FULL FORM OF LASER

- L –Light
- A – Amplification by
- S – Stimulated
- E – Emission of
- R - Radiation

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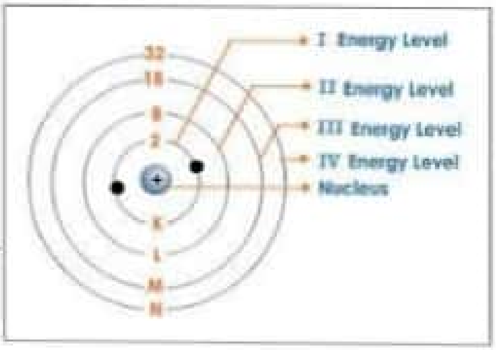
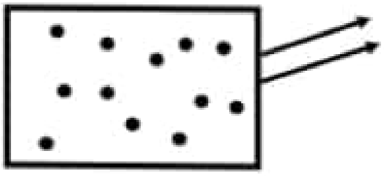
Introduction

Matter & Energy → Solids, Liquids, Gases → Atoms & Molecules $\xrightarrow{\text{Shape}}$ Spherical

E

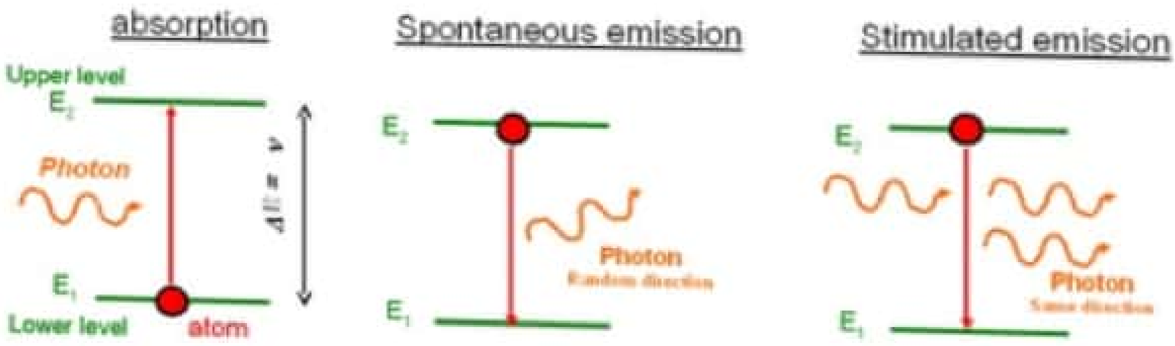


$2n^2$



Energy Radiation

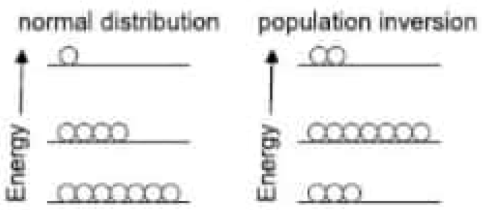
LASER EMISSION



SPECIAL PROPERTIES OF LASER

- Monochromaticity
- Uni -directionality
- High intensity
- Coherency

POPULATION INVERSION

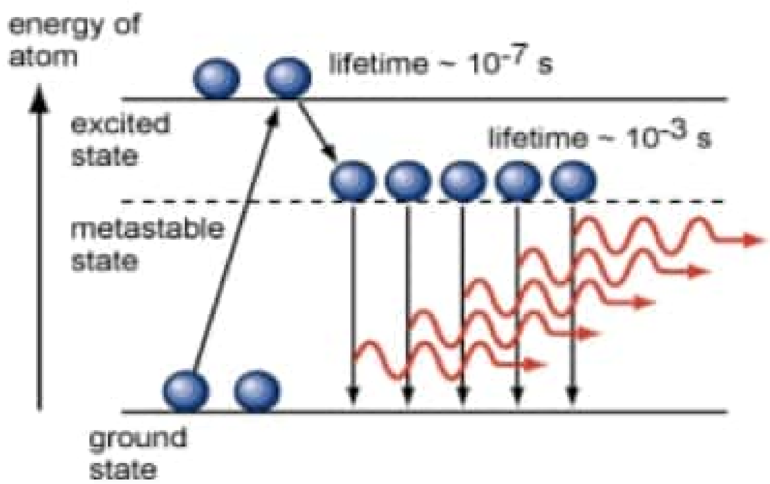


When $N_2 > N_1$

This condition is know as population inversion.

N2 is the number of atoms in in metastable state

N1 is the number of atoms in in ground state



http://www.hk-phy.org/articles/laser/3-states_e.gif

Einstein Coefficient Relation

Einstein showed the interaction of radiation with matter with the help of three processes called stimulated absorption, spontaneous emission and stimulated emission. He showed in 1917 that for proper description of radiation with matter, the process of stimulated emission is essential. Let us first derive the Einstein coefficient relation on the basis of above theory:

Let N_1 be the number of atoms per unit volume in the ground state $E_1$and these atoms exist in the radiation field of photons of energy E_2-E_1=hv such that energy density of the field is E.

Let R_1 be the rate of absorption of light by $E_1 \rightarrow E_2$ transitions by the process called stimulated absorption. This rate of absorption R_1 is proportional to the number of atoms N_1 per unit volume in the ground state and proportional to the energy density E of radiations.

That is $R_1 \propto N_1 E$

Or $R_1 = B_{12} N_1 E$ (1)

Where B_{12} is known as the Einstein's coefficient of stimulated absorption and it represents the probability of absorption of radiation. Energy density e is defined as the incident energy on an atom as per unit volume in a state.

Now atoms in the higher energy level E_2 can fall to the ground state E_1 automatically after 10^{-8} sec by the process called spontaneous emission.

The rate R_2 of spontaneous emission $E_2 \rightarrow E_1$ is independent of energy density E of the radiation field.

R_2 is proportional to number of atoms N_2 in the excited state E_2 thus

$R_2 \propto N_2$

$R_2 = A_{21} N_2$ (2)

Where A_{21} is known as Einstein's coefficient for spontaneous emission and it represents the probability of spontaneous emission.

Atoms can also fall back to the ground state E_1 under the influence of electromagnetic field of incident photon of energy E_2-E_1 =hv by the process called stimulated emission

Rate R_3 for stimulated emission $E_2 \rightarrow E_1$ is proportional to energy density E of the radiation field and proportional to the number of atoms N_2 in the excited state, thus

$R_3 \alpha N_2 E$

Or $R_3 = B_{21} N_2 E$ (3)

Where B_{21} is known as the Einstein coefficient for stimulated emission and it represents the probability of stimulated emission.

In steady state (at thermal equilibrium), the two emission rates (spontaneous and stimulated) must balance the rate of absorption.

Thus $R_1 = R_2 + R_3$

Using equations (1,2, and 3), we get

$N_1 B_{12} E = N_2 A_{21} + N_2 B_{21} E$

Or $N_1 B_{12} E - N_2 B_{21} E = N_2 A_{21}$

Or $(N_1 B_{12} - N_2 B_{21}) E = N_2 A_{21}$

Or $E = N_2 A_{21} / N_1 B_{12} - N_2 B_{21}$

$= N_2 A_{21} / N_2 B_{21} [N_1 B_{12} / N_2 B_{21} - 1]$

[by taking out common N_2B_{21} from the denominator]

Or $$E=A_{21}/B_{21}\ \{1/N_1/N_2(B_{12}/B_{21}-1)\} \quad (4)$$

Einstein proved thermodynamically, that the probability of stimulated absorption is equal to the probability of stimulated emission. Thus

$B_{12}=B_{21}$

Then equation (4) becomes

$$E=A_{21}/B_{21}(1/N_1/N_2-1) \quad (5)$$

From Boltzman's distribution law, the ratio of populations of two levels at temperature T is expressed as

$N_1/N_2=e^{(E_2-E_1)/KT}$

$N_1/N_2=e^{h\nu/KT}$

Where K is the Boltzman's constant and h is the Planck's constant.

Substituting value of N_1/N_2 in equation (5) we get

$$E= A_{21}/B_{21}(1/e^{h\nu/KT}-1) \quad (6)$$

Now according to Planck's radiation law, the energy density of the black body radiation of frequency v at temperature T is given as

$$E = 8\pi h\nu^3/c^3(1/e^{h\nu/KT}) \quad (7)$$

By comparing equations (6 and 7), we get

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

This is the relation between Einstein's coefficients in laser.

Significance of Einstein coefficient relation: This shows that the ratio of Einstein's coefficient of spontaneous emission to the Einstein's coefficient of stimulated absorption is proportional to cube of frequency v. It means that at thermal equilibrium, the probability of spontaneous emission increases rapidly with the energy difference between two states.

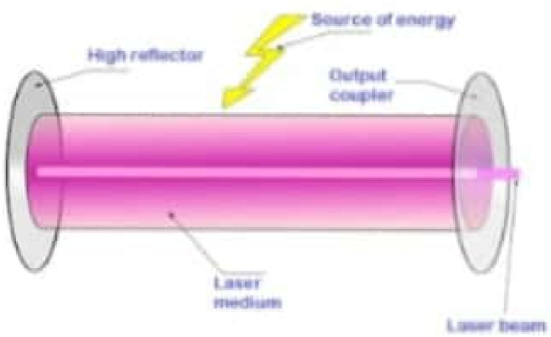
Laser Construction

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.



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 allow 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.

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 escapes 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.

Types of lasers

Lasers are classified into 4 types based on the type of laser medium used:

- Solid-state laser
- Gas laser
- Liquid laser
- Semiconductor laser

Ruby Laser

A ruby laser is a solid-state laser that uses the synthetic ruby crystal as its laser medium. Ruby laser is the first successful laser developed by Maiman in 1960.

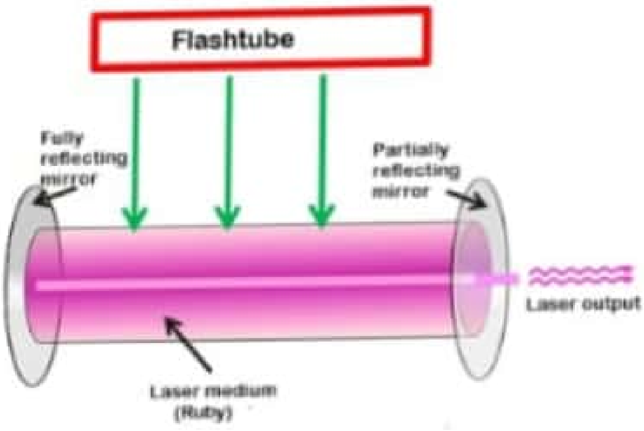
Ruby laser is one of the few solid-state lasers that produce visible light. It emits deep red light of wavelength 694.3 nm.

Construction of ruby laser

A ruby laser consists of three important elements: laser medium, the pump source, and the optical resonator.

Laser medium or gain medium in ruby laser

In a ruby laser, a single crystal of ruby ($Al_2O_3 : Cr^{3+}$) in the form of cylinder acts as a laser medium or active medium. The laser medium (ruby) in the ruby laser is made of the host of sapphire (Al_2O_3) which is doped with small amounts of chromium ions (Cr^{3+}). The ruby has good thermal properties.



Pump source or energy source in ruby laser

The pump source is the element of a ruby laser system that provides energy to the laser medium. In a ruby laser, population inversion is required to achieve laser emission. Population inversion is the process of achieving the greater population of higher energy state than the lower energy state. In order to achieve population inversion, we need to supply energy to the laser medium (ruby).

In a ruby laser, we use flashtube as the energy source or pump source. The flashtube supplies energy to the laser medium (ruby). When lower energy state electrons in the laser medium gain sufficient energy from the flashtube, they jump into the higher energy state or excited state.

Optical resonator

The ends of the cylindrical ruby rod are flat and parallel. The cylindrical ruby rod is placed between two mirrors. The optical coating is applied to both the mirrors. The process of depositing thin layers of metals on glass substrates to make mirror surfaces is called silvering. Each mirror is coated or silvered differently.

At one end of the rod, the mirror is fully silvered whereas, at another end, the mirror is partially silvered. The fully silvered mirror will completely reflect the light whereas the partially silvered mirror will reflect most part of the light but allows a small portion of light through it to produce output laser light.

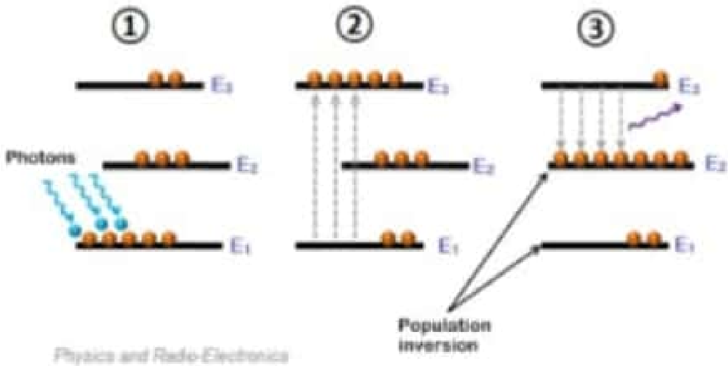
Working of ruby laser

The ruby laser is a three level solid-state laser. In a ruby laser, optical pumping technique is used to supply energy to the laser medium. Optical pumping is a technique in which light is used as energy source to raise electrons from lower energy level to the higher energy level.

Consider a ruby laser medium consisting of three energy levels E_1, E_2, E_3 with N number of electrons.

We assume that the energy levels will be $E_1 < E_2 < E_3$. The energy level E_1 is known as ground state or lower energy state, the energy level E_2 is known as metastable state, and the energy level E_3 is known as pump state.

Let us assume that initially most of the electrons are in the lower energy state (E_1) and only a tiny number of electrons are in the excited states (E_2 and E_3)



When light energy is supplied to the laser medium (ruby), the electrons in the lower energy state or ground state (E_1) gains enough energy and jumps into the pump state (E_3).

The lifetime of pump state E_3 is very small (10^{-8} sec) so the electrons in the pump state do not stay for long period. After a short period, they fall into the metastable state E_2 by releasing radiationless energy. The lifetime of metastable state E_2 is 10^{-3} sec which is much greater than the lifetime of pump state E_3. Therefore, the electrons reach E_2 much faster than they leave E_2. This results in an increase in the number of electrons in the metastable state E_2 and hence population inversion is achieved.

After some period, the electrons in the metastable state E_2 falls into the lower energy state E_1 by releasing energy in the form of photons. This is called spontaneous emission of radiation. When the emitted photon interacts with the electron in the metastable state, it forcefully makes that electron fall into the ground state E_1. As a result, two photons are emitted. This is called stimulated emission of radiation.

When these emitted photons again interacted with the metastable state electrons, then 4 photons are produced. Because of this continuous interaction with the electrons, millions of photons are produced.

In an active medium (ruby), a process called spontaneous emission produces light. The light produced within the laser medium will bounce back and forth between the two mirrors. This stimulates other electrons to fall into the ground state by releasing light energy. This is called stimulated emission. Likewise, millions of electrons are stimulated to emit light. Thus, the light gain is achieved.

The amplified light escapes through the partially reflecting mirror to produce laser light.

Helium-Neon laser

Helium-Neon laser is a type of gas laser in which a mixture of helium and neon gas is used as a gain medium. Helium-Neon laser is also known as He-Ne laser.

What is a gas laser?

A gas laser is a type of laser in which a mixture of gas is used as the active medium or laser medium. Gas lasers are the most widely used lasers.

Gas lasers range from the low power helium-neon lasers to the very high power carbon dioxide lasers. The helium-neon lasers are most commonly used in college laboratories whereas the carbon dioxide lasers are used in industrial applications.

The main advantage of gas lasers (eg: He-Ne lasers) over solid state lasers is that they are less prone to damage by overheating so they can be run continuously.

What is helium-neon laser?

At room temperature, a ruby laser will only emit short bursts of laser light, each laser pulse occurring after a flash of the pumping light. It would be better to have a laser that emits light continuously. Such a laser is called a continuous wave (CW) laser.

The helium-neon laser was the first continuous wave (CW) laser ever constructed. It was built in 1961 by Ali Javan, Bennett, and Herriott at Bell Telephone Laboratories.

Helium-neon lasers are the most widely used gas lasers. These lasers have many industrial and scientific uses and are often used in laboratory demonstrations of optics.

In He-Ne lasers, the optical pumping method is not used instead an electrical pumping method is used. The excitation of electrons in the He-Ne gas active medium is achieved by passing an electric current through the gas.

The helium-neon laser operates at a wavelength of 632.8 nanometers (nm), in the red portion of the visible spectrum.

Helium-neon laser construction

The helium-neon laser consists of three essential components:

- Pump source (high voltage power supply)
- Gain medium (laser glass tube or discharge glass tube)
- Resonating cavity

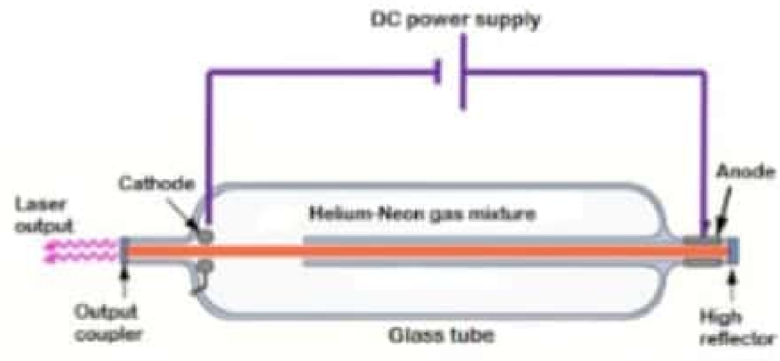
High voltage power supply or pump source

In order to produce the laser beam, it is essential to achieve population inversion. Population inversion is the process of achieving more electrons in the higher energy state as compared to the lower energy state.

In general, the lower energy state has more electrons than the higher energy state. However, after achieving population inversion, more electrons will remain in the higher energy state than the lower energy state.

In order to achieve population inversion, we need to supply energy to the gain medium or active medium. Different types of energy sources are used to supply energy to the gain medium.

In ruby lasers and Nd:YAG lasers, the light energy sources such as flashtubes or laser diodes are used as the pump source. However, in helium-neon lasers, light energy is not used as the pump source. In helium-neon lasers, a high voltage DC power supply is used as the pump source. A high voltage DC supplies electric current through the gas mixture of helium and neon.



Gain medium (discharge glass tube or glass envelope)

The gain medium of a helium-neon laser is made up of the mixture of helium and neon gas contained in a glass tube at low pressure. The partial pressure of helium is 1 mbar whereas that of neon is 0.1 mbar.

The gas mixture is mostly comprised of helium gas. Therefore, in order to achieve population inversion, we need to excite primarily the lower energy state electrons of the helium atoms.

In He-Ne laser, neon atoms are the active centers and have energy levels suitable for laser transitions while helium atoms help in exciting neon atoms.

Electrodes (anode and cathode) are provided in the glass tube to send the electric current through the gas mixture. These electrodes are connected to a DC power supply.

Resonating cavity

The glass tube (containing a mixture of helium and neon gas) is placed between two parallel mirrors. These two mirrors are silvered or optically coated.

Each mirror is silvered differently. The left side mirror is partially silvered and is known as output coupler whereas the right side mirror is fully silvered and is known as the high reflector or fully reflecting mirror.

The fully silvered mirror will completely reflect the light whereas the partially silvered mirror will reflect most part of the light but allows some part of the light to produce the laser beam.

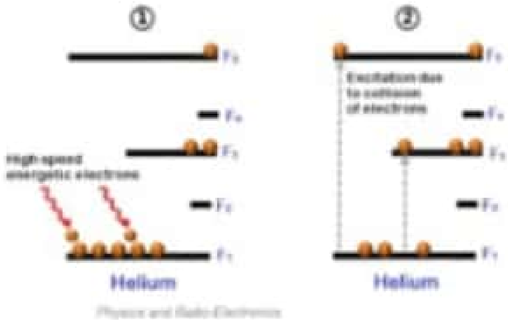
Working of helium-neon laser

In order to achieve population inversion, we need to supply energy to the gain medium. In helium-neon lasers, we use high voltage DC as the pump source. A high voltage DC produces energetic electrons that travel through the gas mixture.

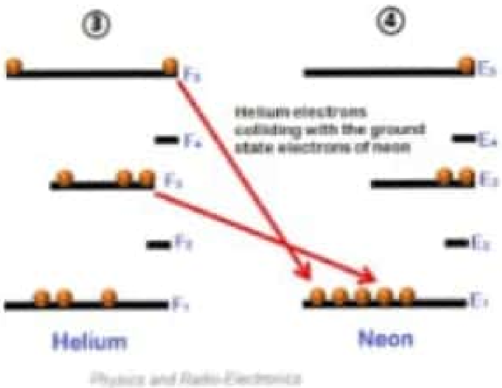
The gas mixture in helium-neon laser is mostly comprised of helium atoms. Therefore, helium atoms observe most of the energy supplied by the high voltage DC.

When the power is switched on, a high voltage of about 10 kV is applied across the gas mixture. This power is enough to excite the electrons in the gas mixture. The electrons produced in the process of discharge are accelerated between the electrodes (cathode and anode) through the gas mixture.

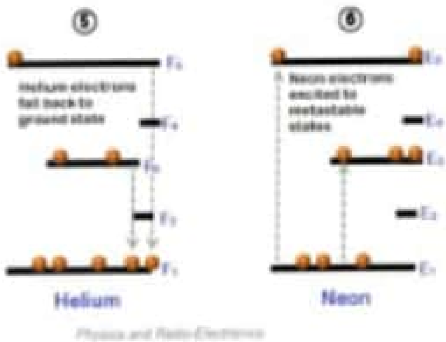
In the process of flowing through the gas, the energetic electrons transfer some of their energy to the helium atoms in the gas. As a result, the lower energy state electrons of the helium atoms gain enough energy and jumps into the excited states or metastable states. Let us assume that these metastable states are $F_3$and F_5.



The metastable state electrons of the helium atoms cannot return to ground state by spontaneous emission. However, they can return to ground state by transferring their energy to the lower energy state electrons of the neon atoms. The energy levels of some of the excited states of the neon atoms are identical to the energy levels of metastable states of the helium atoms. Let us assume that these identical energy states are $F_3 = E_3$ and $F_5 = E_5$. E_3 and E_5 are excited states or metastable states of neon atoms.



Unlike the solid, a gas can move or flow between the electrodes. Hence, when the excited electrons of the helium atoms collide with the lower energy state electrons of the neon atoms, they transfer their energy to the neon atoms. As a result, the lower energy state electrons of the neon atoms gain enough energy from the helium atoms and jumps into the higher energy states or metastable states ($E_3$and E_5) whereas the excited electrons of the helium atoms will fall into the ground state. Thus, helium atoms help neon atoms in achieving population inversion.

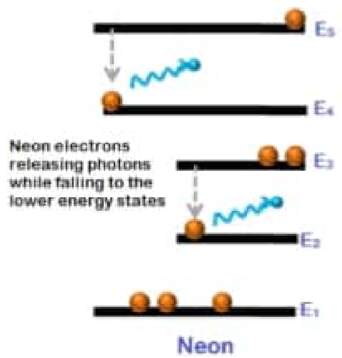


Likewise, millions of ground state electrons of neon atoms are excited to the metastable states. The metastable states have the longer lifetime. Therefore, a large number of electrons will remain in the metastable states and hence population inversion is achieved.

After some period, the metastable states electrons (E_3 and E_5) of the neon atoms will spontaneously fall into the next lower energy states (E_2 and E_4) by releasing photons or red light. This is called spontaneous emission.

The neon excited electrons continue on to the ground state through radiative and nonradiative transitions. It is important for the continuous wave (CW) operation.

⑦



The light or photons emitted from the neon atoms will moves back and forth between two mirrors until it stimulates other excited electrons of the neon atoms and causes them to emit light. Thus, optical gain is achieved. This process of photon emission is called stimulated emission of radiation.

The light or photons emitted due to stimulated emission will escape through the partially reflecting mirror or output coupler to produce laser light.

Advantages of helium-neon laser

- Helium-neon laser emits laser light in the visible portion of the spectrum.
- High stability
- Low cost
- Operates without damage at higher temperatures

Disadvantages of helium-neon laser

- Low efficiency
- Low gain
- Helium-neon lasers are limited to low power tasks

Applications of helium-neon lasers

- Helium-neon lasers are used in industries.
- Helium-neon lasers are used in scientific instruments.
- Helium-neon lasers are used in the college laboratories.

Define efficiency of two level, three level and four level laser.

Efficiency of Laser is defined as the ratio of out energy and input energy. It is denoted by η.

In two level laser efficiency = $\eta = \dfrac{E_2 - E_1}{E_2 - E_1} = 100\%$

In three level laser efficiency = $\eta = \dfrac{E_2 - E_1}{E_3 - E_1} < 100\%$

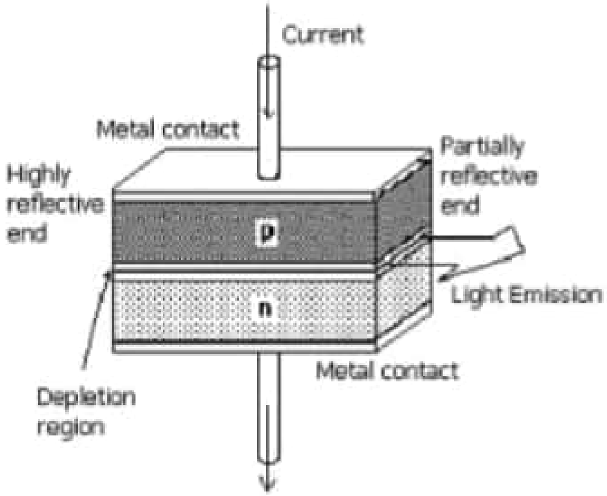
In four level laser efficiency = $\eta = \dfrac{E_3 - E_2}{E_4 - E_1}$

SEMICONDUCTOR LASER

A semiconductor laser is a specially fabricated pn junction device (both the p and n regions are highly doped) which emits coherent light when it is forward biased. It is made from Gallium Arsenide (GaAs) which operated at low temperature and emits light in near IR region. Now the semiconductor lasers are also made to emit light almost in the spectrum from UV to IR using different semiconductor materials. They are of very small size (0.1 mm long), efficient, portable and operate at low power. These are widely used in Optical fibre communications, in CD players, CD-ROM Drives, optical reading, laser printing etc.

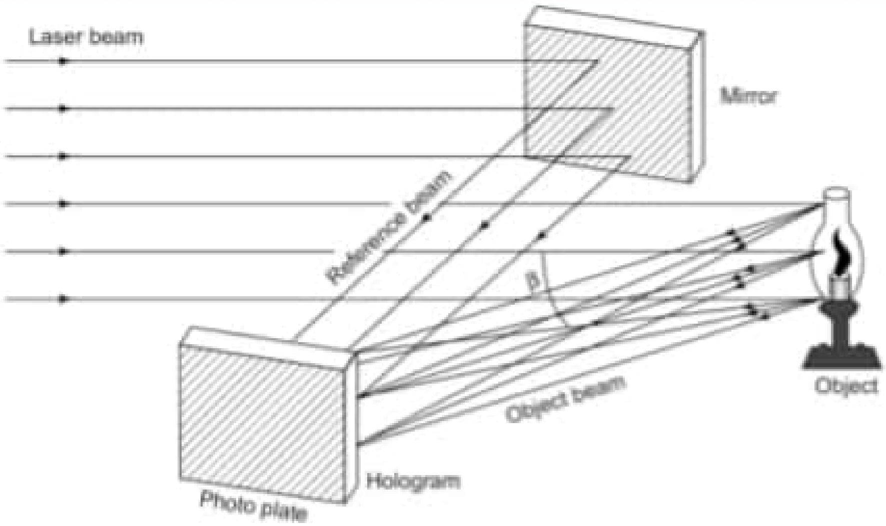
p and n regions are made from same semiconductor material (GaAs). A p type region is formed on the n type by doping zinc atoms. The diode chip is about 500 micrometer long and 100 micrometer wide and thick. the top and bottom faces has metal contacts to pass the current. the front and rare faces are polished to constitute the resonator.

SEMICONDUCTOR LASER



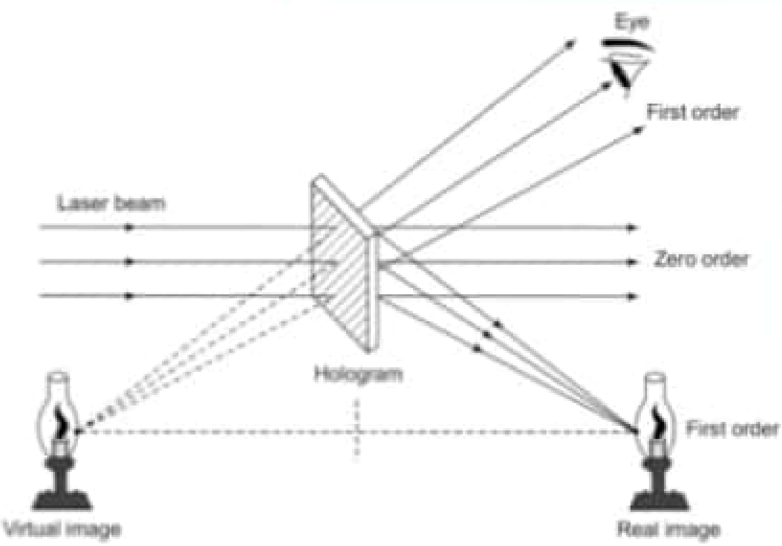
HOLOGRAPHY

Producing 3D image of an object is known as holography



The photographic plate carrying the interference pattern is called a hologram. Holos means "complete" in Greek and gramma means "writing". Thus, a hologram means "complete recording".

HOLOGRAPHY-RECONSTRUCTION OF IMAGE



The hologram acts as a diffraction grating and secondary waves from the hologram interfere constructively in certain directions and interfere destructively in other directions. They form a real image in front of the hologram and a virtual image behind the hologram at the original site of the object.

APPLICATIONS OF LASERS
(In Industry)

Lasers for Industry		
Media	**Laser Wavelength (Nanometers)**	**Major Laser Applications**
Nd:YAG	1,064	Various Laser Metal Processing Welding Medical (Surgery, Eye) Military (Ranging)
Carbon Dioxide	10,600	Materials Processing Surgery
Argon	488 - 514	Parts Inspection Laser Entertainment Laser Eye Treatments
Excimer Gas	193,248	Photoetching Photolithography
GaAs Diode	670,840	Parts Inspection/Vision Systems Bar Code Readers Laser Pointers CD Disk Players
Dye Lasers (Such as Rhodamine 6-G)	400 - 600	Spectroscopy IC Circuit Etching
Ruby Laser	6,943	Metal Hole Drilling

http://www.thefabricator.com/article/safety/safety-fundementals-for-todays-industrial-lasers

APPLICATIONS OF LASERS (In Medical Science)

Carbon dioxide (gas laser)	Infrared/ 10,600	Surgery: Incision and excision by vaporization
Argon (gas laser)	Visible, blue/ 488	Sealing blood vessels in retina, plastic surgery
Argon (gas laser)	Visible, green/ 514	Sealing blood vessels in retina, plastic surgery
Krypton KPT 532 (gas laser)	Visible, green/ 532	Surgery: Cutting, coagulation, and vaporization of tissues
Nd:YAG* (continuous wave - solid state laser)	Infrared/ 1,064	General surgery
Nd:YAG* (Q-switched - solid state laser)	Visible, red/ 632	Ophthalmology: cutting tissues
Helium-Neon (gas laser)	Visible, red/ 632	Alignment: for aiming invisible beams
Ruby (solid state laser)	Visible, red/ 694	Plastic surgery, Dermatology: Destroying tissues
Rhodamine 6G Dye (Tunable - dye laser)	Visible/ 570-650	Treatment of malignant tissues; red (630 nm) commonly used

http://www.chemtec.com/lasers-science-medical-industrial-applications/