Fundamentals of light and electromagnetic waves

Photon and its energy:

- Light behaves mainly like a wave but it can also be considered to consist of tiny packages of energy called photons.
- Photons carry a fixed amount of energy but have no mass.
- The energy of a photon depends on its wavelength.
- Longer wavelength photons have less energy and shorter wavelength photons have more.

Energy of a photon

We can measure the energy of a photon using Einstein's equation:

$$E = hf = \frac{hc}{\lambda}$$

$h = 6.63 \times 10^{-34}$ Js → Planck constant

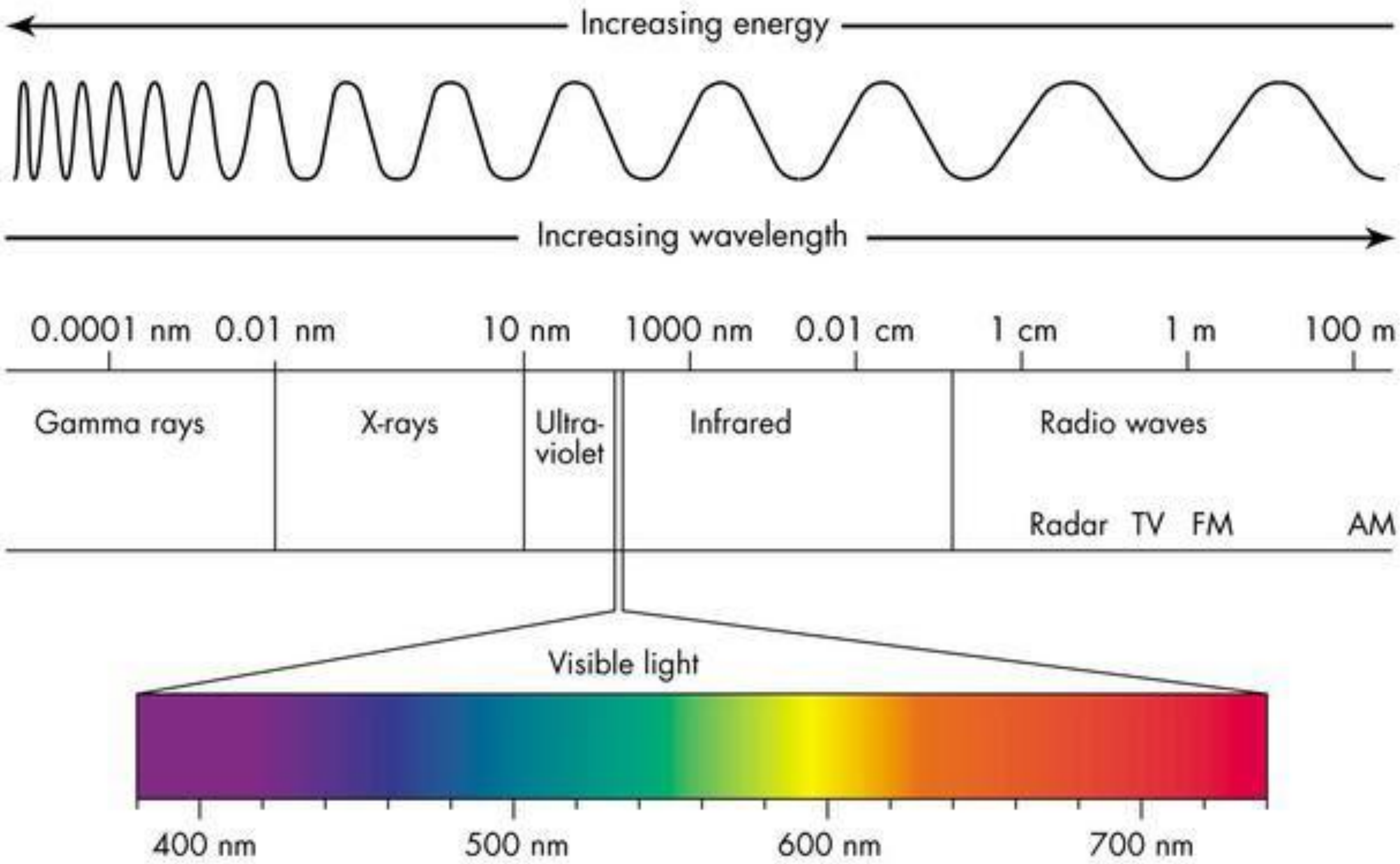
f = frequency of photon/electromagnetic radiation

$c = 3 \times 10^{8}$ m/s → speed of light in a vacuum

λ = wavelength of photon/electromagnetic radiation

A photon of light with an energy of 2.2×10^{-19} Joules is emitted. What is the **frequency** of this photon?

3.3×10^{14} Hz


Increasing energy
Increasing wavelength
0.0001 nm
0.01 nm
10 nm
1000 nm
0.01 cm
1 cm
1 m
100 m
Gamma rays
X-rays
Ultra-
violet
Infrared
Radio waves
Radar
TV
FM
AM
Visible light
400 nm
500 nm
600 nm
700 nm

Electromagnetic spectrum

- The electromagnetic spectrum is the range of frequencies of electromagnetic radiation and their respective wavelengths and photon energies.
- The region on this spectrum with the highest energy (so the shortest wavelengths) are gamma rays and the region with the lowest energy (so the longest wavelengths) are radio waves.
- The visible region of the spectrum has wavelengths from about 400-700 nm.
- The measure of wavelength determines the color on the visible spectrum.
- As you can see in the picture above, a wavelength of 400 nm represents violet and a wavelength of 700 nm represents red.

Photon-Semiconductor Interaction

Light Semiconductor Interaction

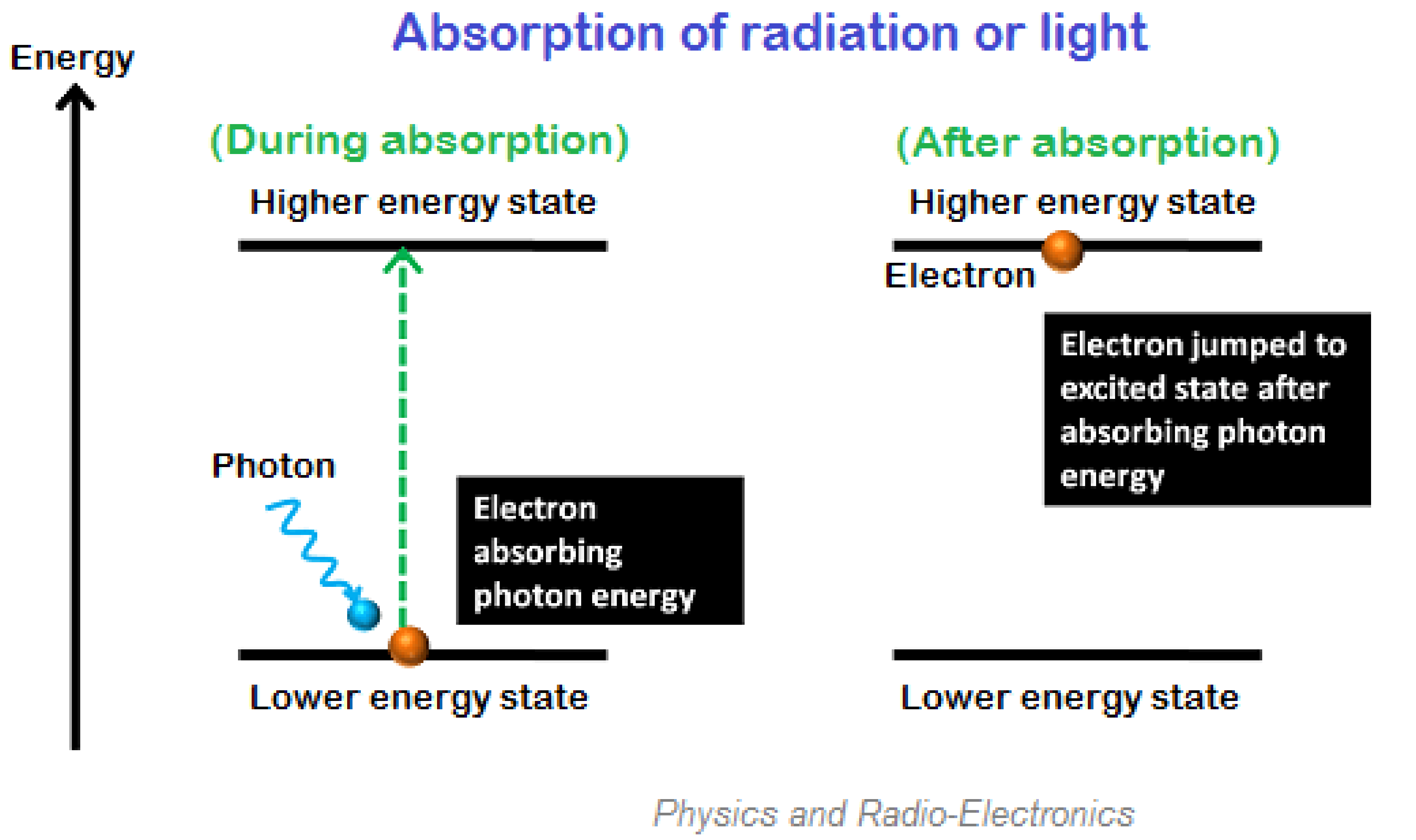
Photons are interacted in three ways with the atoms:

- Absorption of radiation
- Spontaneous emission
- Stimulated emission

Absorption of radiation

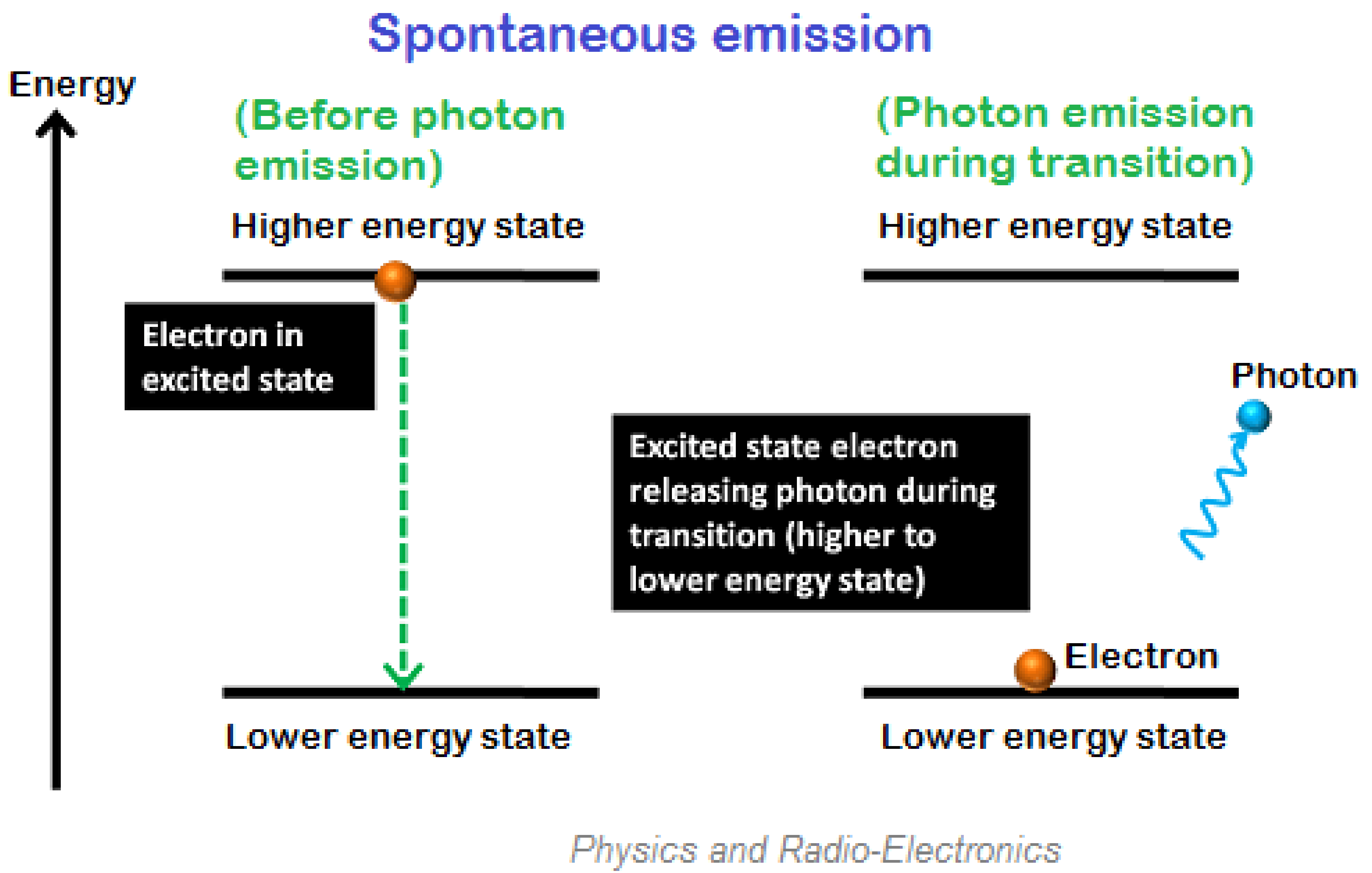
- Absorption of radiation is the process by which electrons in the ground state absorbs energy from photons to jump into the higher energy level.
- The electrons orbiting very close to the nucleus are at the lower energy level or lower energy state whereas the electrons orbiting farther away from the nucleus are at the higher energy level.
- The electrons in the lower energy level need some extra energy to jump into the higher energy level. This extra energy is provided from various energy sources such as heat, electric field, or light.

- Let us consider two energy levels (E_1 and E_2) of electrons.
- E_1 is the ground state or lower energy state of electrons and E_2 is the excited state or higher energy state of electrons.
- The electrons in the ground state are called lower energy electrons or ground state electrons whereas the electrons in the excited state are called higher energy electrons or excited electrons.
- When photons or light energy equal to the energy difference of the two energy levels ($E_2 - E_1$) is incident on the atom, the ground state electrons gains sufficient energy and jumps from ground state (E_1) to the excited state (E_2).

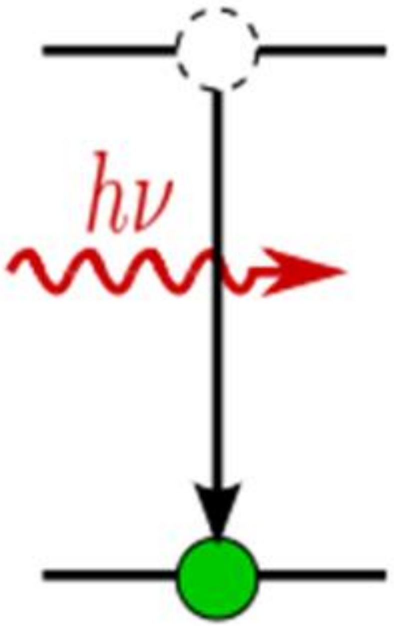

Absorption of radiation or light
Energy
(During absorption)
Higher energy state
Photon
Electron absorbing photon energy
Lower energy state
(After absorption)
Higher energy state
Electron
Electron jumped to excited state after absorbing photon energy
Lower energy state
Physics and Radio-Electronics

Spontaneous emission

- Spontaneous emission is the process by which electrons in the excited state return to the ground state by emitting photons.
- The electrons in the excited state can stay only for a short period. The time up to which an excited electron can stay at higher energy state (E_2) is known as the lifetime of excited electrons. The lifetime of electrons in excited state is 10^{-8} second


Spontaneous emission
Energy
(Before photon emission)
Higher energy state
Electron in excited state
Lower energy state
(Photon emission during transition)
Higher energy state
Photon
Excited state electron releasing photon during transition (higher to lower energy state)
Electron
Lower energy state
Physics and Radio-Electronics

- Thus, after the short lifetime of the excited electrons, they return to the lower energy state or ground state by releasing energy in the form of photons.
- In spontaneous emission, the electrons move naturally or spontaneously from one state (higher energy state) to another state (lower energy state) so the emission of photons also occurs naturally. Therefore, we have no control over when an excited electron is going to lose energy in the form of light.
- The photons emitted in spontaneous emission process constitute ordinary incoherent light.
- Incoherent light is a beam of photons with frequent and random changes of phase.
- In other words, the photons emitted in the spontaneous emission process do not flow exactly in the same direction of incident photons



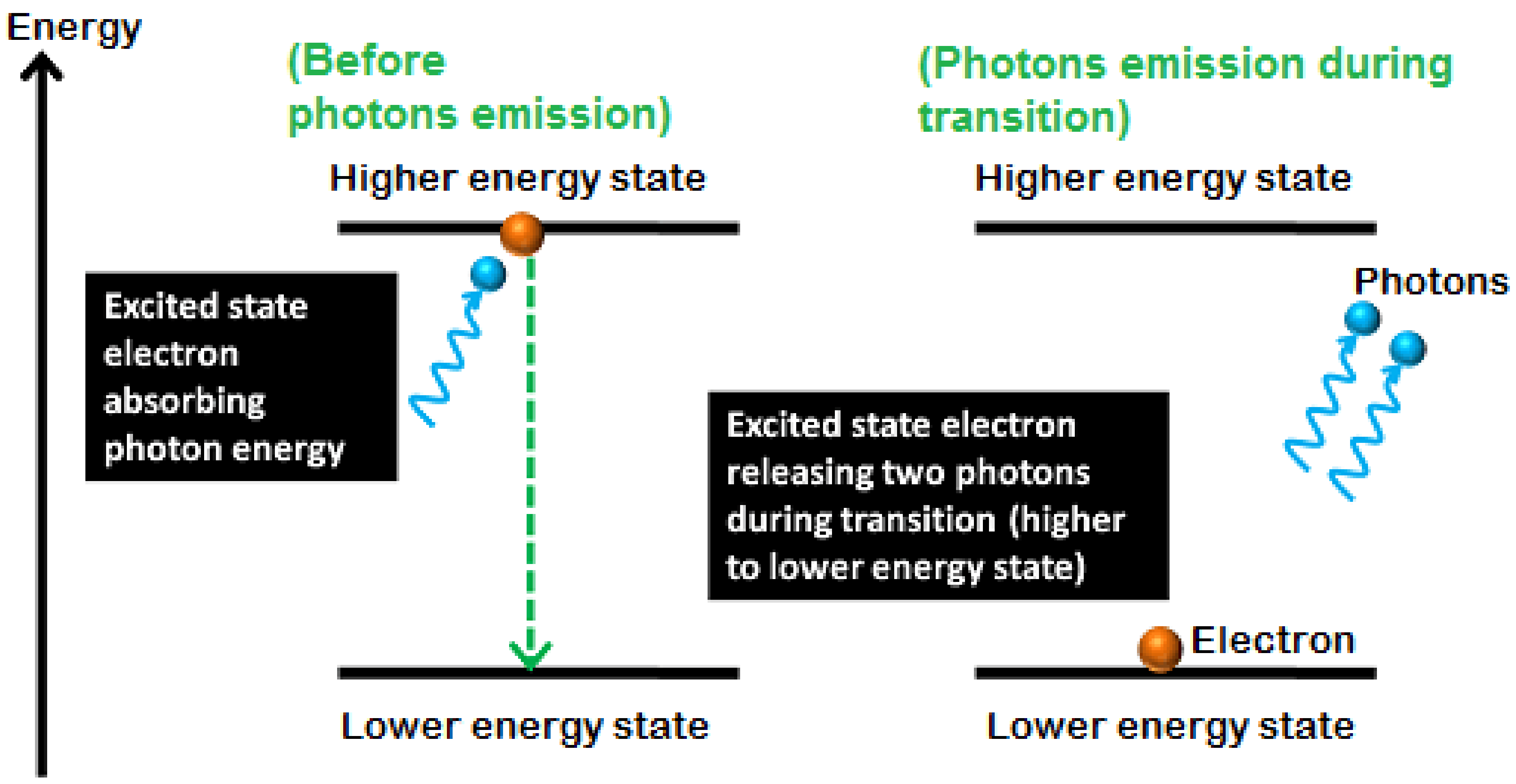
$$E_2 - E_1 = \Delta E = h\nu$$

Stimulated emission

- Stimulated emission is the process by which incident photon interacts with the excited electron and forces it to return to the ground state.
- In stimulated emission, the light energy is supplied directly to the excited electron instead of supplying light energy to the ground state electrons.
- Unlike the spontaneous emission, the stimulated emission is not a natural process it is an artificial process
- In spontaneous emission, the electrons in the excited state will remain there until its lifetime is over. After completing their lifetime, they return to the ground state by releasing energy in the form of light.

- However, in stimulated emission, the electrons in the excited state need not wait for completion of their lifetime.
- An alternative technique is used to forcefully return the excited electron to ground state before completion of their lifetime. This technique is known as the stimulated emission.
- When incident photon interacts with the excited electron, it forces the excited electron to return to the ground state.
- This excited electron release energy in the form of light while falling to the ground state.

Stimulated emission

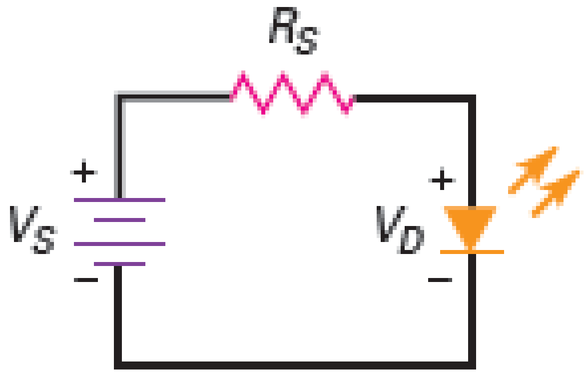


Physics and Radio-Electronics

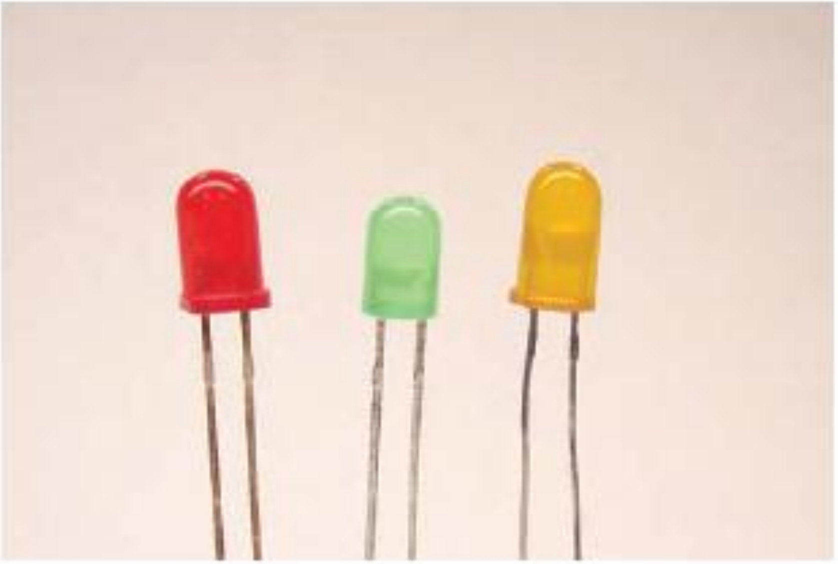
- In stimulated emission, two photons are emitted (one additional photon is emitted), one is due to the incident photon and another one is due to the energy release of excited electron. Thus, two photons are emitted.
- The stimulated emission process is very fast compared to the spontaneous emission process.
- All the emitted photons in stimulated emission have the same energy, same frequency and are in phase. Therefore, all photons in the stimulated emission travel in the same direction.
- The number of photons emitted in the stimulated emission depends on the number of electrons in the higher energy level or excited state and the incident light intensity.

- Number of emitted photons α Number of electrons in the excited state + incident light intensity.

LED- Light Emitting Diode

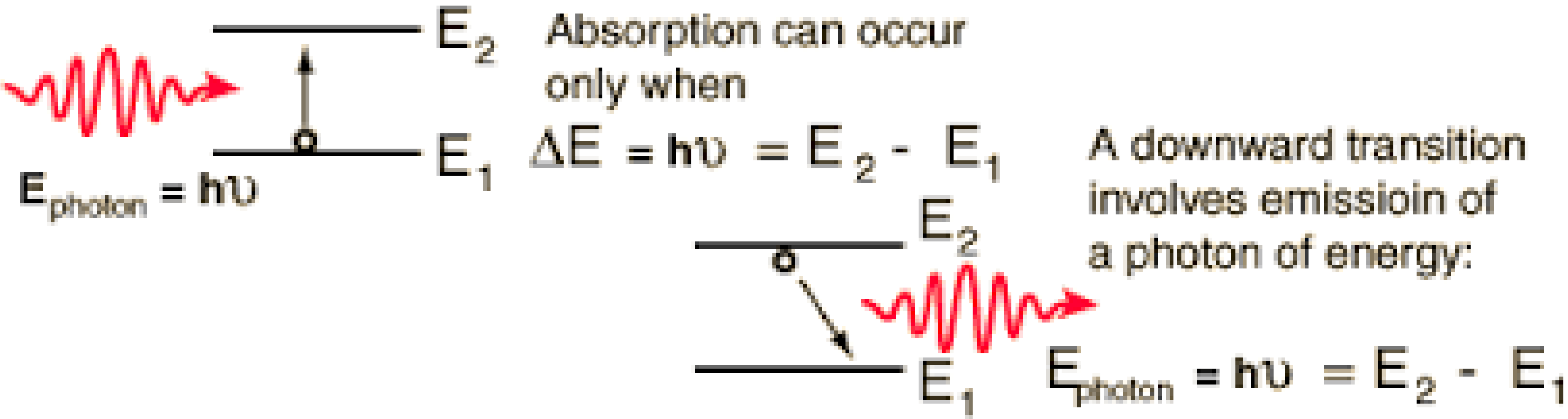


- LEDs have replaced incandescent lamps in many applications because of the LED's lower energy consumption, smaller size, faster switching and longer lifetime.
- Just as in an ordinary diode, the LED has an anode and a cathode that must be properly biased.
- a source connected to a resistor and an LED.
- The outward arrows symbolize the radiated light.



- In a forward-biased LED, free electrons cross the *pn junction and fall into holes.*
- *As these electrons fall from a higher*

  to a lower energy level, they radiate energy in the form of photons.



- In ordinary diodes, this energy is radiated in the form of heat. But in an LED, the energy is radiated as light.
- This effect is referred to as **electroluminescence.**
- The color of the light, which corresponds to the wavelength energy of the photons, is primarily determined by the energy band gap of the semiconductor materials that are used.
- By using elements like gallium, arsenic, and phosphorus, a manufacturer can produce LEDs that radiate red, green, yellow, blue, orange, white or infrared (invisible) light.
- LEDs that produce visible radiation are useful as indicators in applications such as instrumentation panels, internet routers, and so on.
- The infrared LED finds applications in security systems, remote controls, industrial control systems, and other areas requiring invisible radiation

LED Voltage and Current

$$I_S = \frac{V_S - V_D}{R_S}$$

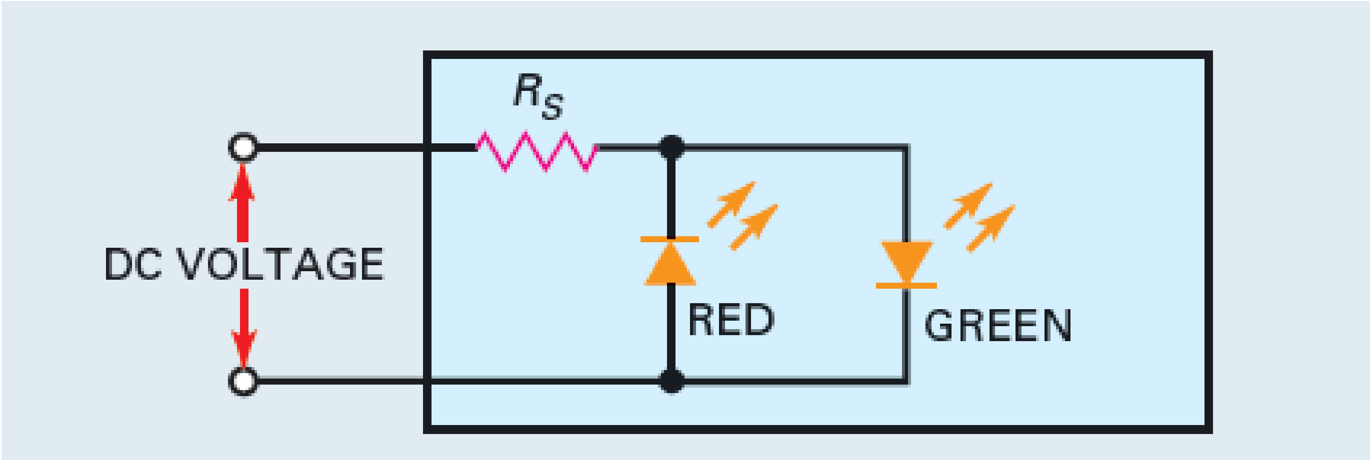
For most commercially available low-power LEDs, the typical voltage drop is from 1.5 to 2.5 V for currents between 10 and 50 mA. The exact voltage drop depends on the LED current, color, tolerance, along with other factors.

LED Brightness and breakdown voltages

- The brightness of an LED depends on the current.
- When *VS is much greater than VD, the brightness of the* LED is approximately constant.
- If *VS is only slightly more than VD, the LED brightness will vary* noticeably from one circuit to the next.
- LEDs have very low breakdown voltages typically between 3 and 5, because of this they are easily destroyed if reversed biased with too much voltage.
- A rectifier diode in parallel with the LED is used to prevent reverse bias destruction of the LED.

Example

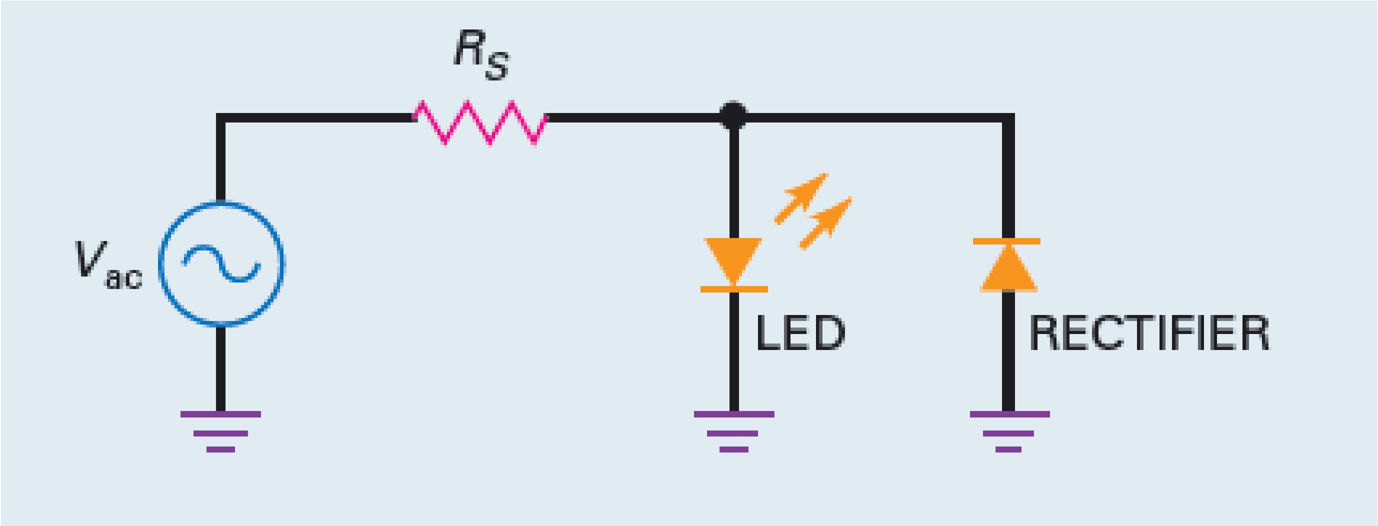
- Figure *shows a voltage-polarity tester. It can be used to test a dc voltage of* unknown polarity. When the dc voltage is positive, the green LED lights up. When the dc voltage is negative, the red LED lights up. What is the approximate LED current if the dc input voltage is 50 V and the series resistance is 2.2 kohm?



SOLUTION We will use a forward voltage of approximately 2 V for either LED. With Eq. (5-13):

$$I_S = \frac{50\ \text{V} - 2\ \text{V}}{2.2\ \text{k}\Omega} = 21.8\ \text{mA}$$

- Figure shows an ac voltage source driving an LED indicator. When there is ac voltage, there is LED current on the positive half-cycles. On the negative half-cycles, the rectifier diode turns on and protects the LED from too much reverse voltage. If the ac source voltage is 20 Vrms and the series resistance is 680 ohm, what is the average LED current? Also, calculate the approximate power dissipation in the series resistor.



SOLUTION The LED current is a rectified half-wave signal. The peak source voltage is 1.414 × 20 V, which is approximately 28 V. Ignoring the LED voltage drop, the approximate peak current is:

$$I_S = \frac{28\ \text{V}}{680\ \Omega} = 41.2\ \text{mA}$$

The average of the half-wave current through the LED is:

$$I_S = \frac{41.2\ \text{mA}}{\pi} = 13.1\ \text{mA}$$

Ignore the diode drops in Fig. 5-23; this is equivalent to saying that there is a short to ground on the right end of the series resistor. Then the power dissipation in the series resistor equals the square of the source voltage divided by the resistance:

$$P = \frac{(20\ \text{V})^2}{680\ \Omega} = 0.588\ \text{W}$$

LASER

Light Amplification by Stimulated Emission of Radiation

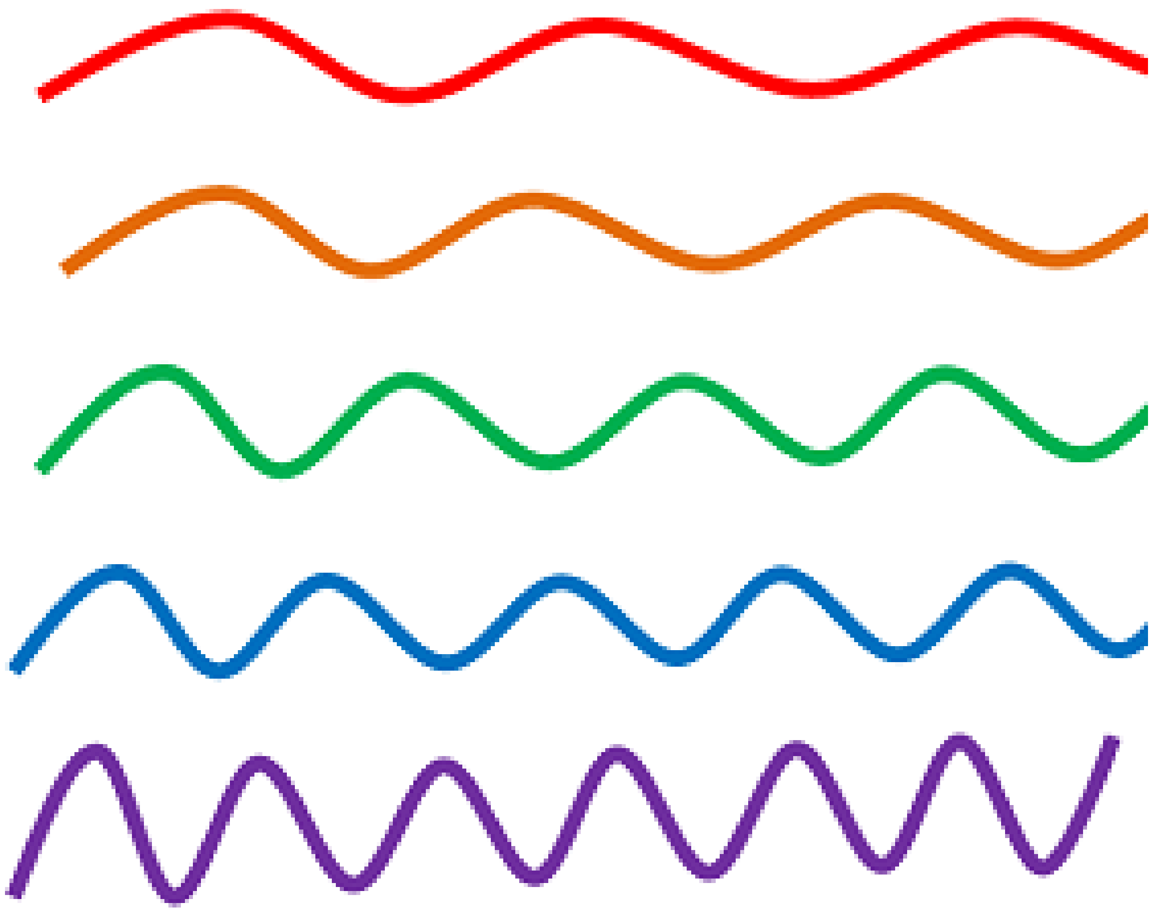
Characteristics of Laser

Laser light has four unique characteristics that differentiate it from ordinary light.

- Coherence
- Directionality
- Monochromatic
- High intensity

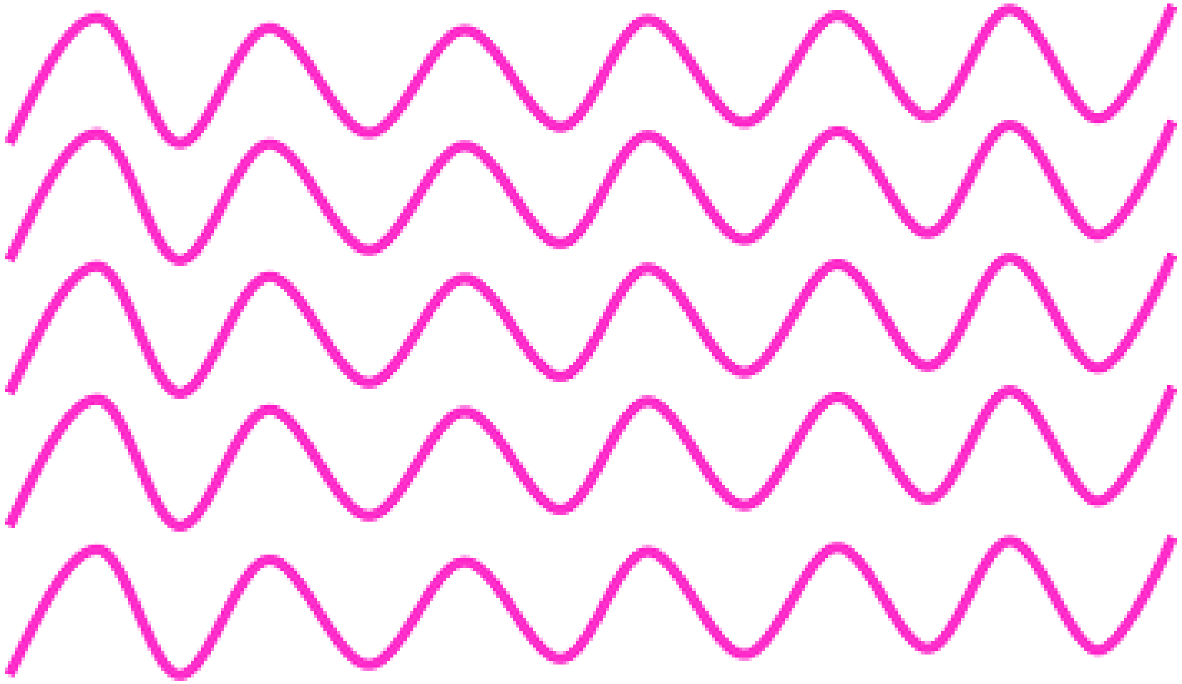
Coherence

- We know that visible light is emitted when excited electrons (electrons in higher energy level) jumped into the lower energy level (ground state).
- The process of electrons moving from higher energy level to lower energy level or lower energy level to higher energy level is called electron transition.
- In ordinary light sources (lamp, sodium lamp and torch light), the electron transition occurs naturally. In other words, electron transition in ordinary light sources is random in time. The photons emitted from ordinary light sources have different energies, frequencies, wavelengths, or colors. Hence, the light waves of ordinary light sources have many wavelengths. Therefore, photons emitted by an ordinary light source are out of phase.



Incoherent light

- In laser, the electron transition occurs artificially. In other words, in laser, electron transition occurs in specific time. All the photons emitted in laser have the same energy, frequency, or wavelength. Hence, the light waves of laser light have single wavelength or color. Therefore, the wavelengths of the laser light are in phase in space and time. In laser, a technique called stimulated emission is used to produce light.
- Thus, light generated by laser is highly coherent. Because of this coherence, a large amount of power can be concentrated in a narrow space

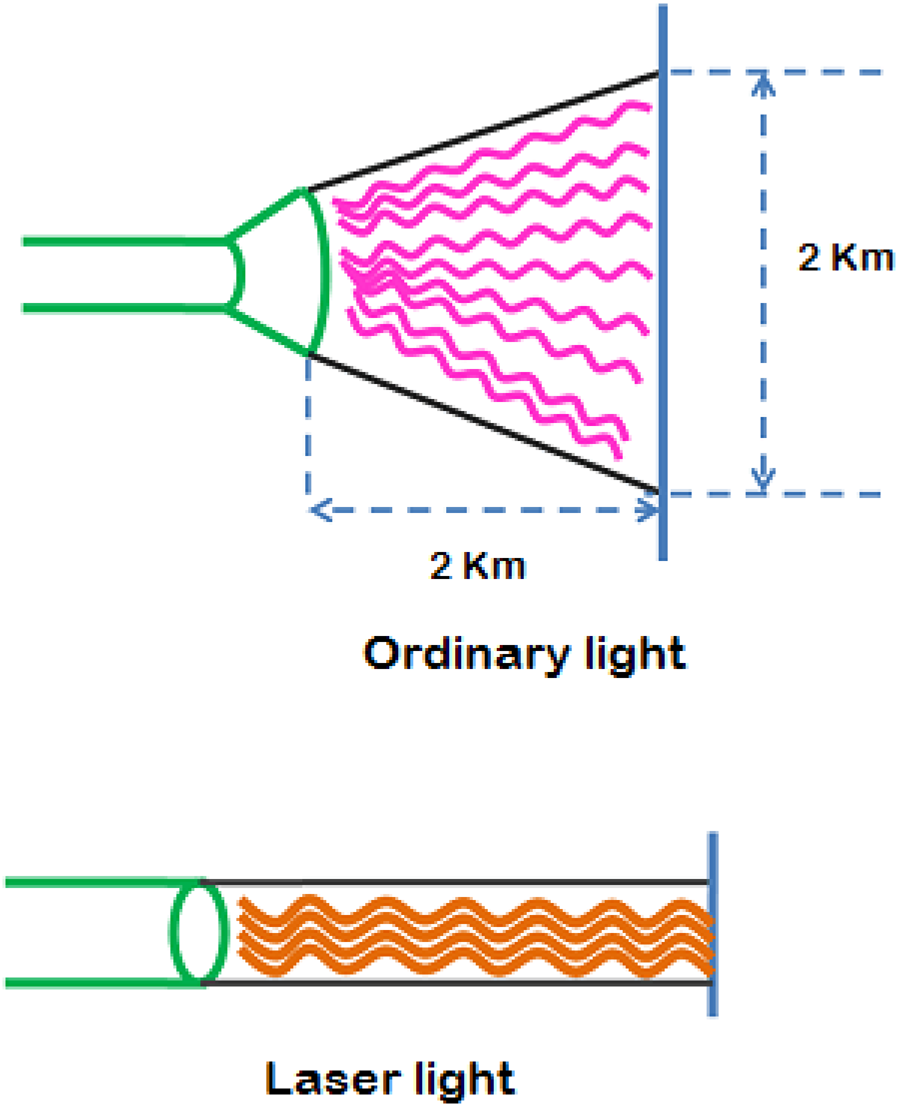


Coherent light waves

Directionality

- In conventional light sources (lamp, sodium lamp and torchlight), photons will travel in random direction. Therefore, these light sources emit light in all directions.

- On the other hand, in laser, all photons will travel in same direction. Therefore, laser emits light only in one direction. This is called directionality of laser light. The width of a laser beam is extremely narrow. Hence, a laser beam can travel to long distances without spreading.



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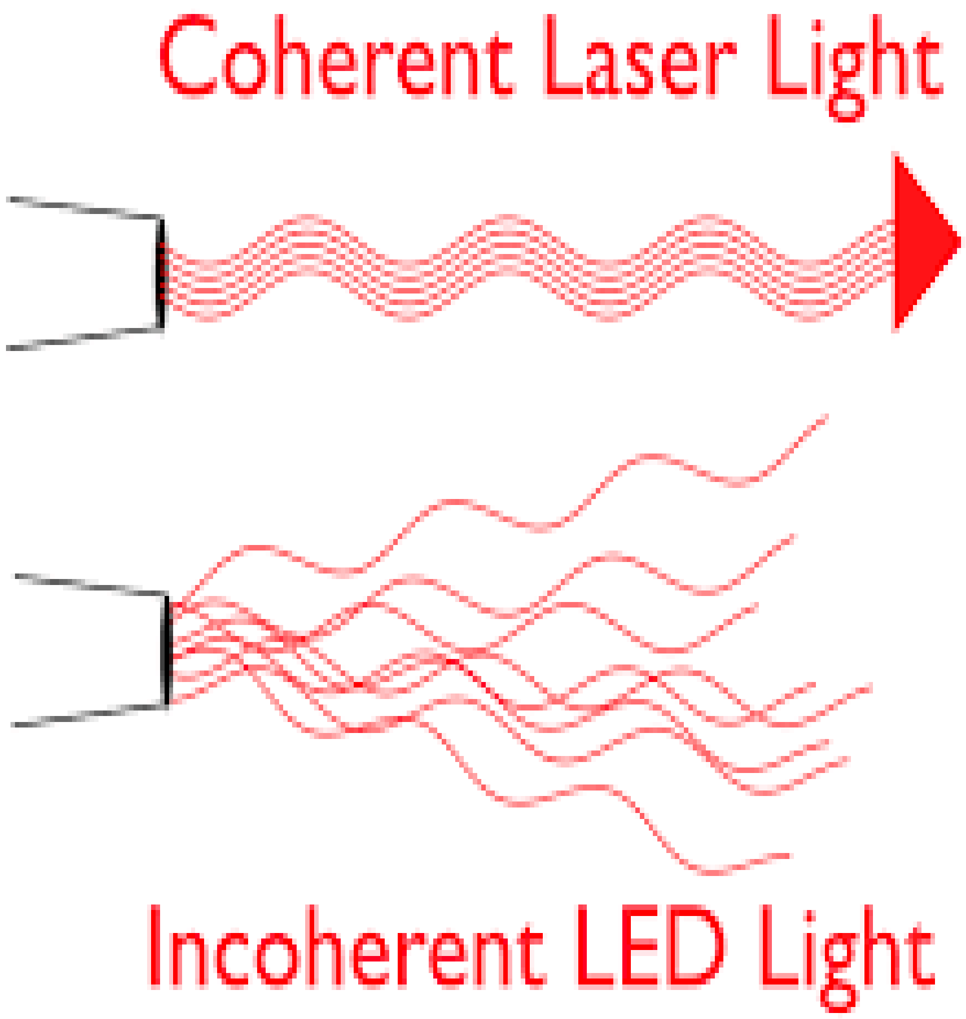


- If an ordinary light travels a distance of 2 km, it spreads to about 2 km in diameter. On the other hand, if a laser light travels a distance of 2 km, it spreads to a diameter less than 2 cm.

Monochromatic

- Monochromatic light means a light containing a single color or wavelength. The photons emitted from ordinary light sources have different energies, frequencies, wavelengths, or colors. Hence, the light waves of ordinary light sources have many wavelengths or colors. Therefore, ordinary light is a mixture of waves having different frequencies or wavelengths.
- On the other hand, in laser, all the emitted photons have the same energy, frequency, or wavelength. Hence, the light waves of laser have single wavelength or color. Therefore, laser light covers a very narrow range of frequencies or wavelengths.

High Intensity

- You know that the intensity of a wave is the energy per unit time flowing through a unit normal area. In an ordinary light source, the light spreads out uniformly in all directions.
- In laser, the light spreads in small region of space and in a small wavelength range. Hence, laser light has greater intensity when compared to the ordinary light.
- Thus, these four properties of laser beam enable us to cut a huge block of steel by melting.

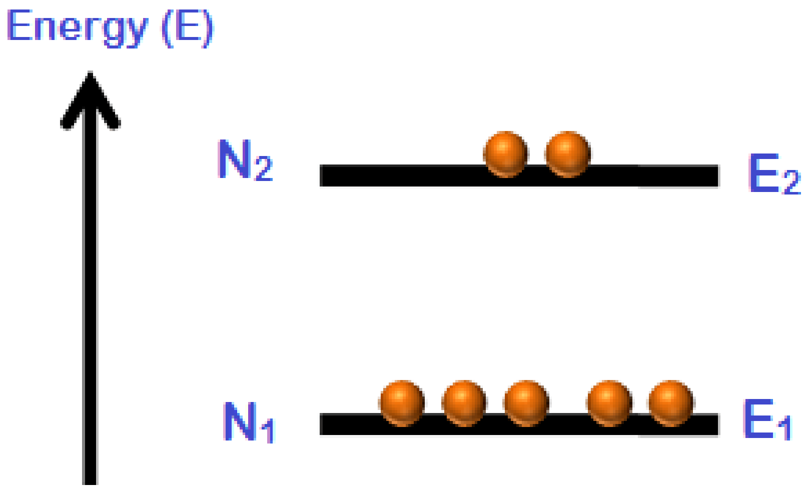
Population Inversion

- Population inversion is the process of achieving greater population of higher energy state as compared to the lower energy state.
- Population inversion technique is mainly used for light amplification.
- The population inversion is required for laser operation.

- Consider a group of electrons with two energy levels E_1 and E_2.
- E_1 is the lower energy state and E_2 is the higher energy state.
- N_1 is the number of electrons in the energy state E_1.
- N_2 is the number of electrons in the energy state E_2.
- The number of electrons per unit volume in an energy state is the population of that energy state.

- Population inversion cannot be achieved in a two energy level system.
- Under normal conditions, the number of electrons (N_1) in the lower energy state (E_1) is always greater as compared to the number of electrons (N_2) in the higher energy state (E_2).

$N_1 > N_2$

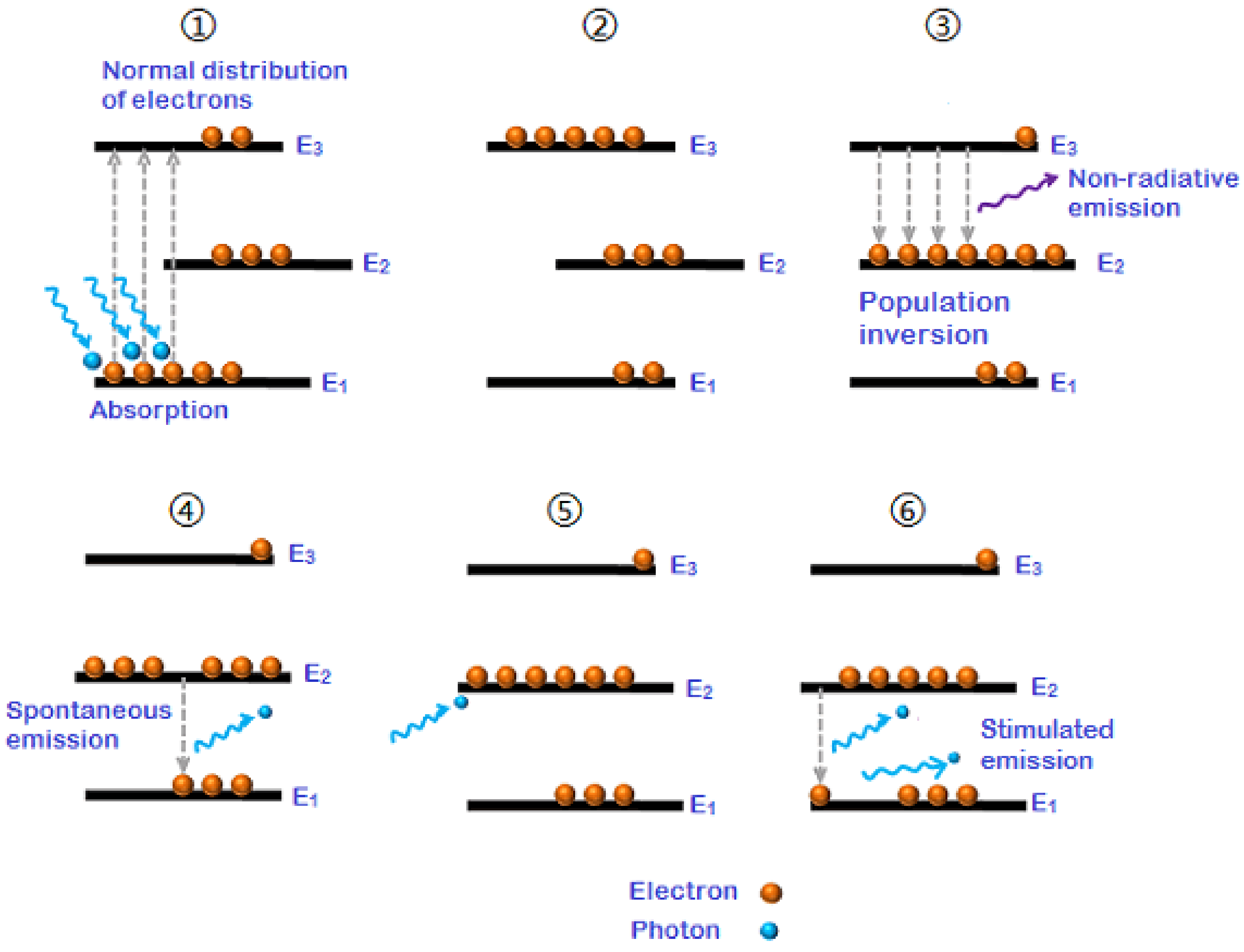


- There are certain substances in which the electrons once excited; they remain in the higher energy level or excited state for longer period.
- Such systems are called active systems or active media which are generally mixture of different elements
- When such mixtures are formed, their electronic energy levels are modified and some of them acquire special properties.
- Such types of materials are used to form 3-level laser or 4-level laser.

3-level Laser

- Consider a system consisting of three energy levels E_1, E_2, E_3 with N number of electrons.
- We assume that the energy level of E_1 is less than than E_2 and E_3, the energy level of E_2 is greater than E_1 and less than E_3, and the energy level of E_3 is greater than E_1 and E_2.
- It can be simply written as $E_1 < E_2 < E_3$. That means the energy level of E_2 lies in between E_1 and E_3.

Population inversion in 3-level laser



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- The energy level E_1 is known as the ground state or lower energy state and the energy levels E_2 and E_3 are known as excited states.
- The energy level E_2 is sometimes referred to as Meta stable state. The energy level E_3 is sometimes referred to as pump state or pump level.
- The N number of electrons in the system occupies these three energy levels.
- Let N_1 be the number of electrons in the energy state E_1, N_2 be the number of electrons in the energy state E_2 and N_3 be the number of electrons in the energy state E_3.

- To get laser emission or population inversion, the population of higher energy state (E_2) should be greater than the population of the lower energy state (E_1).
- Under normal conditions, the higher an energy level is, the lesser it is populated. For example, in a three level energy system, the lower energy state E_1 is highly populated as compared to the excited energy states E_2 and E_3.
- On the other hand, the excited energy state E_2 is highly populated as compared to the excited energy state E_3. It can be simply written as $N_1 > N_2 > N_3$.

- Under certain conditions, the greater population of higher energy state (E_2) as compared to the lower energy state (E_1) is achieved. Such an arrangement is called population inversion.
- Let us assume that initially the majority of electrons will be in the lower energy state or ground state (E_1) and only a small number of electrons will be in excited states (E_2 and E_3).
- When we supply light energy which is equal to the energy difference of E_3 and E_1, the electrons in the lower energy state (E_1) gains sufficient energy and jumps into the higher energy state (E_3). This process of supplying energy is called pumping.

- The lifetime of electrons in the energy state E_3 is very small as compared to the lifetime of electrons in the energy state E_2.
- Therefore, electrons in the energy level E_3 does not stay for long period.
- After a short period, they quickly fall to the Meta stable state or energy state E_2 and releases radiation less energy instead of photons.
- Because of the shorter lifetime, only a small number of electrons accumulate in the energy state E_3.

- The electrons in the Meta stable state E_2 will remain there for longer period because of its longer lifetime.
- As result, a large number of electrons accumulate in Meta stable state.
- Thus, the population of metal stable state will become greater than the population of energy states E_3 and E_1.
- It can be simply written as $N_2 > N_1 > N_3$.
- In a three level energy system, we achieve population inversion between energy levels E_1 and E_2.
- After completion of lifetime of electrons in the Meta stable state, they fall back to the lower energy state or ground state E_1 by releasing energy in the form of photons. This process of emission of photons is called spontaneous emission.

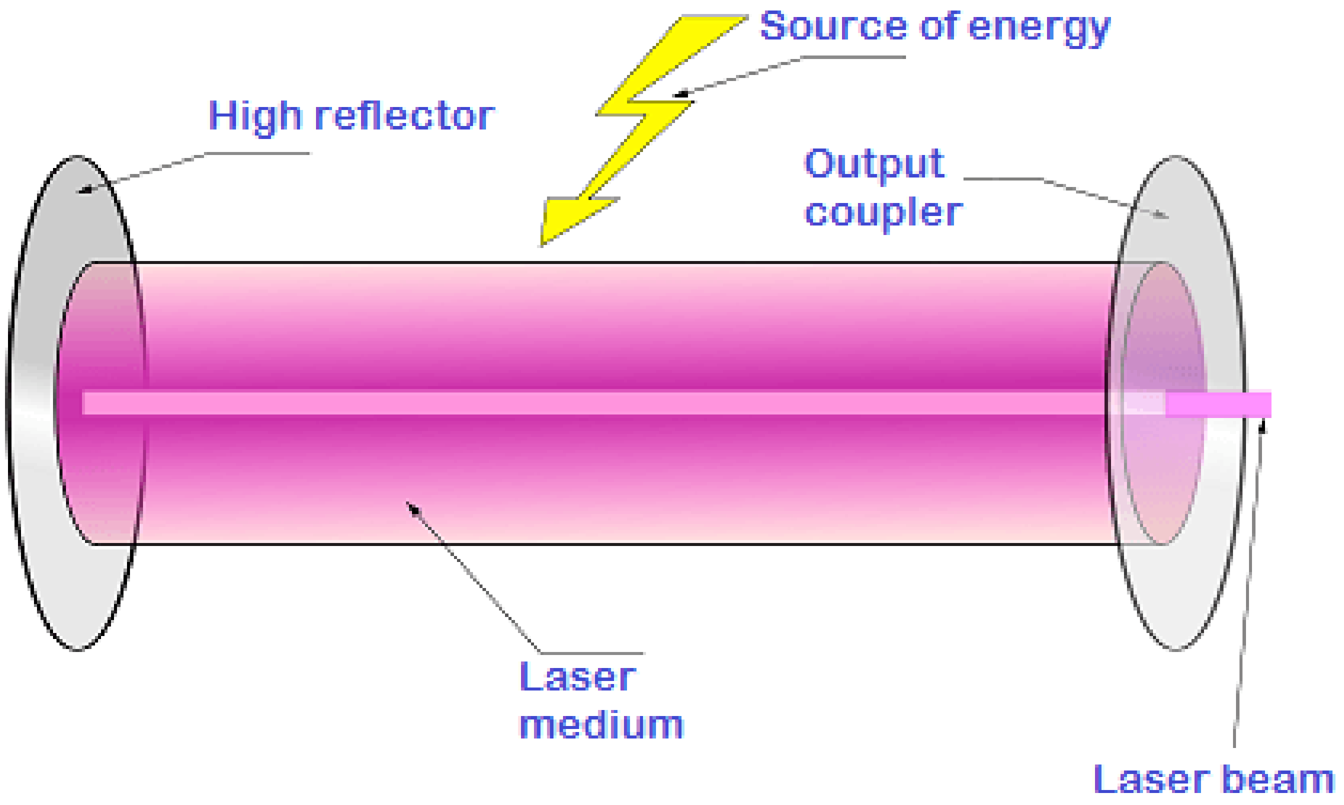
- When this emitted photon interacts with the electron in the Meta stable state E_2, it forces that electron to fall back to the ground state. As a result, two photons are emitted. This process of emission of photons is called stimulated emission.
- When these photons again interacted with the electrons in the Meta stable state, they forces two Meta stable state electrons to fall back to the ground state. As a result, four photons are emitted. Likewise, a large number of photons are emitted

Laser Construction

- A laser or laser system consists of three important components: a pump source, laser medium and optical resonator.

Pump Source

- The pump source or energy source is the part of a laser system that provides energy to the laser medium. To get laser emission, first we need to produce population inversion. Population inversion is the process of achieving greater number of electrons in higher energy state as compared to the lower energy state.
- The source of energy supplies sufficient amount of energy to the laser medium by which the electrons in the lower energy state are excited to the higher energy state. As a result, we get population inversion in the active medium or laser medium. Examples of energy sources include electric discharges, light from another laser, chemical reactions, and flash lamps. The type of energy source used is mostly depends on the laser medium. Excimer laser uses chemical reaction as energy source, a helium laser uses an electric discharge as energy source and Nd:YAG laser uses light focused from diode laser as energy source.


Source of energy
High reflector
Output
coupler
Laser
medium
Laser beam

Laser Medium

- The laser medium is a medium where spontaneous and stimulated emission of radiation takes place. Generally, the population of lower energy state is greater than the higher energy state. However, after achieving population inversion, the population of higher energy state becomes greater than the lower energy state.

- After receiving sufficient energy from source, the electrons in the lower energy state or ground state are excited to the higher energy state (in the laser medium). The electrons in the excited state do not stay for long period because the lifetime of electrons in the excited state is very small. Hence, after a short period, the electrons in the excited state will fall back to the ground state by releasing energy in the form of light or photons. This is called spontaneous emission. In spontaneous emission, each electron emits a single photon while falling to the ground state.

- When these emitted photons collide with the electrons in the excited state or meta stable state, it forces meta stable electrons to fall back to the ground state. As a result, electrons again release energy in the form of photons. This is called stimulated emission. In stimulated emission, each electron emits two photons while falling to the ground state.

- When these emitted photons are again interacted with the meta stable state electrons then again two photons are emitted by each electron. Thus, millions of photons are generated by using only a small number of photons.
- If we use electrical energy as energy source then a single photon or few photons (which are produced spontaneously) will produce large number of photons by stimulated emission process. Thus, light amplification is achieved in laser medium. Laser medium is also known as active medium or gain medium.
- The laser medium will determine the characteristics of the laser light emitted. The laser medium can be solid, liquid, or gaseous.
- Ruby laser is an example for solid-state laser. In this, a ruby crystal is used as an active medium. In this laser, xenon discharge tube which provides a flash light acts as pump source.
- Helium – Neon laser is an example for gaseous laser. In this, neon is used as an active medium. In this laser, radio frequency (RF) generator acts as pump source.

Optical Resonator

- The laser medium is surrounded by two parallel mirrors which provides feedback of the light. One mirror is fully reflective (100 % reflective) whereas another one is partially reflective (<100 % reflective). These two mirrors as a whole is called optical resonator. Optical resonator is also known as optical cavity or resonating cavity.
- These two mirrors are given optical coatings which determine their reflective properties. Optical coating is a thin layer of material deposited on materials such as mirror or lens. Each mirror is coated differently. Therefore, each mirror will reflect the light differently. One mirror will completely reflect the light whereas another one will partially reflect the light.
- The completely reflective mirror is called high reflector whereas the partially reflective mirror is called output coupler. The output coupler will allows some of the light to leave the optical cavity to produce the laser's output beam.
- When energy is supplied to the laser medium, the lower energy state electrons in the laser medium will moves to excited state. After a short period, the electrons in the excited state will fall back to the ground state by releasing energy in the form of photons or light. This process of emission of photons is called spontaneous emission. Thus, light is produced in an active medium by a process called spontaneous emission.

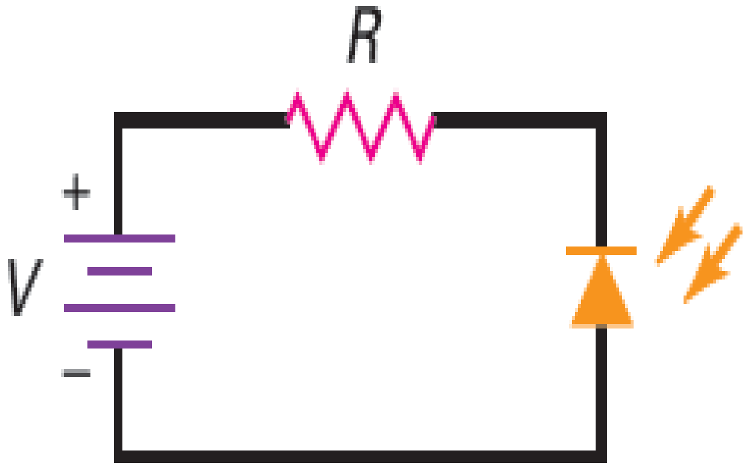
Optical Resonator

- The light generated within the laser medium will bounce back and forth between the two mirrors. This stimulates other electrons to release light while falling to the ground state. Likewise, a large number of electrons are stimulated to emit light. Thus, optical gain is achieved.
- This amplified light escapes through the partially reflecting mirror. The process of stimulating electrons of other atoms to produce light in the laser medium is called stimulated emission.
- The light in the laser medium is reflected many hundreds of times between the mirrors before it escape through the partially reflecting mirror. The light escaped from the partially reflecting mirror is produced by the stimulated emission process. Hence, this light will travel to large distances without spreading in the space.

Photodiode

- one component of reverse current in a diode is the flow of minority carriers.
- These carriers exist because thermal energy keeps dislodging valence electrons from their orbits, producing free electrons and holes in the process.
- The lifetime of the minority carriers is short, but while they exist, they can contribute to the reverse current.

- When light energy bombards a *pn junction, it can dislodge valence* electrons.
- The more light striking the junction, the larger the reverse current in a diode.
- A **photodiode has been optimized for its sensitivity to light.**
- In this diode, a window lets light pass through the package to the junction.
- The incoming light produces free electrons and holes.
- The stronger the light, the greater the number of minority carriers and the larger the reverse current.


R
+
V
−