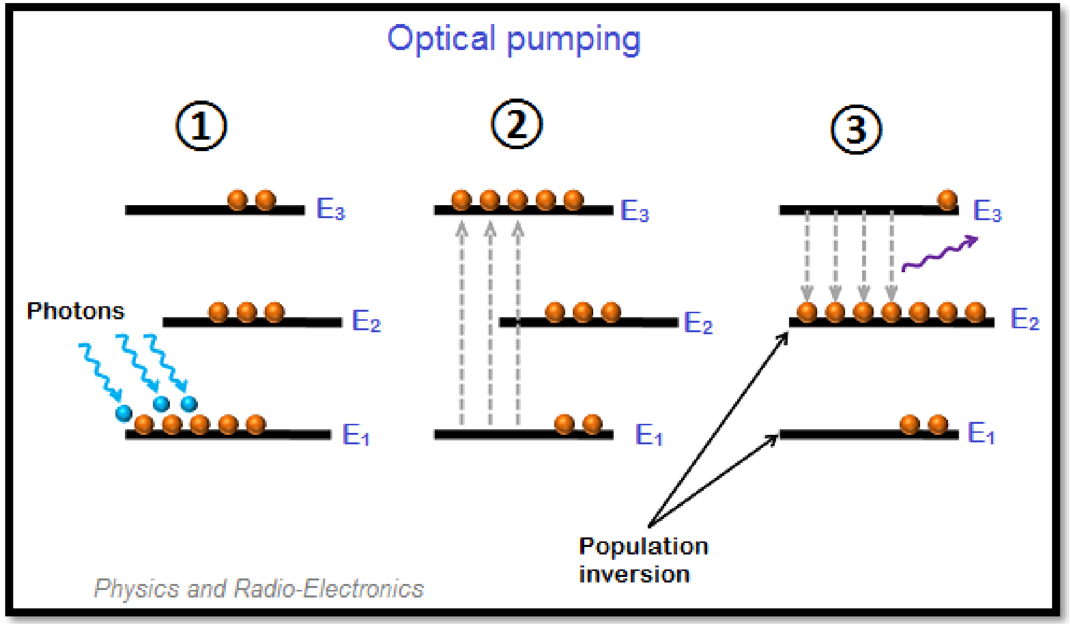
Methods:

- **Electrical current (in diode lasers)- (injection pumping)**
- Light from flash lamps or other lasers (optical pumping)
- Electrical discharge (in gas lasers)
- Chemical reactions (in chemical lasers)

Components of Laser : Pumping techniques

I. Optical pumping:

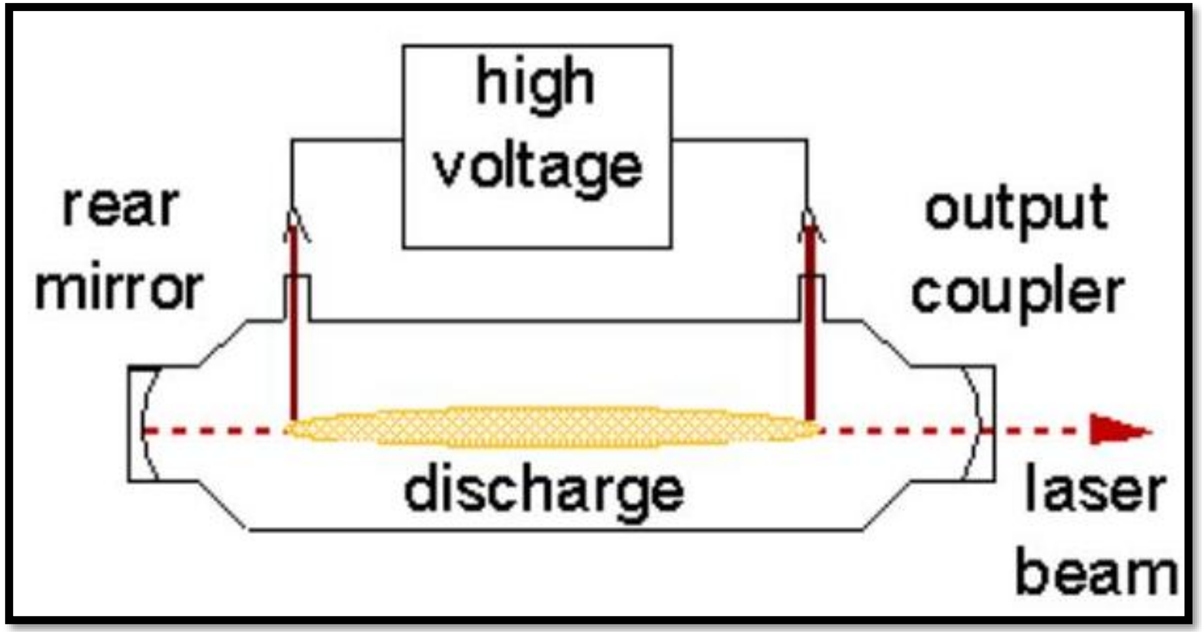
- Majorly used in solid state laser.
- Xenon flash tubes are used for optical pumping.
- Examples of optically pumped lasers are ruby, Nd: YAG Laser



Components of Laser : Pumping techniques

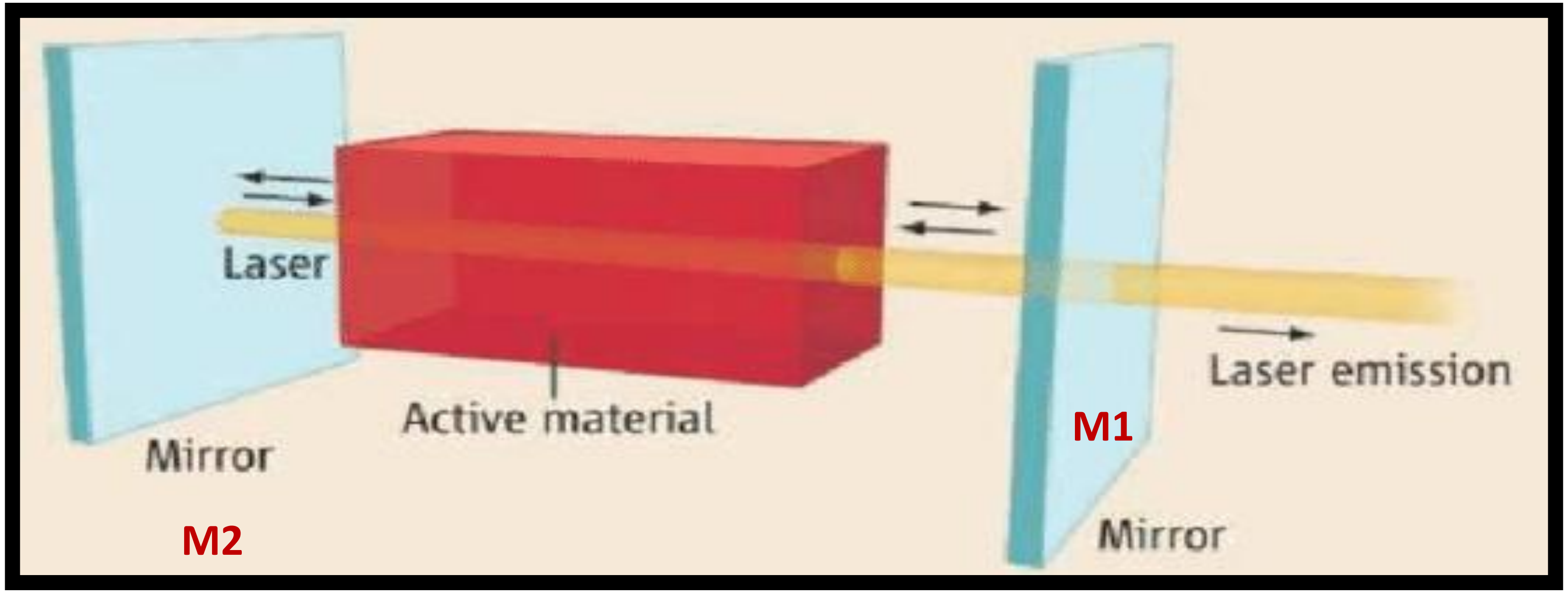
II. Electrical discharge pumping

- Electrical discharge pumping is used in gas lasers.
- Electrical discharge pumped lasers are He-Ne laser, CO_2 laser, argon-ion laser, etc



Components of Laser: Optical Cavity/Resonator

3.) Optical resonator is a pair of plane parallel mirrors set on optic axis which defines the direction of laser output. One is perfectly reflecting mirror and the other surface is partially reflecting mirror. In this resonant cavity, the intensity of photons is raised tremendously through stimulated emission process (amplification of stimulated photons).



Components of Laser

3) Optical Resonator (Cavity) : Traps photons and amplifies light via multiple reflections between two mirrors placed parallel to each other around the active medium.

•Components:

Two Mirrors:

- One fully reflective mirror (100%)
- One partially reflective mirror (output coupler, allows some light to escape as the laser beam)

•**Purpose: Ensures that photons move back and forth to sustain stimulated emission, building up the laser beam's intensity.**

Working of Laser: Lasing Action

- The atoms excited with the light of suitable wavelength jumps from ground states E_1 to excited state E_2 by absorbing incident photons. They can't remain in excited state for more than 10^{-8} s and drops back by **spontaneous emission.**

- During this, many of the atoms get dropped in the **metastable state** where the atoms can stay for a longer time than that of its excited state as the lifetime of an atom in metastable state is greater than its excited state. So, due to their longer stay, a large number of atoms exist in the metastable state than that in ground state indicating **population inversion ($N_2 >> N_1$)**.

- When population inversion is achieved using pumping, then one or more atoms may be excited spontaneously by emitting a photon hv. This photon acts as a stimulant and is made to strike the atoms present in the metastable state.

- The atoms thus gets excited and it is stimulated to emit a photon of same energy as that of the stimulating photon.

Working of Laser: Lasing Action

- As the both stimulated and stimulating photons passes through active medium, it initiates the process of stimulated emission in the active medium by repeated stimulated emission with the help of optical resonator.

- Photons travelling parallel to the optic axis of the resonator are partially reflected by M1 and transmitted part of beam gives laser output. The photons emitted in the other direction will traverse a relatively short path length in the material and die out soon.

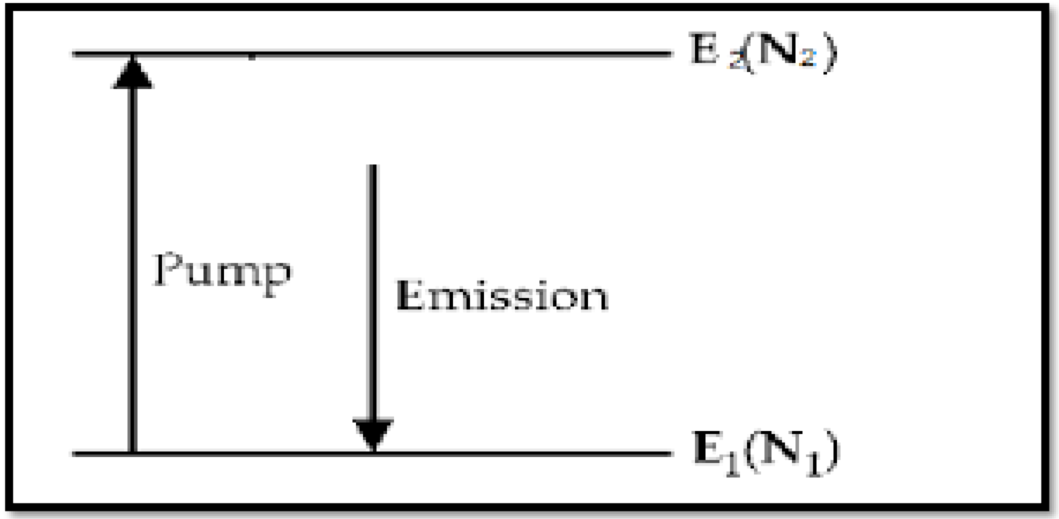
- Reflected photons acts as a positive feedback for active medium as they enter again into the active medium and initiates further stimulated emission. These photons are totally reflected back by the second totally reflecting mirror M2 into active medium and their number increases due to further stimulated emission.

- Multiplication of photons occur and light gets amplified. These photons have same energy, direction and phase as that of incident photons. **Hence, a highly intense , monochromatic and unidirectional LASER light is obtained.**

Schemes for Population Inversion

I. Two-level System:

- Two energy level E1 and E2
- Einstein coefficients (or constants) for the upward (B_{12}) and downward (B_{21}) transitions can be found easily and are equal, i.e. $B_{12} = B_{21}$.
- **Population inversion cannot be achieved in two level system.**
- **Solution: Metastable state**
- Metastable state : an energy state where electrons can stay for a longer time.



Semiconductor diode Laser

- ✓ A semiconductor diode laser is a specially fabricated PN junction device, which emits coherent light when it is forward biased. It was demonstrated in 1962 by US groups led by R.Hall.
- ✓ It is made from Gallium arsenide (GaAs) which operated at low temperatures and emitted light in the near IR region.
- ✓ The PN-junction lasers can emit light almost anywhere in the spectrum from UV to IR. Diode lasers are remarkably small in size (0.1 mm long). They have high efficiency of the order of 40%. Modulating the biasing current easily modulates the laser output. They operate at low powers.
- ✓ In spite of their small size and low power requirement, they produce power outputs equivalent to that of He-Ne lasers. The chief advantage of a diode laser is that it is portable.
- ✓ Because of the rapid advances in semiconductor technology, diode lasers are mass produced for use in optical fibre communications, in CD players, CD-ROM drives, optical reading, high speed laser printing etc.

Semiconductor Laser: Construction

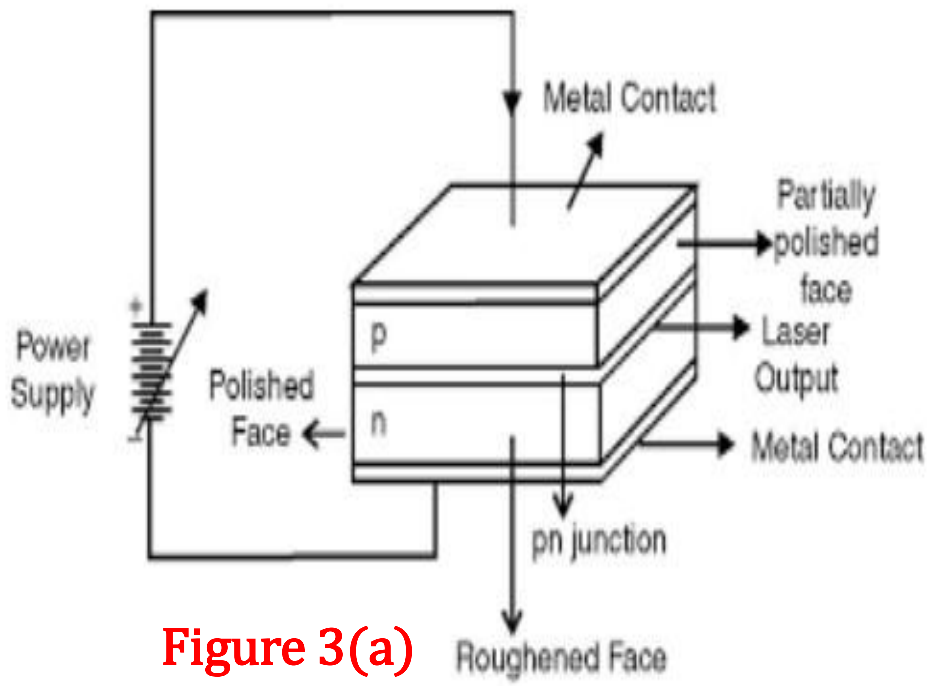


Figure 3(a)

- A simple diode makes use of the same semiconductor material, say, GaAs on both sides of the junction.
- Starting with a heavily doped n-type GaAs material, a p-region is formed on its top.
- The diode is extremely small in size. Typical diode chips are 500 μm long and about 100 μm wide and thick.
- The top and bottom faces are metallized and metal contacts are provided to pass current through the diode.

- The front and rear faces are polished parallel to each other and perpendicular to the plane of the junction. The polished faces constitute the Fabry Perot resonator.
- The two remaining sides of the diode are roughened to eliminate lasing action in that direction. The entire structure is packaged in small case like the metal case.

Semiconductor Laser: Construction

In diode laser P-type & N-type Layers made from semiconductor materials like gallium arsenide (GaAs), doped to create p-type (positive) and n-type (negative) regions.

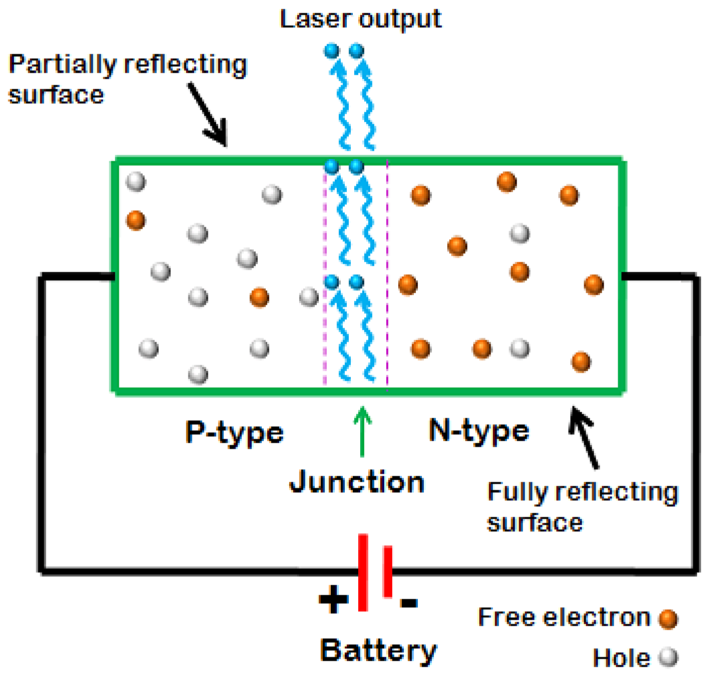
- **Active Region** (Intrinsic Layer): A thin undoped (intrinsic) layer of GaAs or similar material is sandwiched between the p- and n-layers. Photon generation through electron-hole recombination occurs here.

- **Optical Cavity:** The faces of the diode (created by cleaving or polishing) act as mirrors, one highly reflective and the other partially reflective to trap and amplify light within the device.

- **Metal Contacts:** Enable external voltage to be applied across the junction, forward-biasing the diode.

Semiconductor Laser: Working

- Population inversion is required for producing stimulated emission.
- A semiconductor cannot be regarded as two-level atomic system. It consists of electrons and holes distributed in the respective energy bands. Therefore, laser action in semiconductors involves energy bands rather than discrete levels.
- In semiconductors, electrons are not associated with specific atoms but are injected into the conduction band from the external circuit.
- Therefore, the conduction band plays the role of excited level while the valence band plays the role of ground level. Population inversion requires the presence of a large concentration of electrons in the conduction band and a large concentration of holes in the valence band.



Laser diode

Figure 3(b)

A simple way to achieve population inversion is to use a semiconductor in the form of a PN-junction diode formed from heavily doped p-type and n-type semiconductors.

Semiconductor Laser (For Information only)

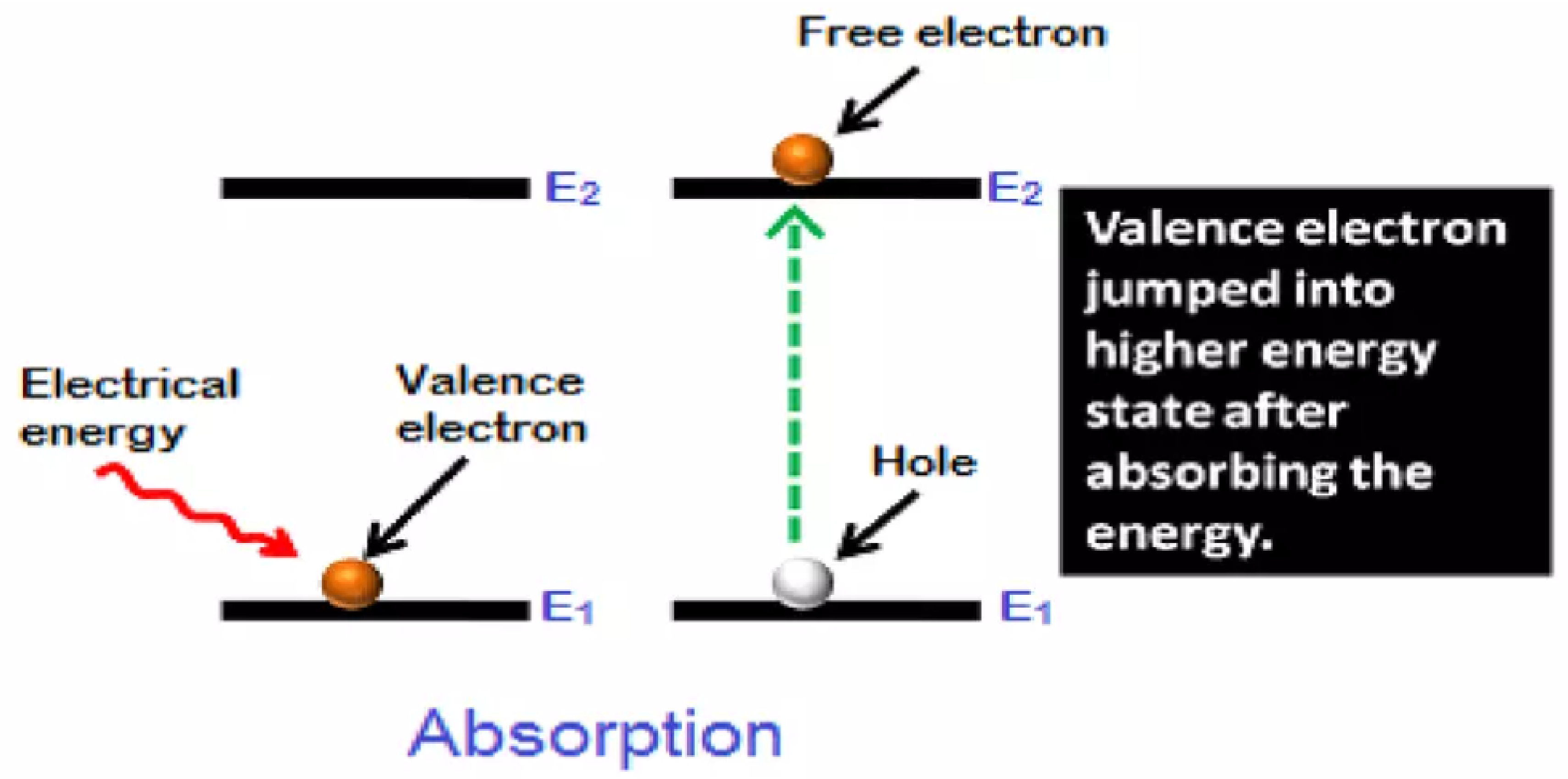
- **Absorption of energy:** Absorption of energy is the process of absorbing energy from the external energy sources.

➢ In laser diodes, electrical energy or DC voltage is used as the external energy source. When the DC voltage or electrical energy supplies enough energy to the valence electrons or valence band electrons, they break bonding with the parent atom and jumps into the higher energy level (conduction band). The electrons in the conduction band are known as free electrons.

➢ When the valence electron leaves the valence shell, an empty space is created at the point from which electron left. This empty space in the valence shell is called a hole.

Semiconductor Laser (For Information only)

- Thus, both free electrons and holes are generated as a pair because of the absorption of energy from the external DC source.



Semiconductor Laser (For Information only)

Spontaneous emission:

- Spontaneous emission is the process of emitting light or photons naturally while electrons falling to the lower energy state.

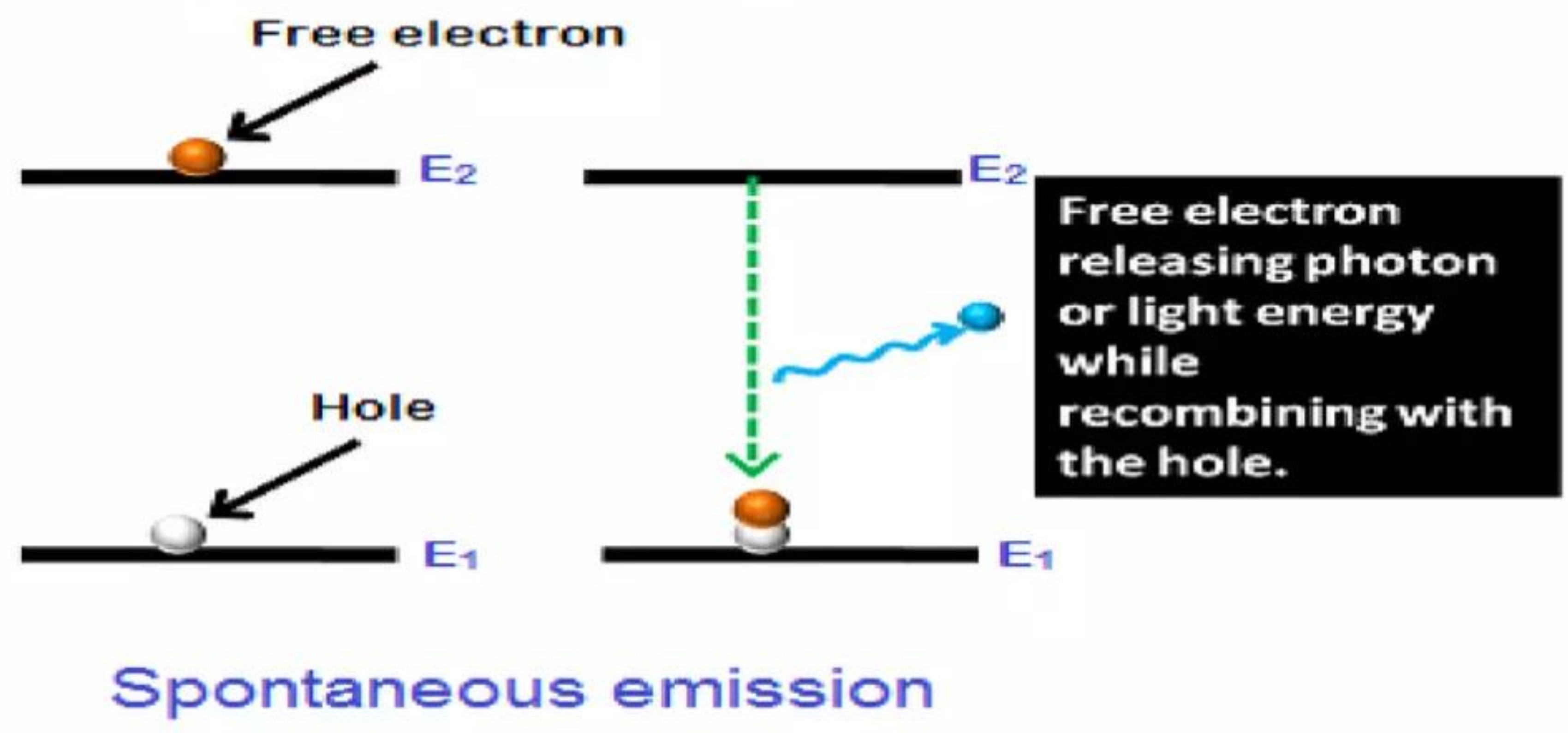
- In laser diodes, the valence band electrons or valence electrons are in the lower energy state. Therefore, the holes generated after the valence electrons left are also in the lower energy state.

- On the other hand, the conduction band electrons or free electrons are in the higher energy state. In simple words, free electrons have more energy than holes.

- The free electrons in the conduction band need to lose their extra energy in order to recombine with the holes in the valence band.

Semiconductor Laser (For Information only)

- The free electrons in the conduction band will not stay for long period. After a short period, the free electrons recombine with the lower energy holes by releasing energy in the form of photons.



Semiconductor Laser (For Information only)

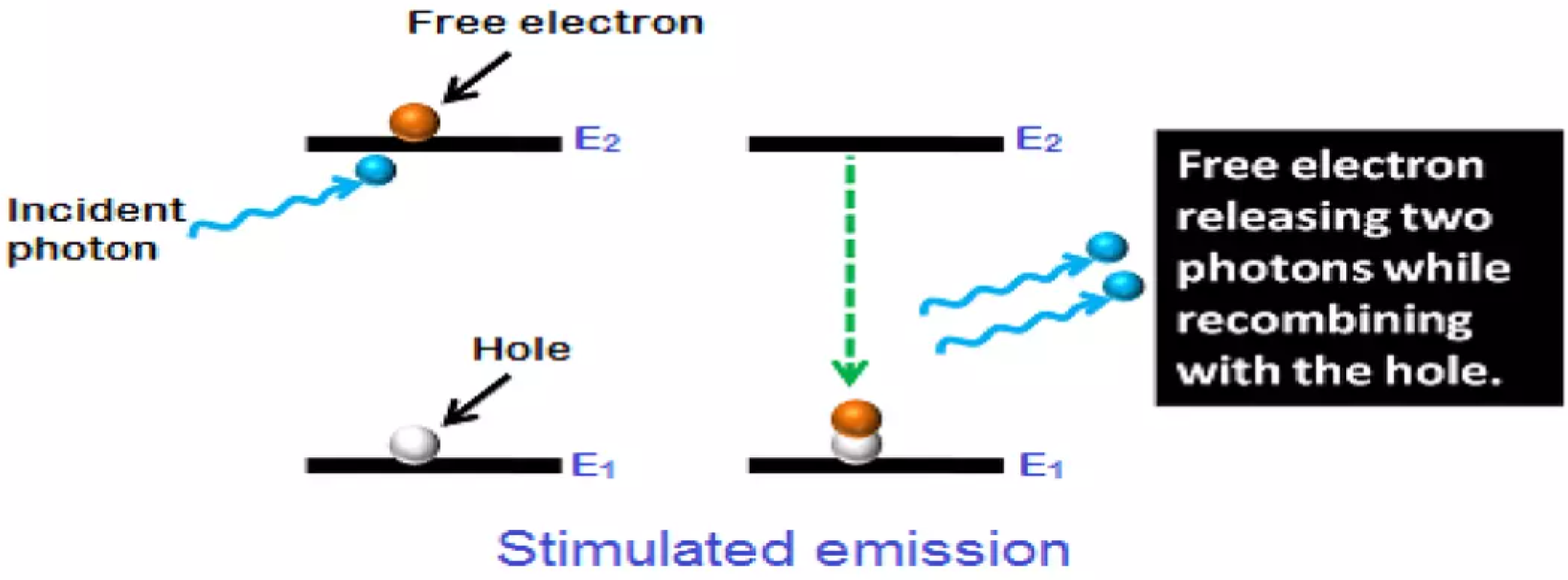
Stimulated emission:

- Stimulated emission is the process by which excited electrons or free electrons are stimulated to fall into the lower energy state by releasing energy in the form of light. The stimulated emission is an artificial process.

- In stimulated emission, the excited electrons or free electrons need not wait for the completion of their lifetime. Before the completion of their lifetime, the incident or external photons will force the free electrons to recombine with the holes. In stimulated emission, each incident photon will generate two photons.

Semiconductor Laser (For Information only)

- All the photons generated due to the stimulated emission will travel in the same direction. As a result, a narrow beam of high-intensity laser light is produced.

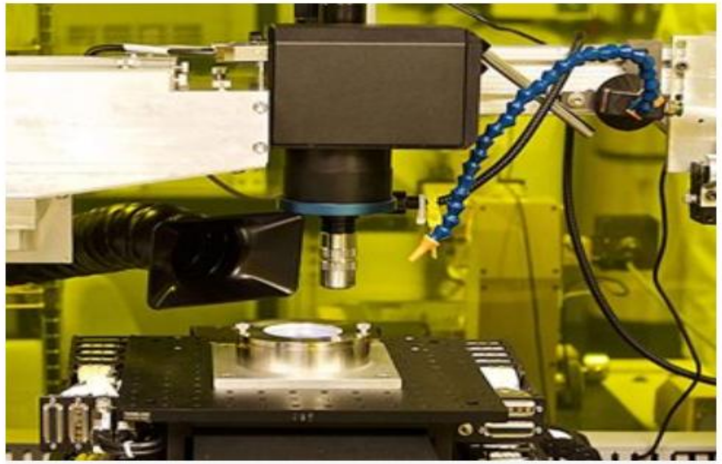


Semiconductor Laser: Working

- **Forward Biasing:** An external voltage is applied so that electrons (from n-type) and holes (from p-type) are injected into the active region.
- **Carrier Recombination**: Electrons and holes recombine in the active region, releasing energy as photons.
- **Stimulated Emission**: Initial photons stimulate further recombination events, producing more photons of exactly the same phase, direction, and energy.
- **Optical Resonance**: The photons reflect back and forth between the two end mirrors, stimulating even more emissions.
- **Laser Output**: When the rate of stimulated emission exceeds loss, intense, coherent, and monochromatic light is emitted from the partially reflective end.
- **GaAs laser emits light at a wavelength of 9000 Å in IR region**

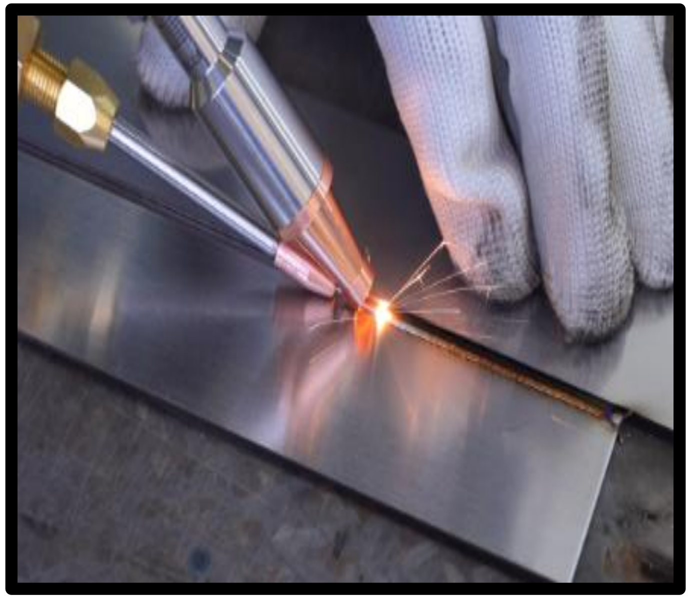
APPLICATIONS of LASERS

Laser Drilling

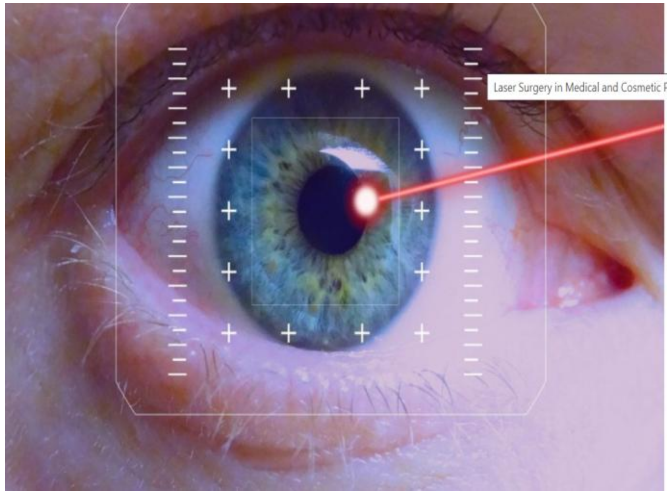


Lasers are incredibly accurate at drilling micron-sized holes in a wide range of materials. Image: Laser Light

Laser Welding



Laser cutting



Lasers in Medical sectors

Semiconductor Laser: Application & Uses

Diode lasers are widely used due to their compact size, low power requirement, and efficiency:

- Telecommunications: As the light source for fiber-optic data transmission and multiplexing.
- Consumer Electronics: In CD/DVD/Blu-ray players and recorders.
- Printing & Scanning: In laser printers, barcode, and QR code scanners.
- Laser Pointers: Compact and energy-efficient sources for pointing and classroom demonstrations.

Semiconductor Laser: Application & Uses

- Medical Field: For eye and dental surgery, hair removal, skin therapy, photodynamic treatments, and soft tissue surgery.

- Industrial Applications: Material processing including cutting, engraving, welding, laser marking.

- Scientific Research: Spectroscopy, microscopy, material analysis.

- Sensing and Measurement: For distance measurement (lidar), range finding, and optical metrology

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