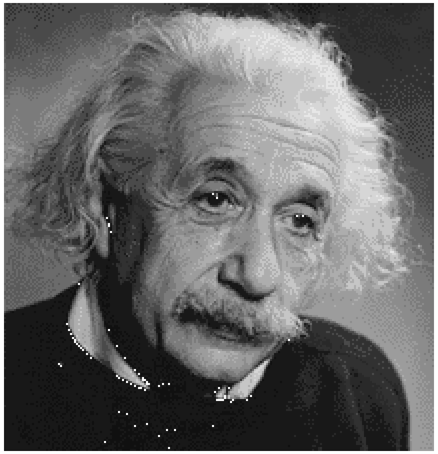
LASER

Light Amplification by Stimulated Emission of Radiation

Principle and applications



The process which makes lasers possible, Stimulated Emission, was proposed in 1917 by Albert Einstein. No one realized the incredible potential of this concept until the 1950's, when practical research was first performed on applying the theory of stimulated emission to making lasers. It wasn't until 1960 that the first true laser was made by Theodore Maimam, out of synthetic ruby. Many ideas for laser applications quickly followed, including some that never worked, like the laser eraser. Still, the early pioneers of laser technology would be shocked and amazed to see the multitude of ways that lasers are used by everyone, everyday, in today's worlds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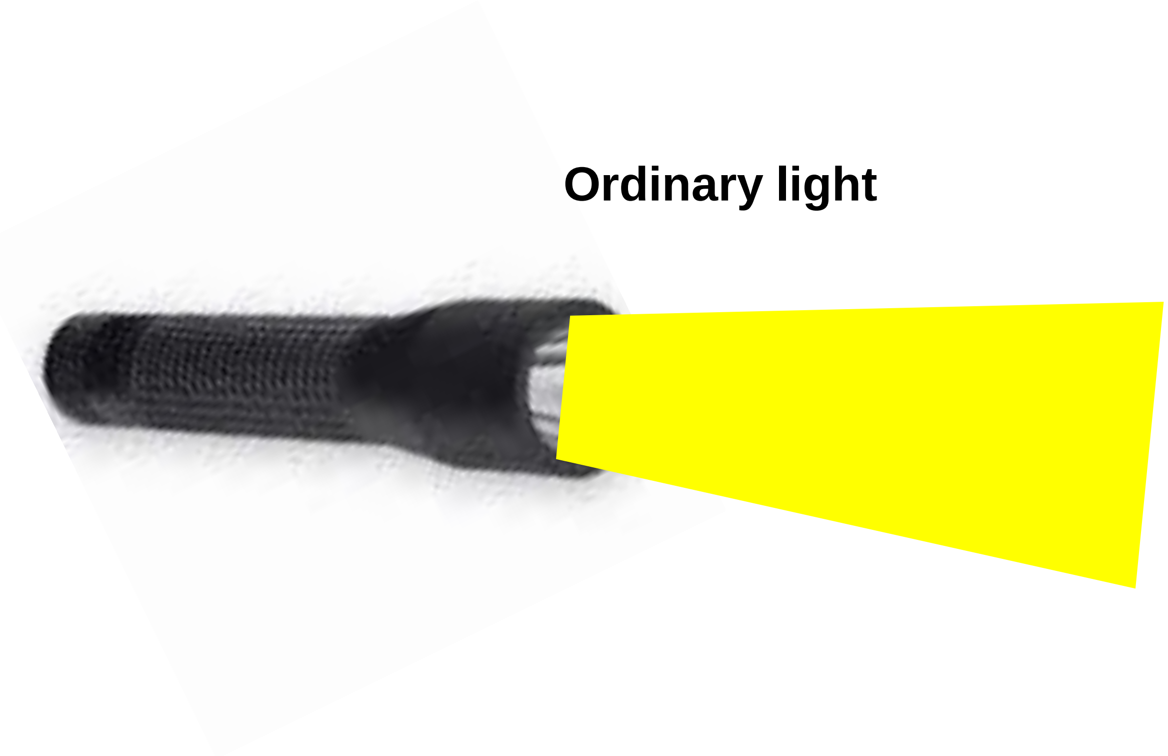
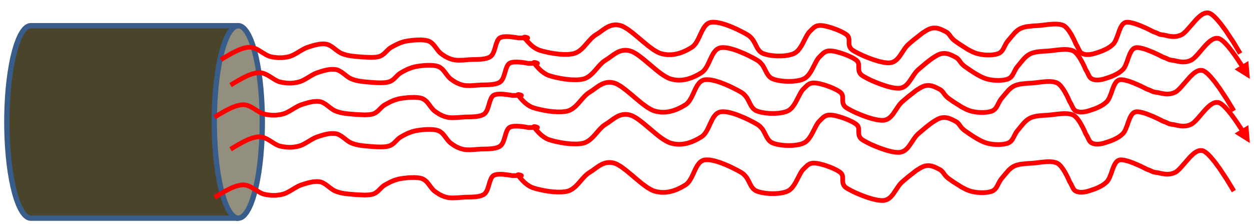
Ordinary light

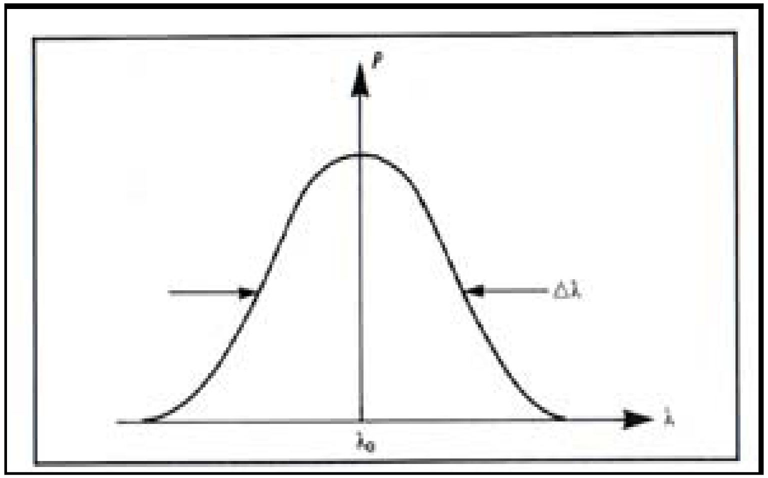


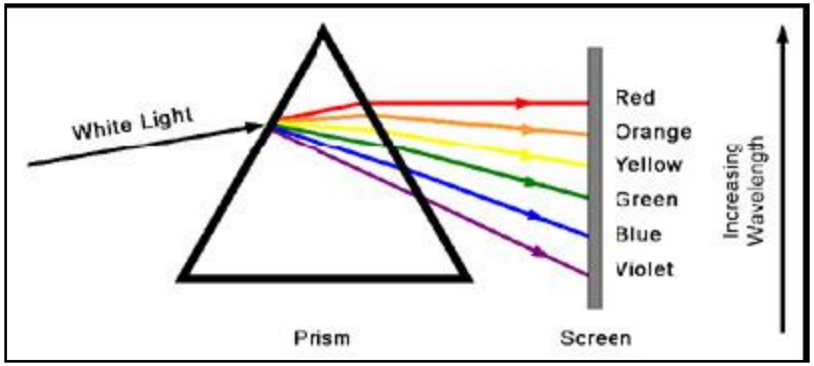
laser light :- 1. directional 2. coherent 3. high intensity 4. Monochromatic

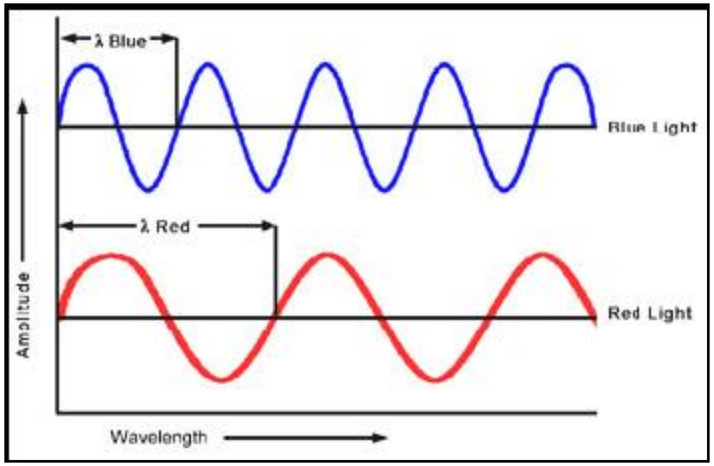


Properties of LASER light

- **Monochromaticity:**

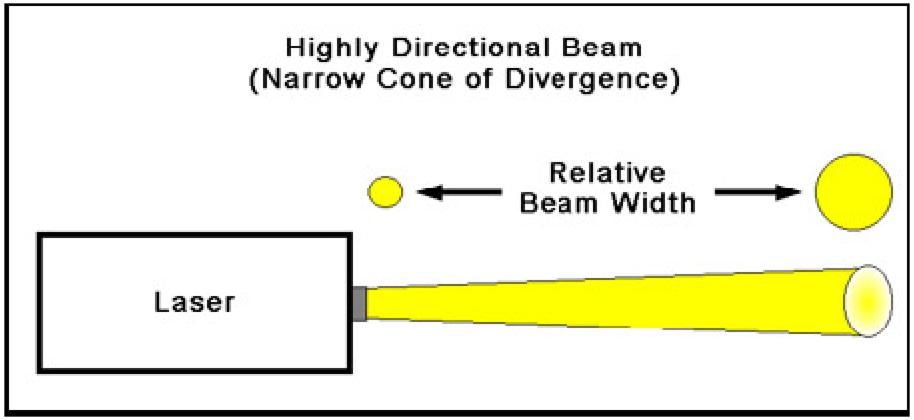






Properties of LASER light

- **Directionality:**



Conventional light source

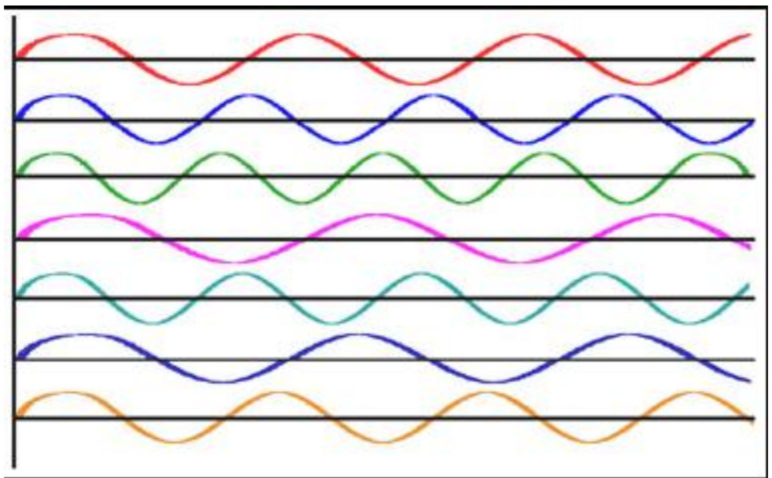
Beam Divergence angle (θd)

- **Highly Intense:** since highly directional, coherent entire output is concentrated in a small region and intensity becomes very high

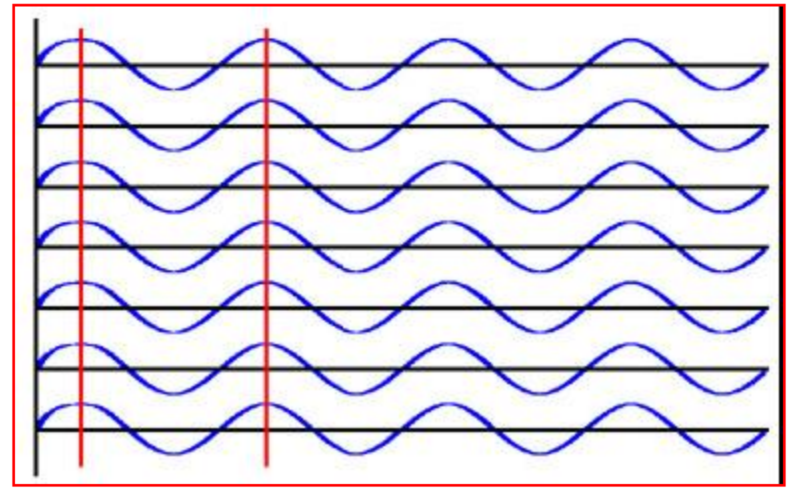
$$\mathbf{I = (10/\lambda)^2 P}$$

P= power radiated by laser

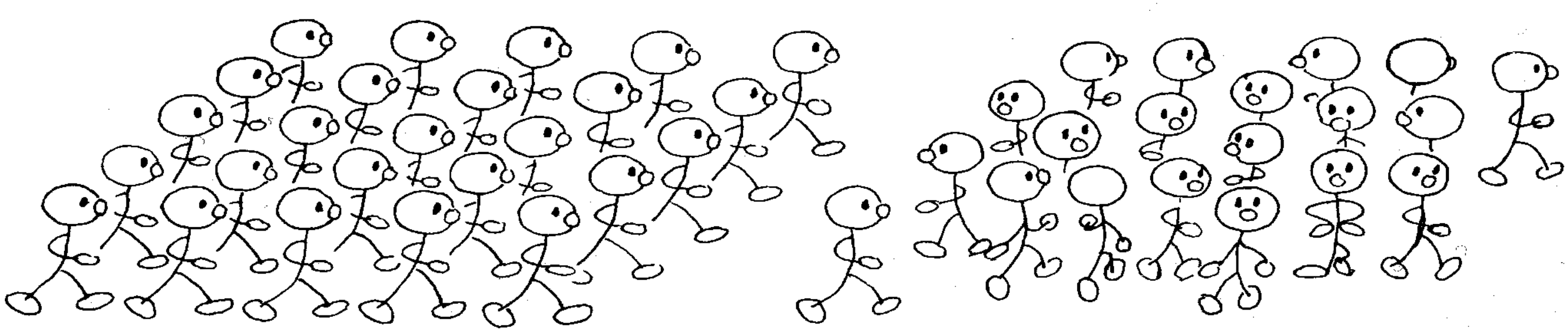
Properties of LASER light



Incoherent light waves



coherent light waves



Coherent

Incoherent

Laser History

- Was based on Einstein’s idea of the “particlewave duality” of light, more than 30 years earlier
- Invented in 1958 by Charles Townes (Nobel prize in Physics 1964) and Arthur Schawlow of Bell Laboratories
- The first patent (1958) MASER =

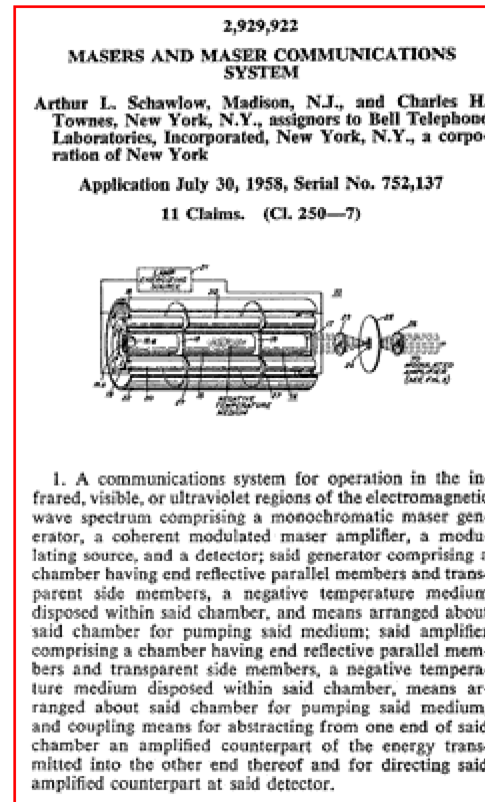
  Microwave Amplification

  by Stimulated Emission of Radiation
- **1958: Schawlow, A.L. and Townes, C.H**. –

  Proposed the realization of masers for

  light and infrared

got **Nobel prize**



2,929,922

MASERS AND MASER COMMUNICATIONS SYSTEM

Arthur L. Schawlow, Madison, N.J., and Charles H. Townes, New York, N.Y., assignors to Bell Telephone Laboratories, Incorporated, New York, N.Y., a corporation of New York

Application July 30, 1958, Serial No. 752,137

11 Claims. (Cl. 250—7)

1. A communications system for operation in the infrared, visible, or ultraviolet regions of the electromagnetic wave spectrum comprising a monochromatic maser generator, a coherent modulated maser amplifier, a modulating source, and a detector; said generator comprising a chamber having end reflective parallel members and transparent side members, a negative temperature medium disposed within said chamber, and means arranged about said chamber for pumping said medium; said amplifier comprising a chamber having end reflective parallel members and transparent side members, a negative temperature medium disposed within said chamber, means arranged about said chamber for pumping said medium, and coupling means for abstracting from one end of said chamber an amplified counterpart of the energy transmitted into the other end thereof and for directing said amplified counterpart at said detector.

1917: Einstein, A. - Concept and theory of stimulated light emission
1948: Gabor, D. - Invention of holography
1951: Charles H Townes, Alexander Prokhorov, Nikolai G Basov, Joseph Weber – The invention of the MASER (Microwave Amplification of Stimulated Emission of Radiation) at Columbia University, Lebedev Laboratories, Moscow and University of Maryland.
1956: Bloembergen, N. - Solid-state maser- [Proposal for a new type of solid state maser] at Harvard University.
1958: Schawlow, A.L. and Townes, C.H. - Proposed the realization of masers for light and infrared at Columbia University .
1960: Maiman, T.H. - Realization of first working LASER based on Ruby at Hughes Research Laboratories.
1961: Javan, A., Bennet, W.R. and Herriot, D.R. - First gas laser : Helium- Neon (He-Ne laser) at Bell Laboratories.
1961: Fox, A.G., Li, T. - Theory of optical resonators at Bell Laboratories.
1962: Hall,R. - First Semiconductor laser (Gallium-Arsenide laser) at General Electric Lab
1962: McClung,F.J and Hellwarth, R.W. - Giant pulse generation / Q-Switching.
1962: Johnson, L.F., Boyd, G.D., Nassau, K and Sodden, R.R. - Continuous wave solid-state laser.
1964: Geusic, J.E., Markos, H.M., Van Uiteit, L.G. - Development of first working Nd:YAG LASER at Bell Labs.
1964: Patel, C.K.N. - Development of CO2 LASER at Bell Labs.
1964: Bridges, W. - Development of Argon Ion LASER a Hughes Labs.

1965: Pimentel, G. and Kasper, J. V. V. - First chemical LASER at University of California, Berkley.

1965: Bloembergen, N. - Wave propagation in nonlinear media.

1966: Silfvast, W., Fowles, G. and Hopkins - First metal vapor LASER - Zn/Cd – at University of Utah.

1966: Walter, W.T., Solomon, N., Piltch, M and Gould, G. - Metal vapor laser.

1966: Sorokin, P. and Lankard, J. - Demonstration of first Dye Laser action at IBM Labs.

1966: AVCO Research Laboratory, USA. - First Gas Dynamic Laser based on CO_2

1970: Nikolai Basov's Group - First Excimer LASER at Lebedev Labs, Moscow based on Xenon (Xe) only.

1974: Ewing, J.J. and Brau, C. - First rare gas halide excimer at Avco Everet Labs.

1977: John M J Madey's Group - First free electron laser at Stanford University.

1977: McDermott, W.E., Pehelkin, N.R,. Benard, D.J and Bousek, R.R. – Chemical Oxygen Iodine Laser (COIL).

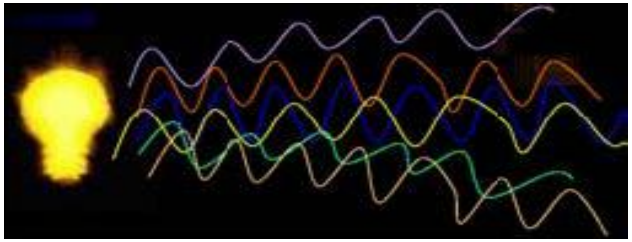
1980: Geoffrey Pert's Group - First report of X-ray lasing action, Hull University, UK

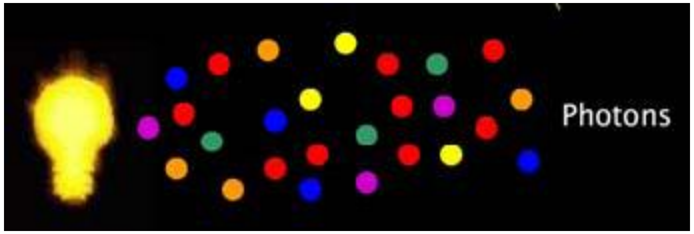
1984: Dennis Matthew's Group - First reported demonstration of a "laboratory" X-ray laser from Lawrence Livermore Labs.

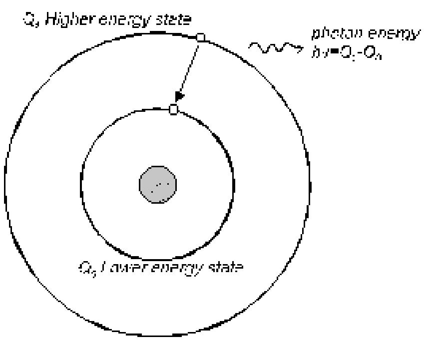
1999: Herbelin,J.M., Henshaw, T.L., Rafferty, B.D., Anderson, B.T., Tate, R.F., Madden, T.J., Mankey II, G.C and Hager, G.D. - All Gas-Phase Chemical Iodine Laser (AGIL).

The wave-particle-duality

- Louis de Broglie(1923) : **λ = h/ m·v = h/p**





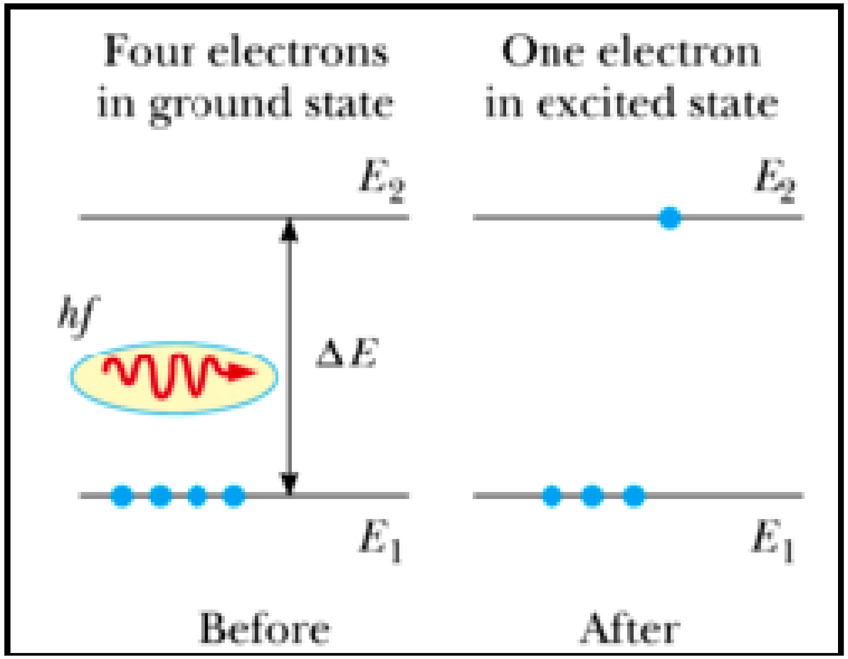


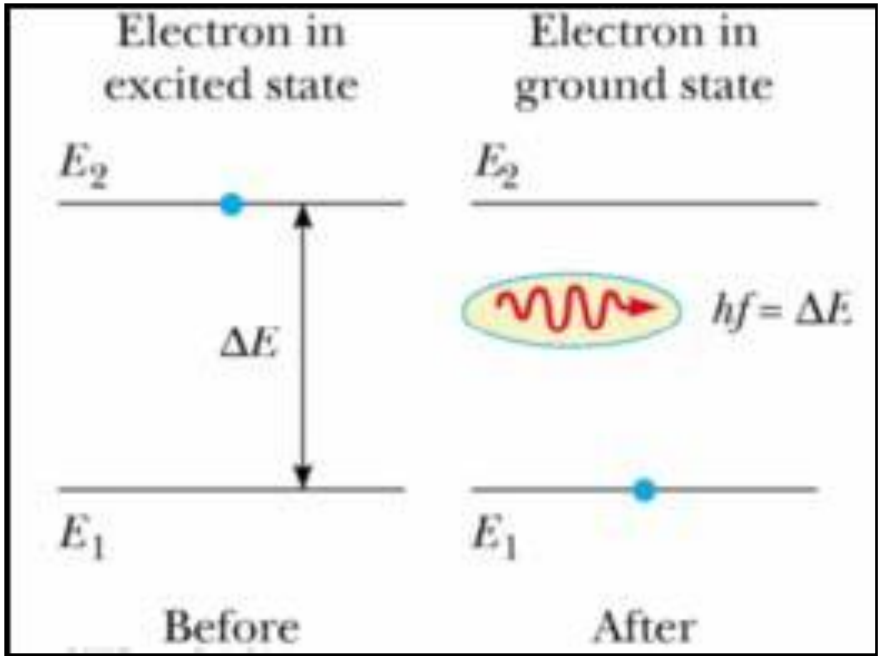
•To raise an electron from one energy level to another, “input“ energy is required
•When falling from one energy level to another, there will be an energy Output

By Plank’s law E = hν

Atomic transitions

- *Stimulated absorption* *Spontaneous emission as lifetime of excited atoms is short (10^{-9}s)*





Energy of the photon emitted= hv = ΔE
emitted freq. v = (E2-E1) / h

Population of atoms & normal distribution

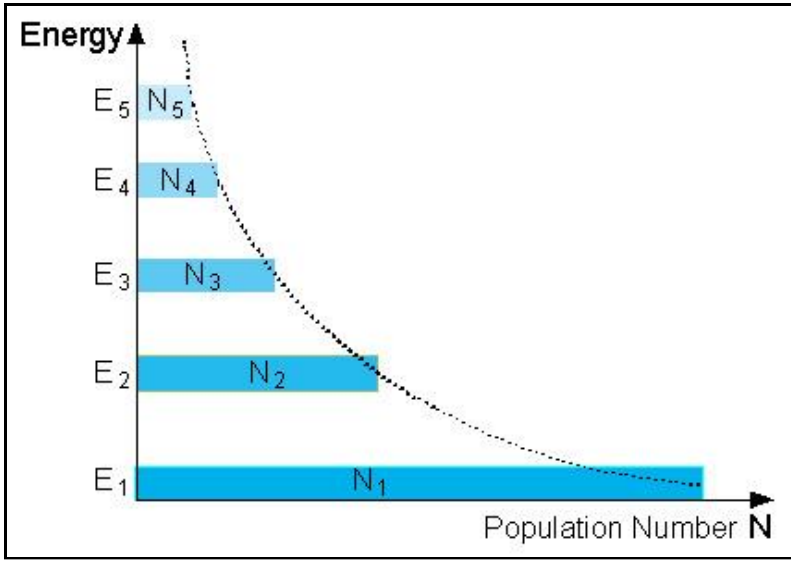
- Distribution of atoms in the energy levels at any temp. 'T' is given by the Boltzmann's distribution formula

$N \approx \exp(-E / k_\beta T)$

For two energy levels E1 and E2 such

that E2>E1

Relative population



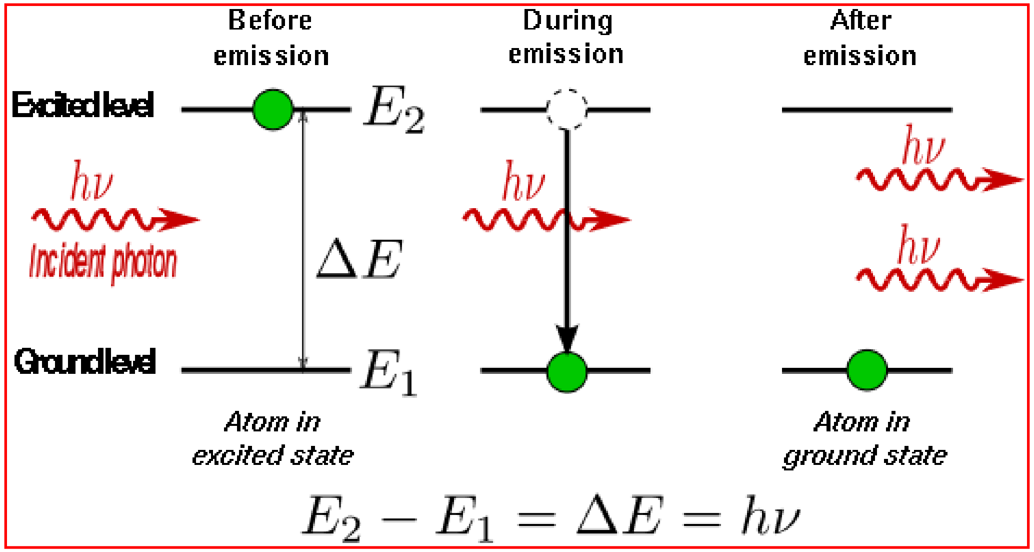
$$\mathbf{N2 / N1 = \exp[-(E2 - E1)/ k_\beta T]}$$

With **ΔE = E2- E1**

N1 > N2
Or, N1> N2> N3> N4> N5

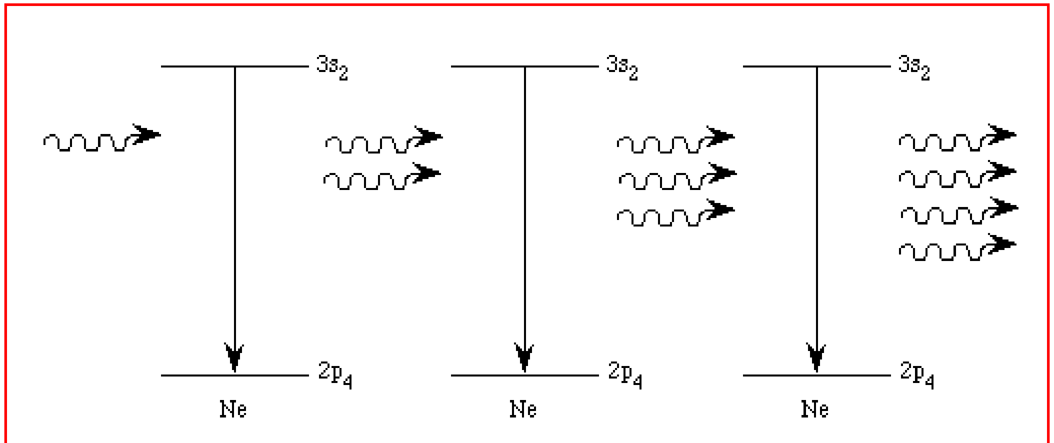
which is called "normal distribution" or "thermal equilibrium condition"

- If spontaneous emission is the only emission process, Then thermal equilibrium will be destroyed,
- since N1 > N2 probability of induced absorption is more, giving rise to N2> N1
- According to Einstein another emission process is possible which is induced by the incident light called **stimulated emission**



Stimulated Emission

In case of stimulated emission, atoms in an upper energy level can be triggered or stimulated in phase by an incoming photon of a specific energy. The incident photon must have an energy corresponding to the energy difference between the upper and lower states. **One Photon with E= hv produces two photons with the same energy .**The emitted photons have the same energy as Incident photon. These photons are in phase with the triggering photon and also travel in its direction. Hence photons can be multiplied in number and light can be amplified by stimulated emission process



(a)

Spontaneous emission	Stimulated emission
1.Can not be controlled from outside 2. Probabilistic or random process 3. Emitted photons are random in direction. Phase and state of polarisation 4. Not monochromatic 5. Not coherent 6. Output is broad and less intense 7. In the output photons are not multiplied.	1. Is controlled from outside 2. Energy transition takes place between Definite selected energy levels 3. Emitted photons are same in direction. Phase and state of polarisation 4. Are monochromatic 5. Are all coherent 6. Output narrow and highly intense. 7. In the output photons are not multiplied.

Einstein's relation

- If ρ (ν) is the incident photon density
- Rate of absorption $R_{abs.} = A_{12} N_1 \rho(\nu)$
- Rate of spontaneous emission $R_{sp.} = E_{21} N_2$
- Rate of stimulated emission $R_{st.} = E'_{21} N_2 \rho(\nu)$
- At equilibrium net upward transition = net downward transition
- Or, $\mathbf{E_{12} N_1 \rho(\nu) = E_{21} N_2 + E'_{21} N_2 \rho(\nu)}$

Where A_{12}, $\mathbf{E_{21}}$, $\mathbf{E'_{21}}$ are Einstein's co- efficients

- Solving the equation and putting the value of ρ (ν) from Plank's formula for radiation density we get

$$\frac{R_{sp.}}{R_{st.}} = \frac{8\pi h\nu^3}{c^3}$$

- This is called **Einstein's relation,** which shows **that stimulated emission is inversely proportional to third power of the frequency of incident radiation, hence laser action is difficult for high freq. radiation**

Population inversion: necessary condition for stimulated emission

- For more stimulated emission (lasing action) necessary conditions are
- 1. radiation density in the medium is high
- 2. population at the excited level is high ---N2 > N1, which is called population inversion

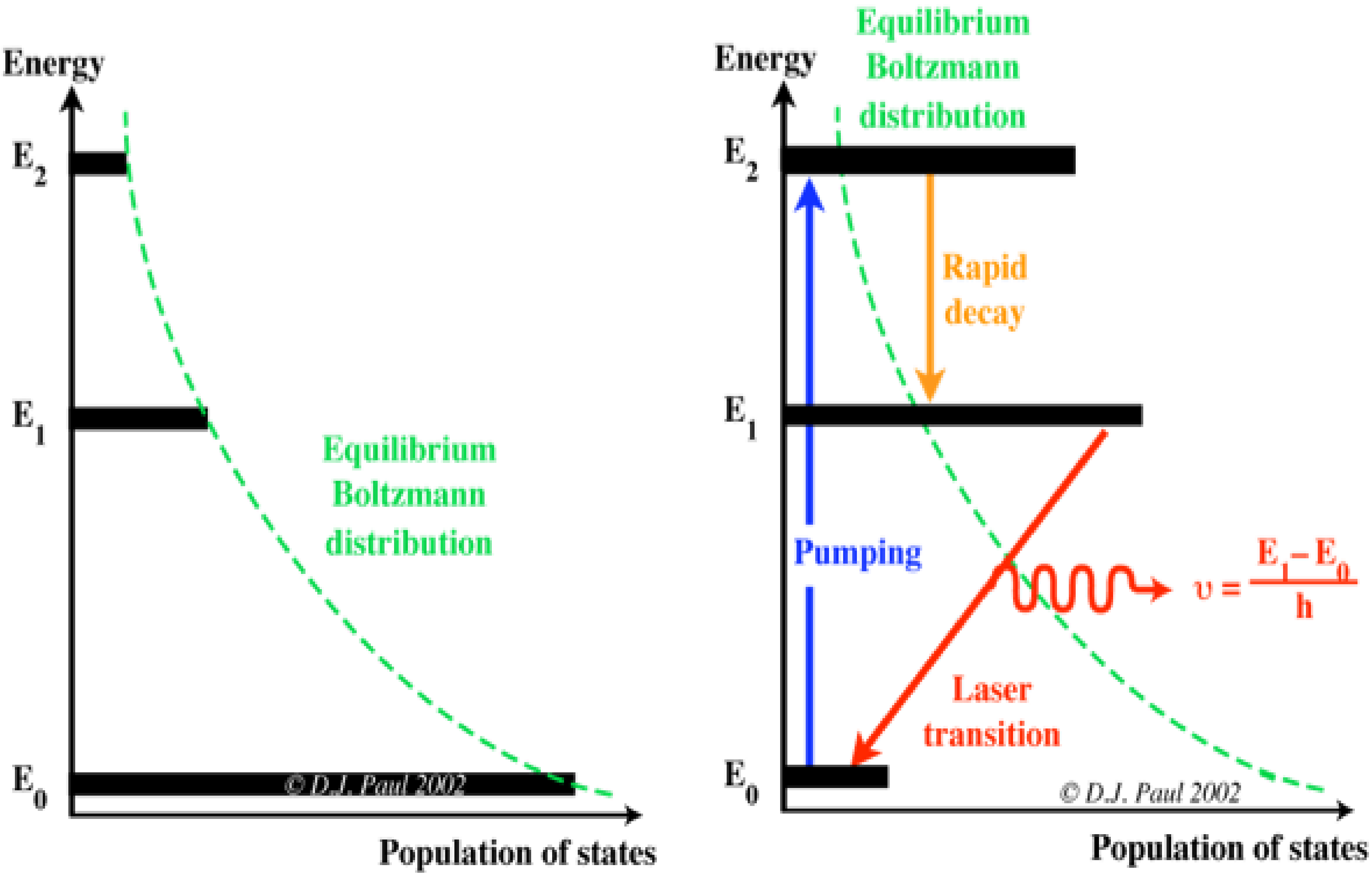
This condition cannot be achieved under thermal equilibrium conditions. This implies that in order to create population inversion, one must look for **non-thermal equilibrium** system and thus the need for special laser materials.

To achieve population inversion, i.e., N2 > N1,

'T ' must be negative in the expression:

$$\mathbf{N2 / N1 = exp [- (E2- E1)/ k_{\beta}T]}$$

For which population inversion is also known as a **" negative temperature state "** means a **non-thermal equilibrium state**


Energy
E_2
E_1
E_0
Equilibrium Boltzmann distribution
© D.J. Paul 2002
Population of states
Energy
Equilibrium Boltzmann distribution
E_2
Rapid decay
E_1
Pumping
$\upsilon = \frac{E_1 - E_0}{h}$
Laser transition
E_0
© D.J. Paul 2002
Population of states

PUMPING

Absorption of the energy by the atoms, electrons, ions or molecules as the case may be, of the medium is a primary requisite in the generation of laser. In order to excite these elements to higher energy levels, an **excitation or pumping mechanism** is necessary. Under the equilibrium state, as per Boltzman's conditions, higher energy levels are much less populated than the lower energy levels. One of the requirements of laser action is population inversion in the levels concerned. i.e. to have larger population in the upper levels than in the lower ones. Otherwise absorption will dominate at the cost of stimulated emission. There are various types of excitation or pumping mechanisms available, the most commonly used ones are **optical, electrical, thermal , direct introduction or chemical techniques**, which depends on the type of the medium employed

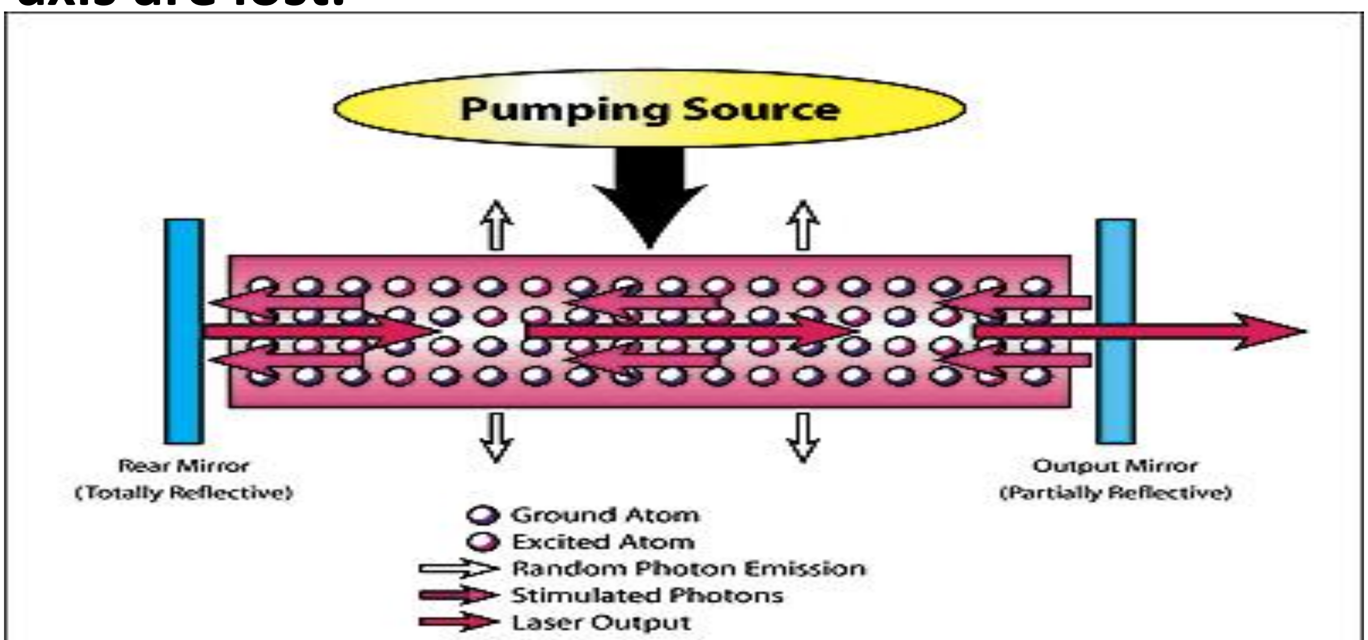
Metastable states and active medium

- In case of spontaneous emission of a photon, the probability of its emission is inversely related to the average length of time that an atom can reside in the upper level of the transition before it relaxes. This time is known as the SPONTANEOUS LIFETIME. Typically, the spontaneous lifetime is of the order of 10^{-8} - 10^{-9} sec. The shorter the spontaneous lifetime, the greater is the probability that spontaneous emission will occur
- In certain materials, there are energy levels, which has the spontaneous lifetime of the order of microseconds to a few milliseconds. These levels are known as **METASTABLE** levels. The probability of transitions involving metastable levels is relatively low.
- A medium with a suitable set of energy levels (**metastable state**), in which pumping is possible to activate or support laser action is called an **active medium.** It can be a crystal, solid, liquid, semiconductor or gas medium

Optical resonator

- Suppose we can produce a large number of atoms all in excited states. If one of the atoms emitted spontaneously, then the emitted photon would stimulate other atoms to emit. These emitted photons would, in turn, stimulate further emission. The result would be an intense burst of coherent radiation
- **Optical resonator:** Optical resonator plays a very important role in the generation of the laser output, in providing high directionality to the laser beam as well as producing gain in the active medium by overcoming various losses. **In order to sustain laser action, one has to confine the laser medium and the pumping mechanism in a special way that should promote stimulated emission rather than spontaneous emission. In practice, photons need to be confined in the system to allow the number of photons created by stimulated emission to exceed all other**

mechanisms. **This is achieved by bounding the laser medium between two mirrors** . On one end of the active medium is the high reflectance mirror (100% reflecting) or the rear mirror and on the other end is the partially reflecting or transmissive mirror or the output coupler. The laser emanates from the output coupler, as it is partially transmissive. Stimulated photons can bounce back and forward along the cavity, creating more stimulated emission as they go. This is called **optical feedback**. In the process**, any photons which are either not of the correct frequency or do not travel along the optical axis are lost.**



Components of laser system:

1. **Active medium**
2. **Pumping device**
3. **Stimulating agent**
4. **Optical resonator**

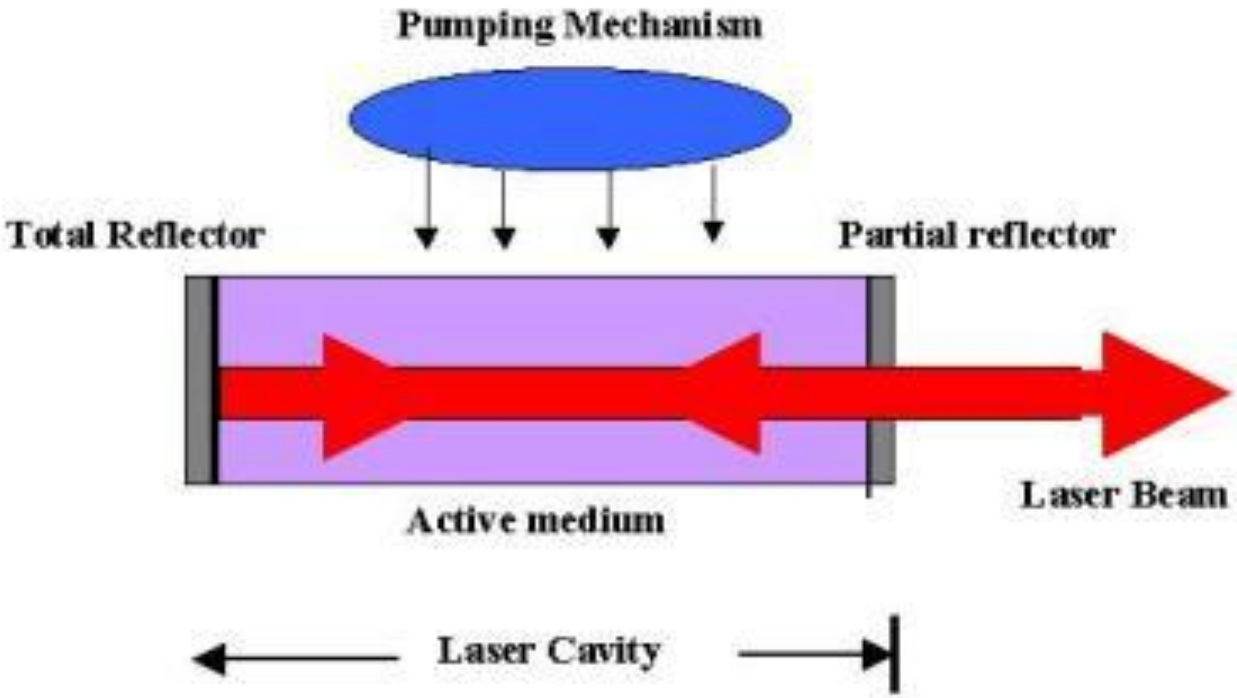


Fig. 2: *Basic Laser System*

Pumping schemes

Two level pumping Scheme

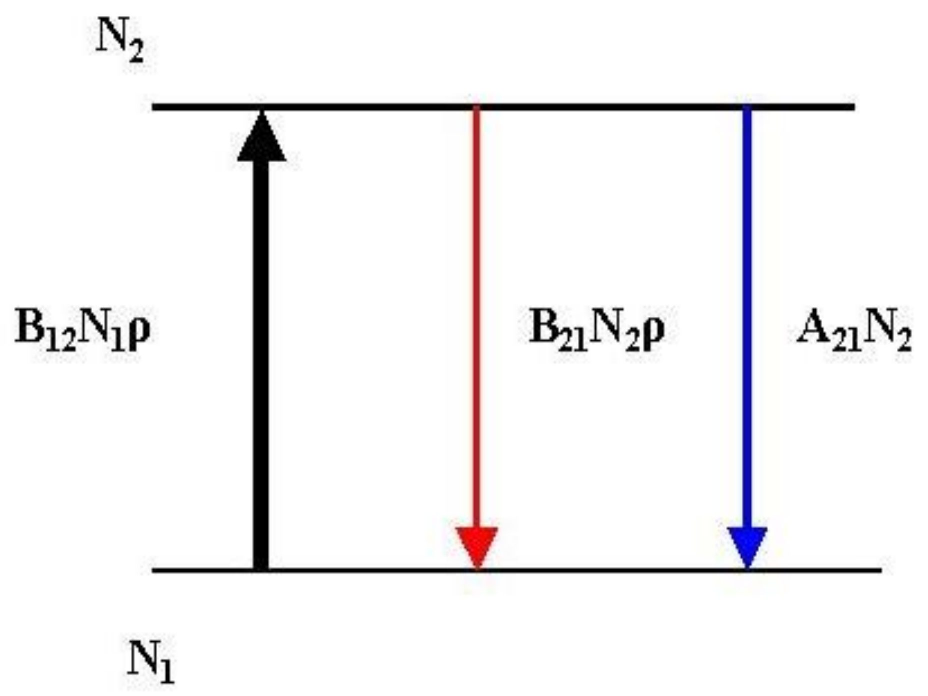


Fig 1: *Spontaneous and stimulated processes in a two-level system*

A two level laser is not possible

Three level pumping Scheme

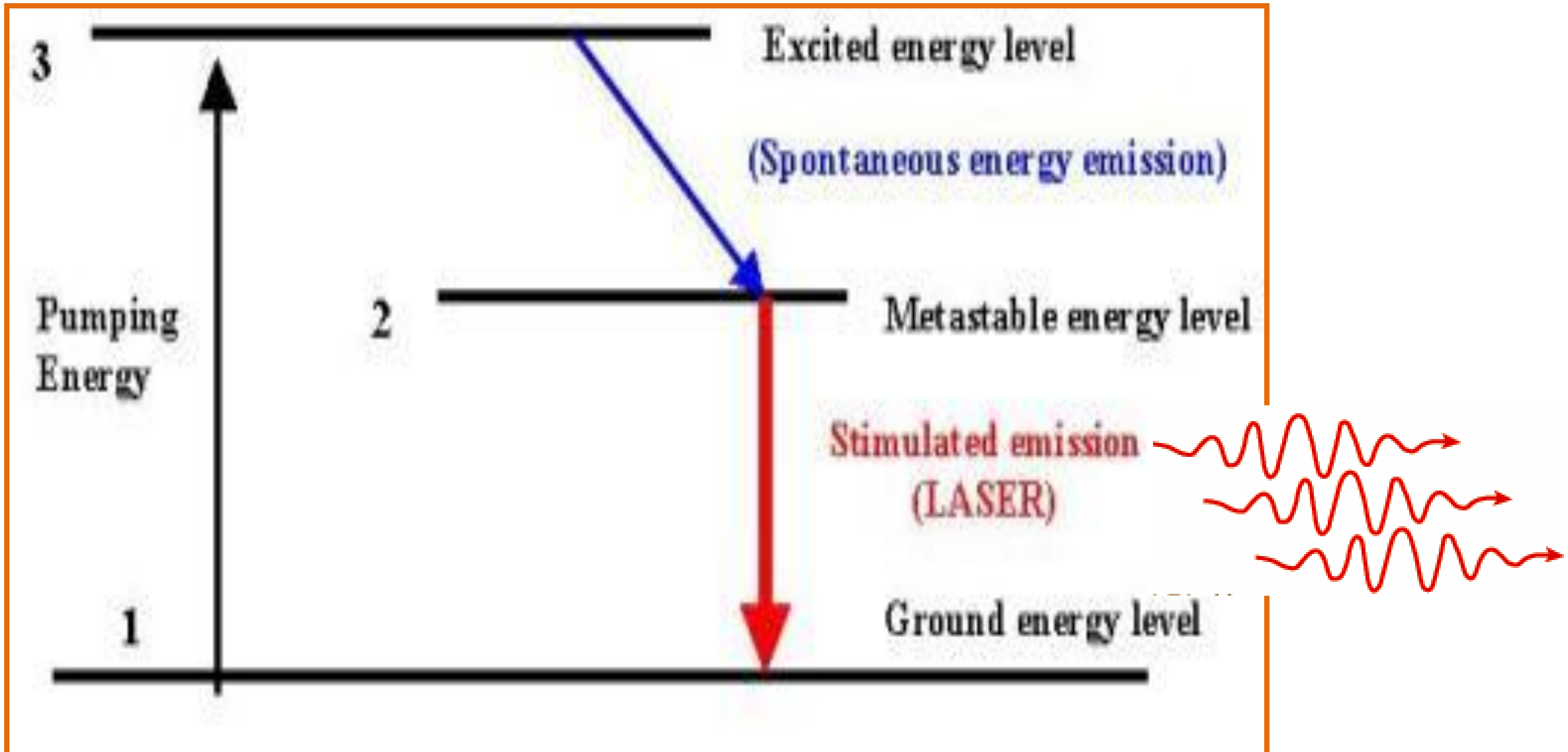


Fig. 3a: *Energy States of Three – level Active Medium*

$E2-E1 \approx k_\beta T$

1- Ground state and lower laser level

3- Pump level

2- Upper laser level and metastable state

In three level laser, pumping energy required is high & output is in pulsed mode (PW)

Four level pumping Scheme

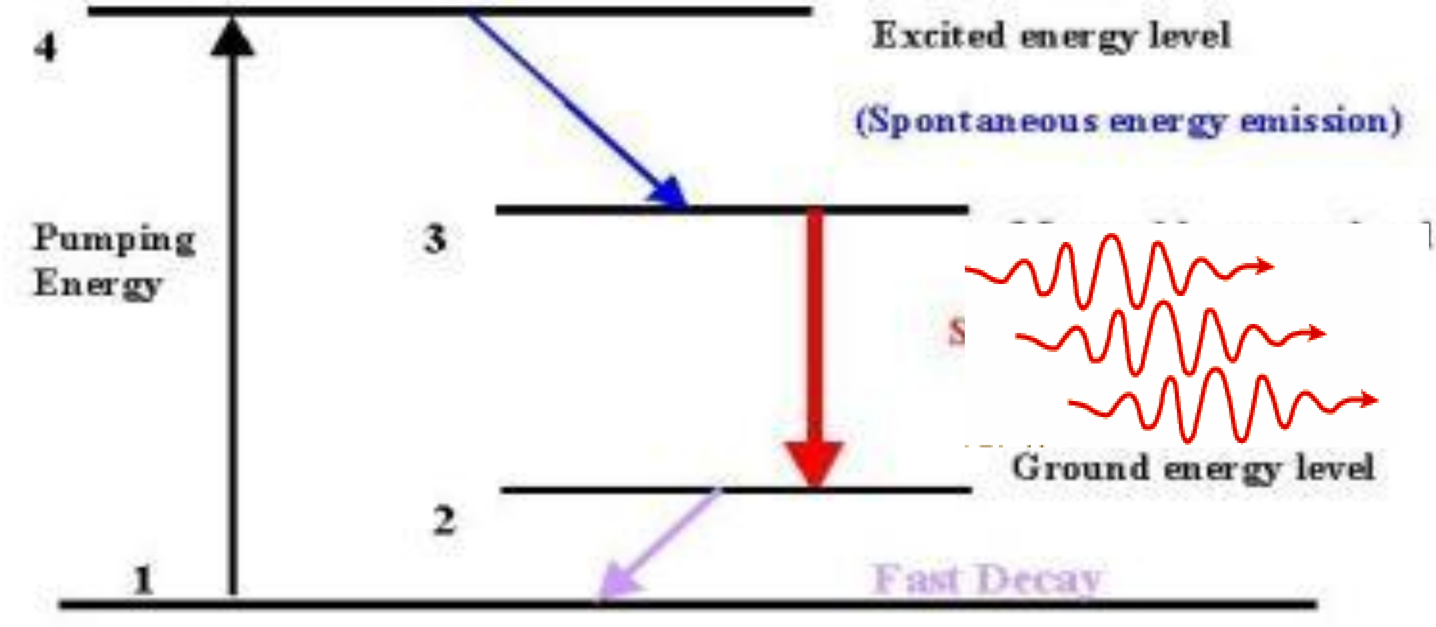


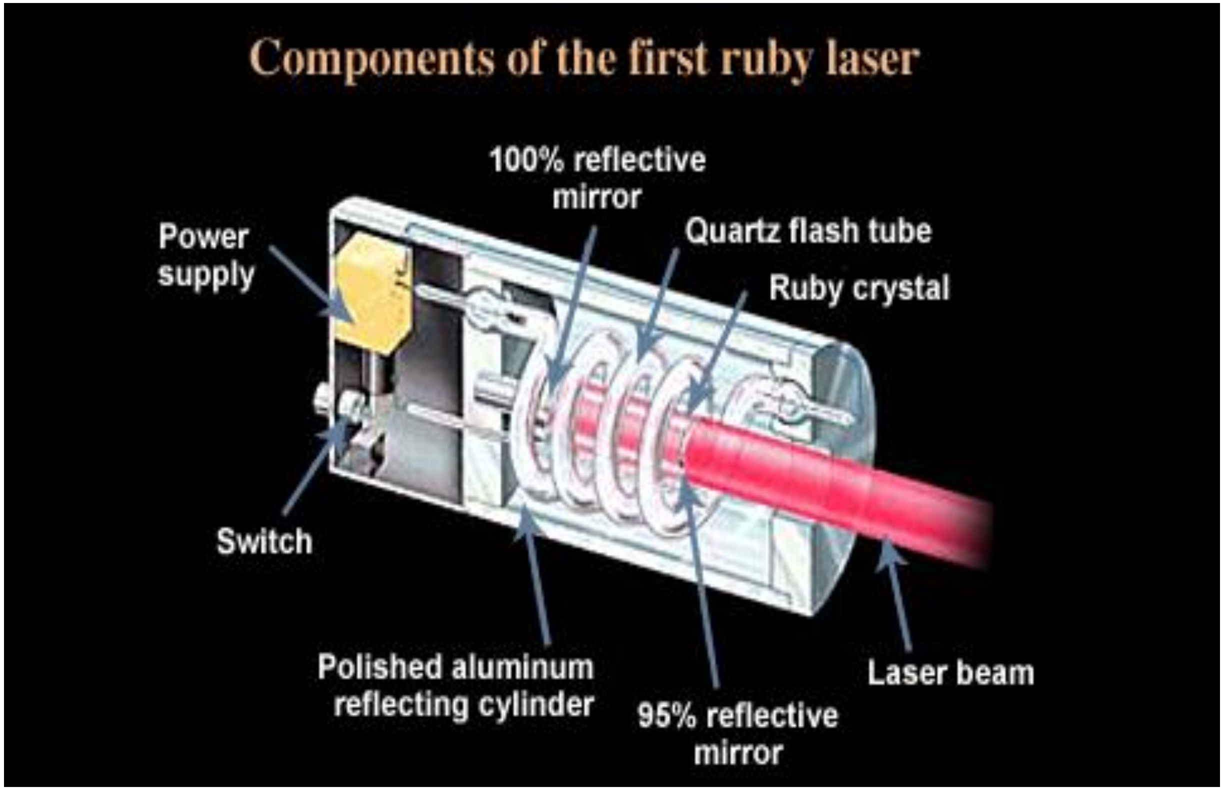
Fig. 3b: *Energy States of Four – level Active Medium*

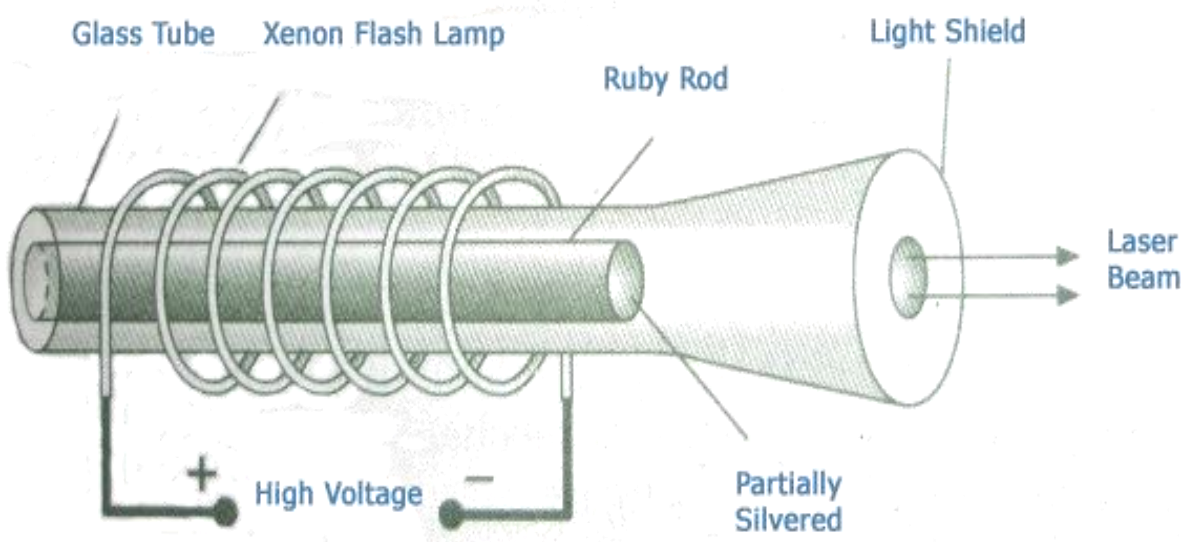
$E2-E1 >>> k_{\beta} T$
1- ground state and is pumped
2- lower laser level
3- higher energy level and metastable state
4- pump level

In four level laser, pumping energy is less & output in continous mode (CW)

Ruby laser

- It was the first type of laser invented, and was first operated by Theodore H. "Ted" Maiman
- The **active laser medium** (laser gain/amplification medium) is a **synthetic ruby rod**. Ruby is an aluminum oxide crystal in which some of the aluminum atoms have been replaced with chromium atoms(0.05% by weight). Chromium gives ruby its characteristic red color and is responsible for the lasing behavior of the crystal. Chromium atoms absorb green and blue light and emit or reflect only red light. For a ruby laser, a crystal of ruby is formed into a cylinder
- The rod's ends had to be polished with great precision, such that the ends of the rod were flat to within a quarter of a wavelength of the output light, and parallel to each other within a few seconds of arc. **The finely polished ends of the rod were silvered: one end completely, the other only partially.**
-


Components of the first ruby laser
100% reflective mirror
Power supply
Quartz flash tube
Ruby crystal
Switch
Polished aluminum reflecting cylinder
95% reflective mirror
Laser beam


Glass Tube
Xenon Flash Lamp
Light Shield
Ruby Rod
Laser Beam
+
High Voltage
−
Partially Silvered

- **A xenon lamp is rolled over ruby rod and is used for pumping ions to excited state**.
- Ruby laser is based on **three level pumping scheme** . The upper energy level E3 is the pump level, short-lived, E1 is ground state, E2 is metastable state with lifetime of 0.003 sec.
- Pumping is done

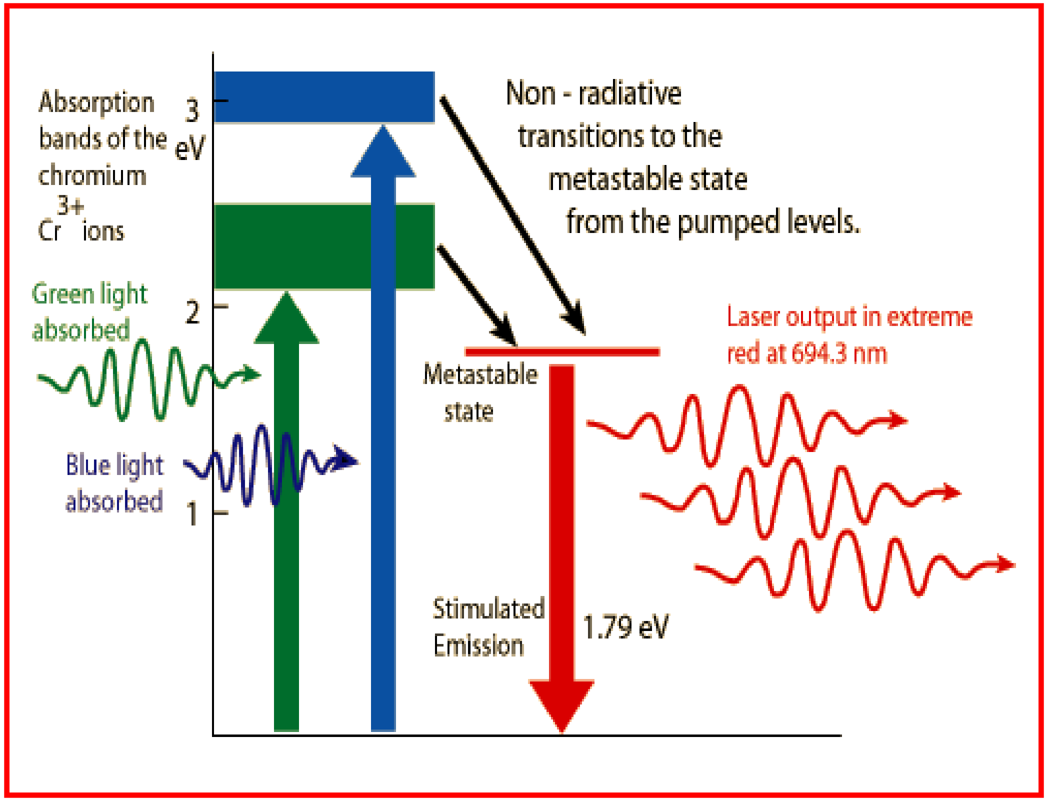
between E1 and E3

with pumping frequency

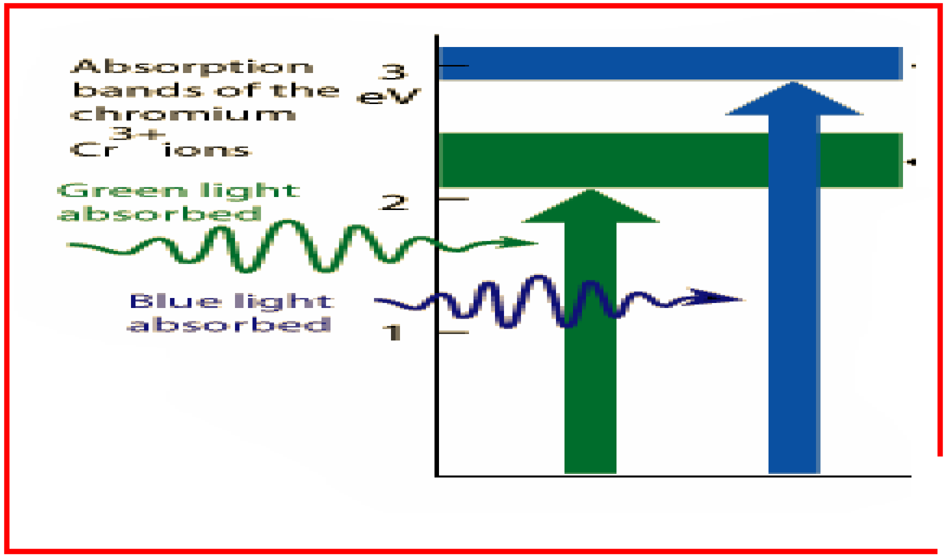
$$\nu = (E3 - E1) / h$$

- Lasing action is between
- E2(ULL) and E1 (LLL) with stimulating frequency

$$\nu = (E2 - E1) / h$$



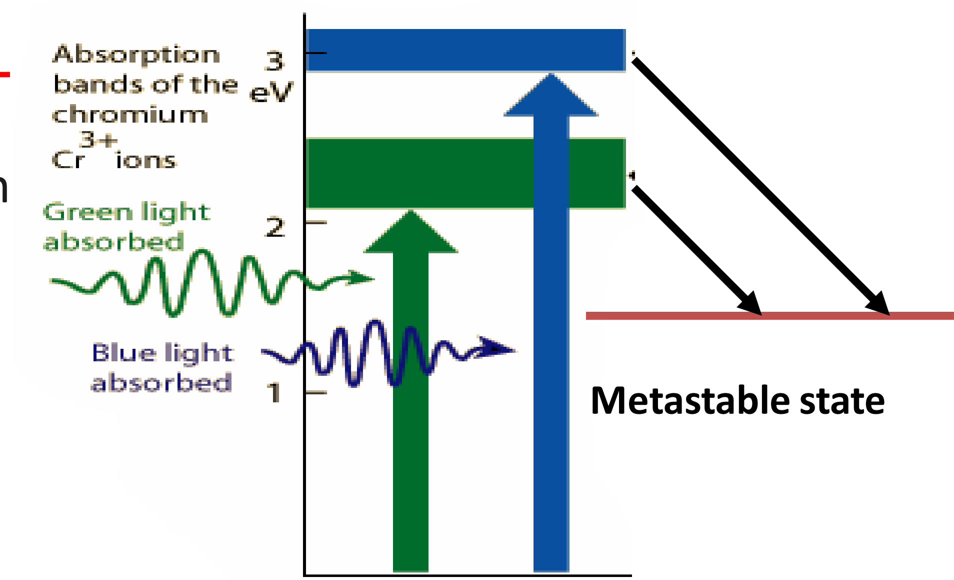
- When a flash of light falls on ruby rod, radiations of wavelength 5500 are absorbed by Cr3+ which are pumped to E3.



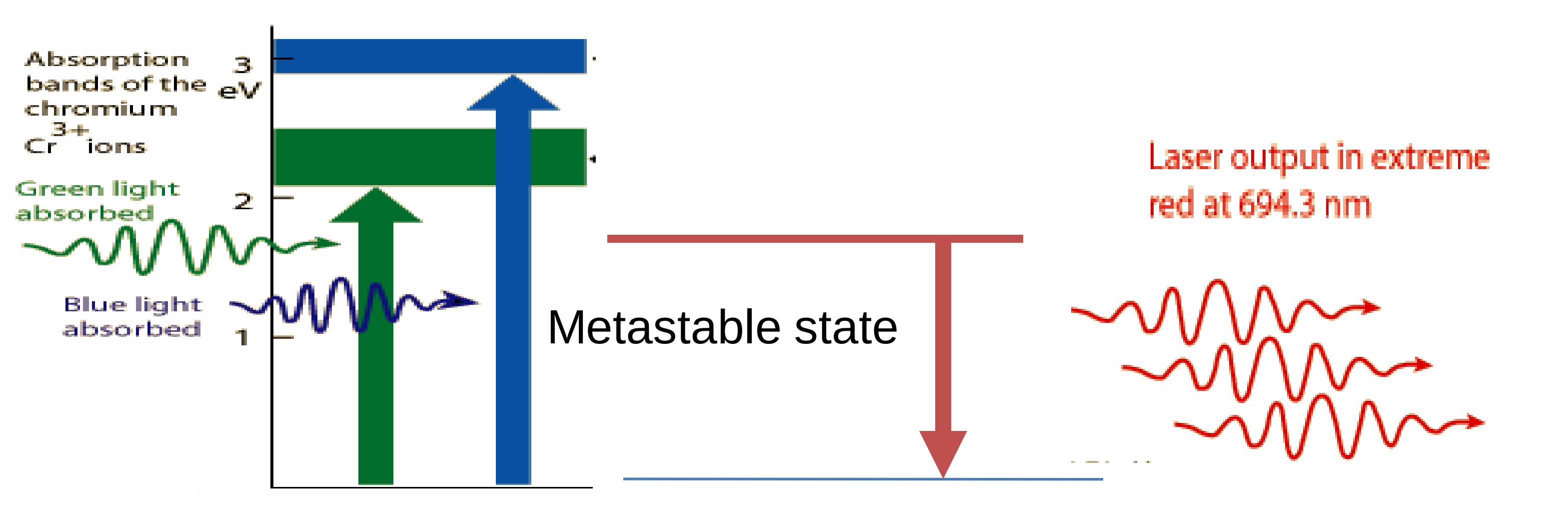
The ions after giving a part of their energy to crystal lattice decay to E2 state undergoing non-radiation transitions

- In metastable state , the concentration of ions increases while that of E1 decreases.

Hence,population inversion is achieved



A spontaneous emission photon by Cr^{3+} ion at E2 level initiates the stimulated emission by other Cr^{3+} ions in metastable state



Applications

Ruby lasers have declined in use with the discovery of better lasing media. They are still used in a number of applications where short pulses of red light are required. Holographers around the world produce holographic portraits with ruby lasers, in sizes up to a metre squared.

Many non-destructive testing labs use ruby lasers to create holograms of large objects such as aircraft tires to look for weaknesses in the lining.

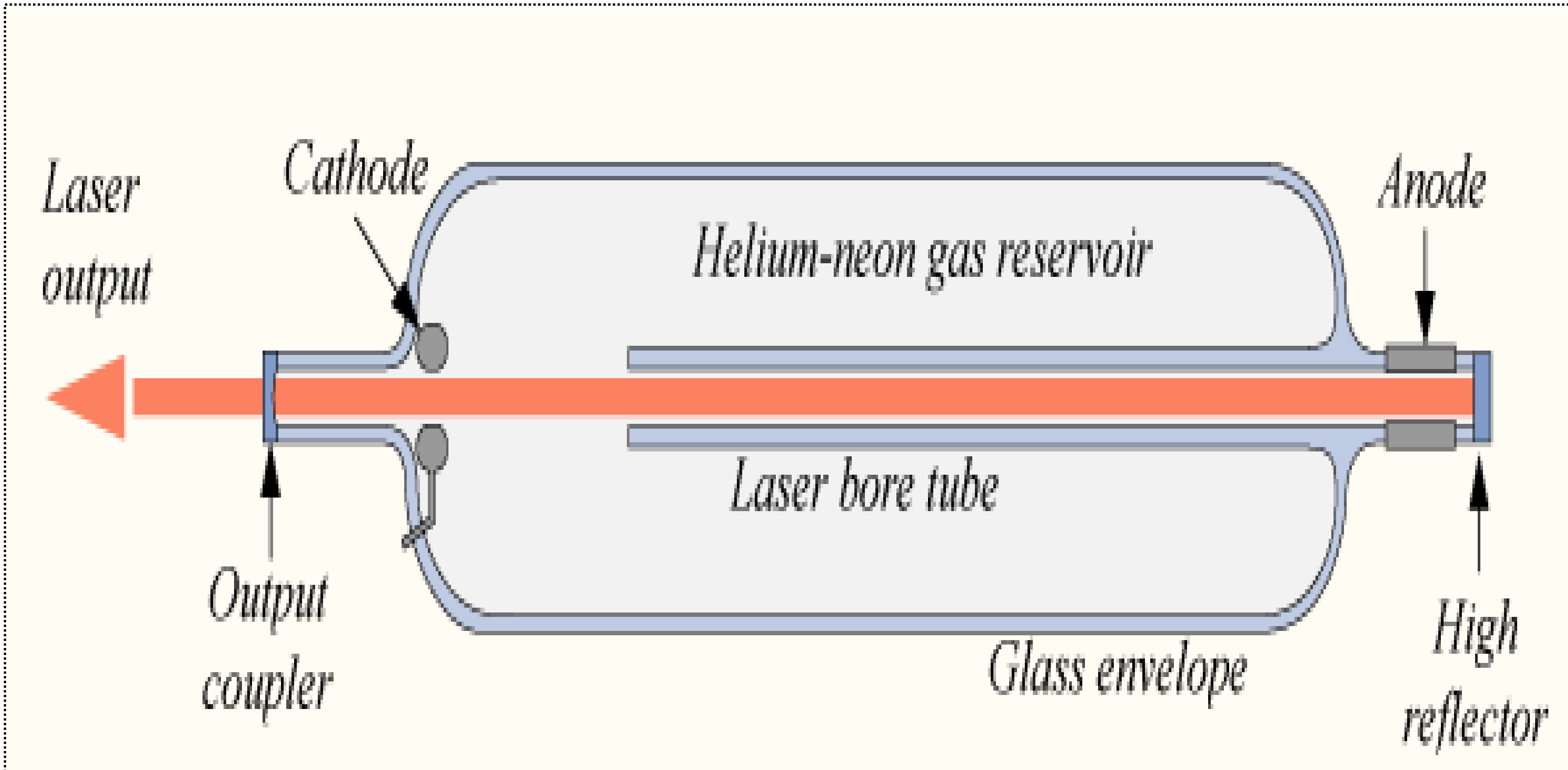
Ruby lasers were used extensively in tattoo and hair removal

He-Ne Laser

- Gas laser :-- Helium-neon laser (He-Ne laser)
- Invented by Javan et. al. in 1961
- Operation wavelength: 632.8 nm, in the red portion of the visible spectrum.
- It operates in Continuous Working (CW) mode.
- Pump source: electrical discharge
- He-Ne laser is a four-level laser.
- It operates in Continuous Working (CW) mode
- Gain medium : ratio 5:1 mixture of helium and neon gases
- The energy or pump source of the laser is provided by an electrical discharge of around 1000 volts through an anode and cathode at each end of the glass tube. A current of 5 to 100 mA is typical for CW operation.

•The optical cavity of the laser typically consists of a plane, high-reflecting mirror at one end of the laser tube, and a concave output coupler mirror of approximately 1% transmission at the other end.

•HeNe lasers are normally small, with cavity lengths of around 15 cm up to 0.5 m, and optical output powers ranging from 1 mW to 100 mW.



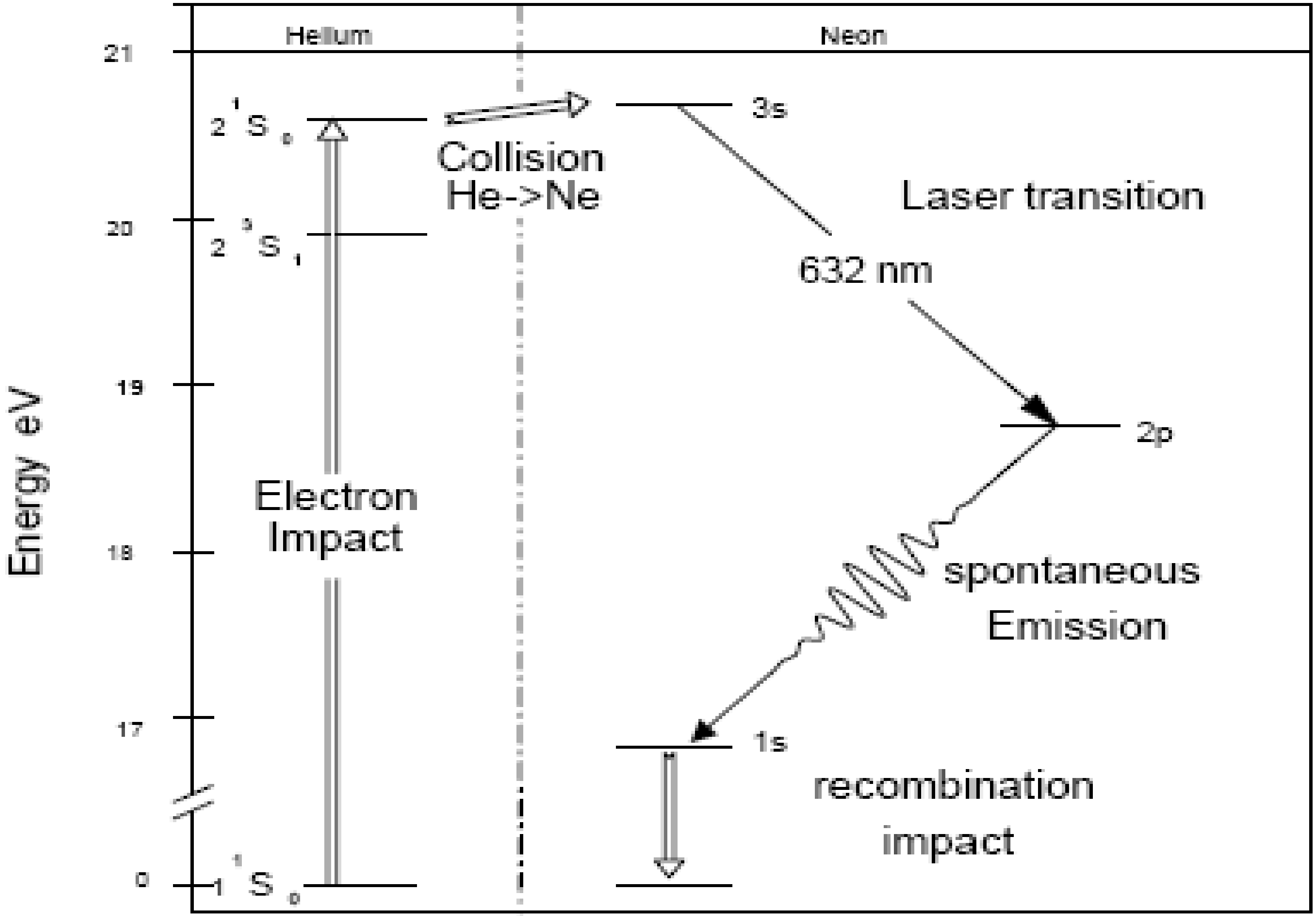


Fig. 1: Excitation and Laser process for the visible Laser emission

Working of He-Ne laser

- When the power is switched on, An energetic electron collisionally excites a He atom to the state labeled 21So . A He atom in this excited state is often written He*(21So), where the asterisk means that the He atom is in an excited state.
- The excited He atom collides with an unexcited Ne atom and the atoms exchange internal energy, with an unexcited He atom and excited Ne atom, written Ne*(3s2), resulting. This energy exchange process occurs with high probability only because of the accidental near equality of the two excitation energies of the two levels in these atoms. Thus, the purpose of population inversion is fulfilled
- When the excited Ne atom passes from metastable state(3s) to lower level(2p), it emits photon of wavelength 632 nm.
- This photon travels through the gas mixture parallel to the axis of tube, it is reflected back and forth by the mirror ends until it stimulates an excited Ne atom and causes it to emit a photon of 632nm with the stimulating photon.

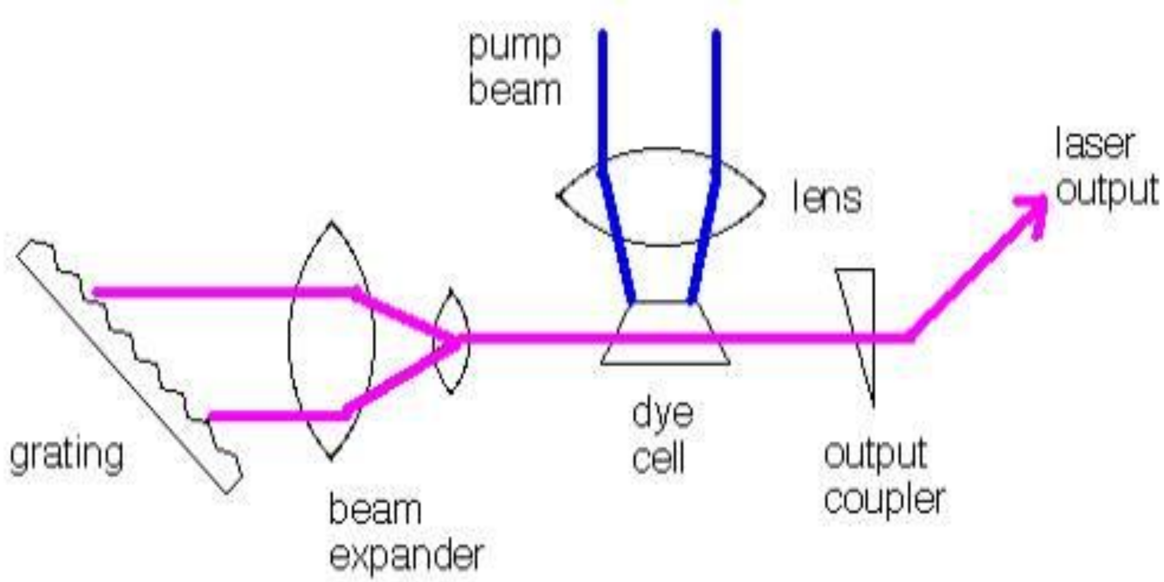
•The stimulated transition from (3s) level to (2p) level is laser transition.
•This process is continued and when a beam of coherent radiation becomes sufficiently strong, a portion of it escape through partially silvered end.
•The Ne atom passes to lower level 1s emitting spontaneous emission. and finally the Ne atom comes to ground state through collision with tube wall and undergoes radiationless transition

Applications:

1.The Narrow red beam of He-Ne laser is used in supermarkets to read bar codes.
2.The He- Ne Laser is used in Holography in producing the 3D images of objects.
3. He-Ne lasers have many industrial and scientific uses, and are often used in laboratory demonstrations of optics.

Liquid Laser

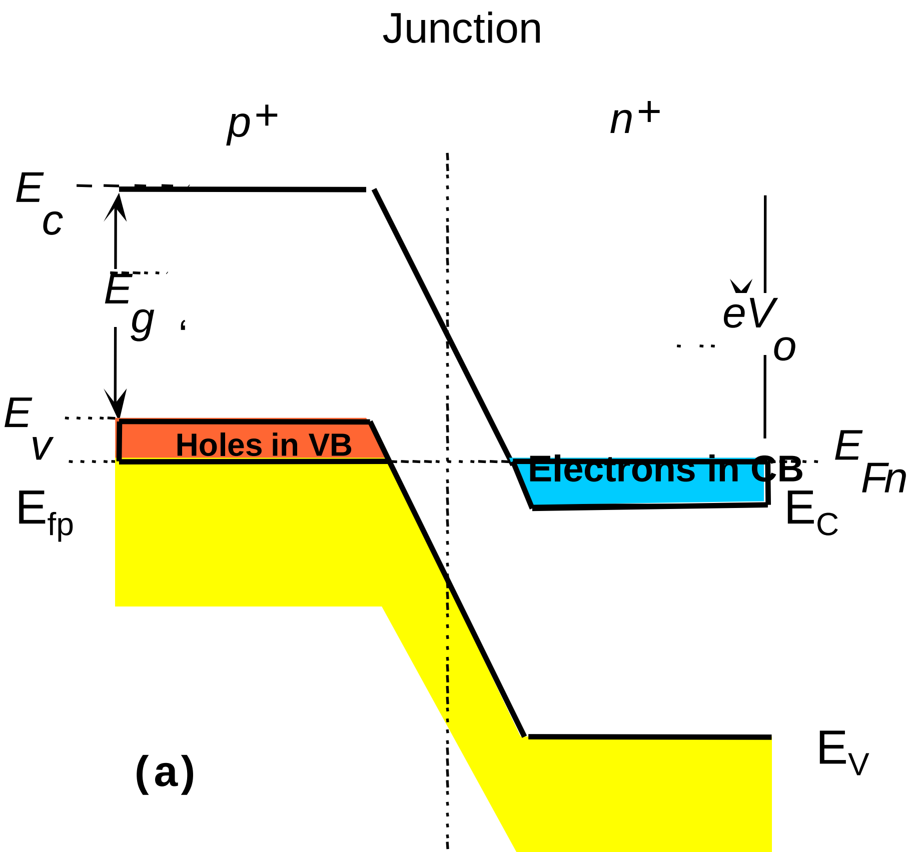
- Can be used for a wide range of wavelengths as the tuning range of the laser depends on the exact dye used.
- A Dye laser
- Gain medium: complex organic dyes, such as rhodamine 6G, in liquid solution or suspension.
- Pump source: other lasers or flashlamp.
- Suitable for tunable lasers

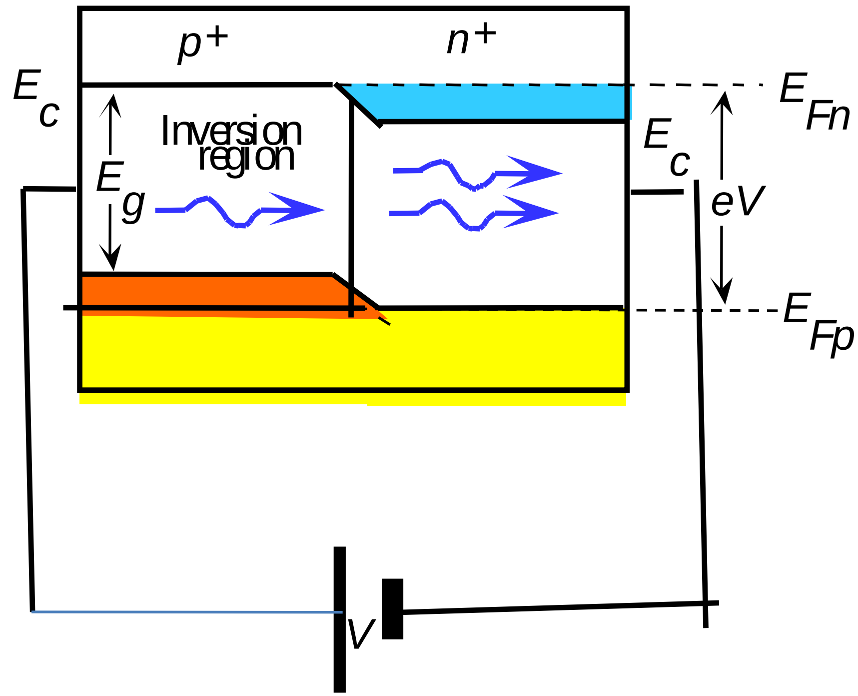


A dye laser can be considered to be basically a four-level system.
The energy absorbed by the dye creates a population inversion, moving the electrons into an excited state.

Semiconductor laser

- Valence band (E_v) acts as the lower energy state
- Conduction band (E_c) as higher energy state





•P-n junction must be degenerately doped.

•Fermi level in valance band (p) and conduction band (n).

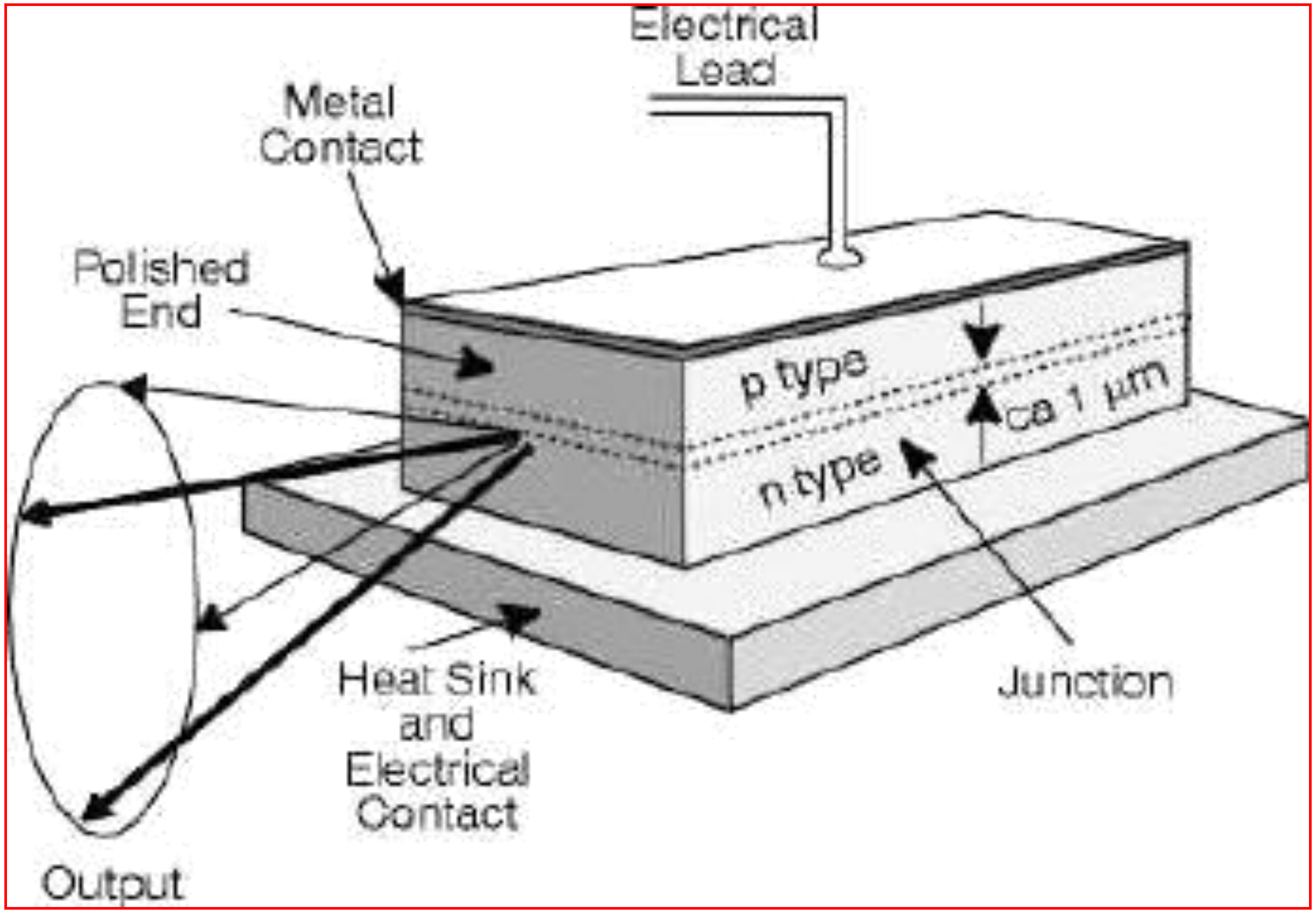
•No bias, built n potential; eV_o barrier to stop electron and holes movement

•Forward bias, $eV > E_g$

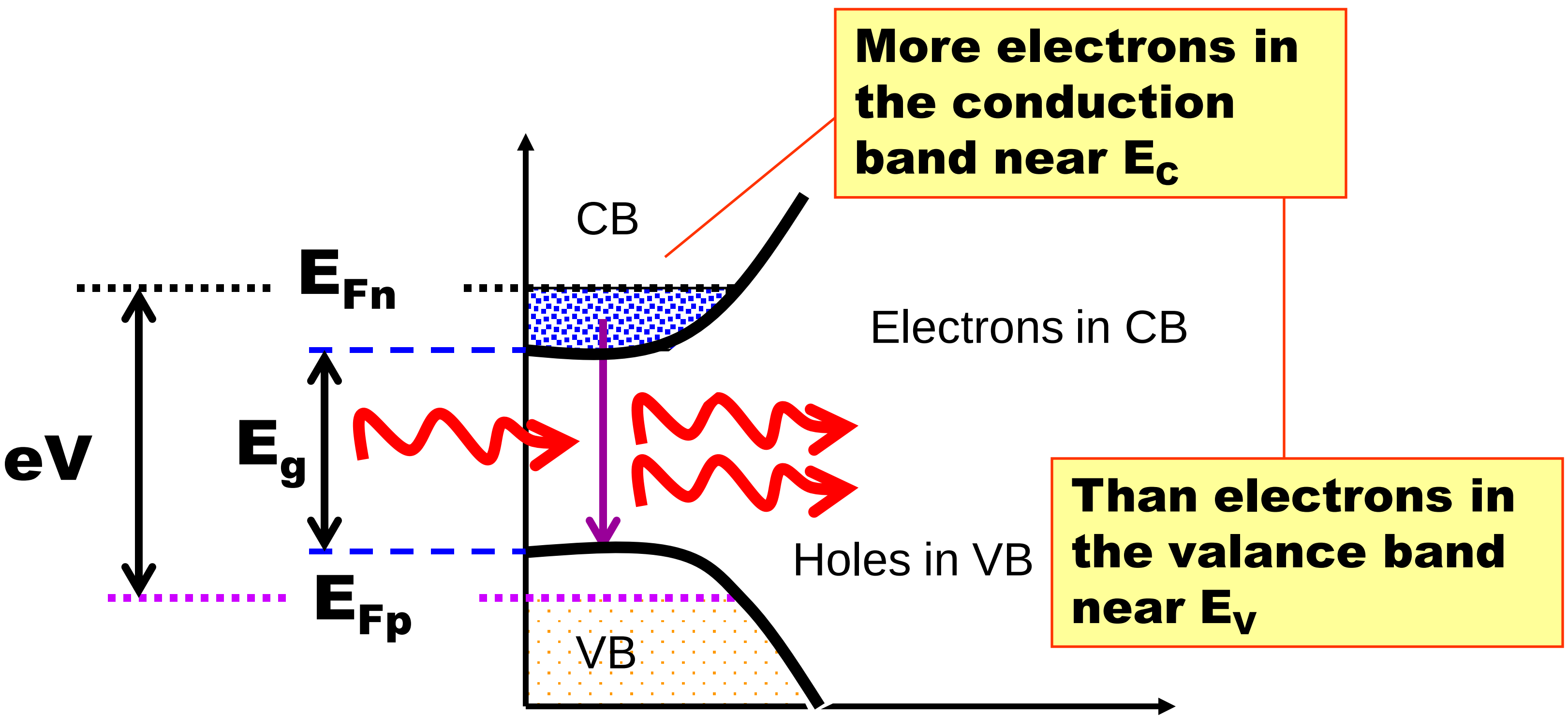
•Built in potential diminished to zero

•Electrons and holes can diffuse to the space charge layer

- Suppose that the degenerately doped p-n junction is forward biased by a voltage greater than the band gap; $eV > E_g$
- The separation between E_{Fn} and E_{Fp} is now the applied potential energy
- The applied voltage diminished the built-in potential barrier, eV_o to almost zero.
- Electrons can now flow to the p-side
- Holes can now flow to the n-side



Population Inversion in Diode Laser



E_{Fn}-E_{fP} = eV

eV > E_g

eV = forward bias voltage

Fwd Diode current pumping → injection pumping

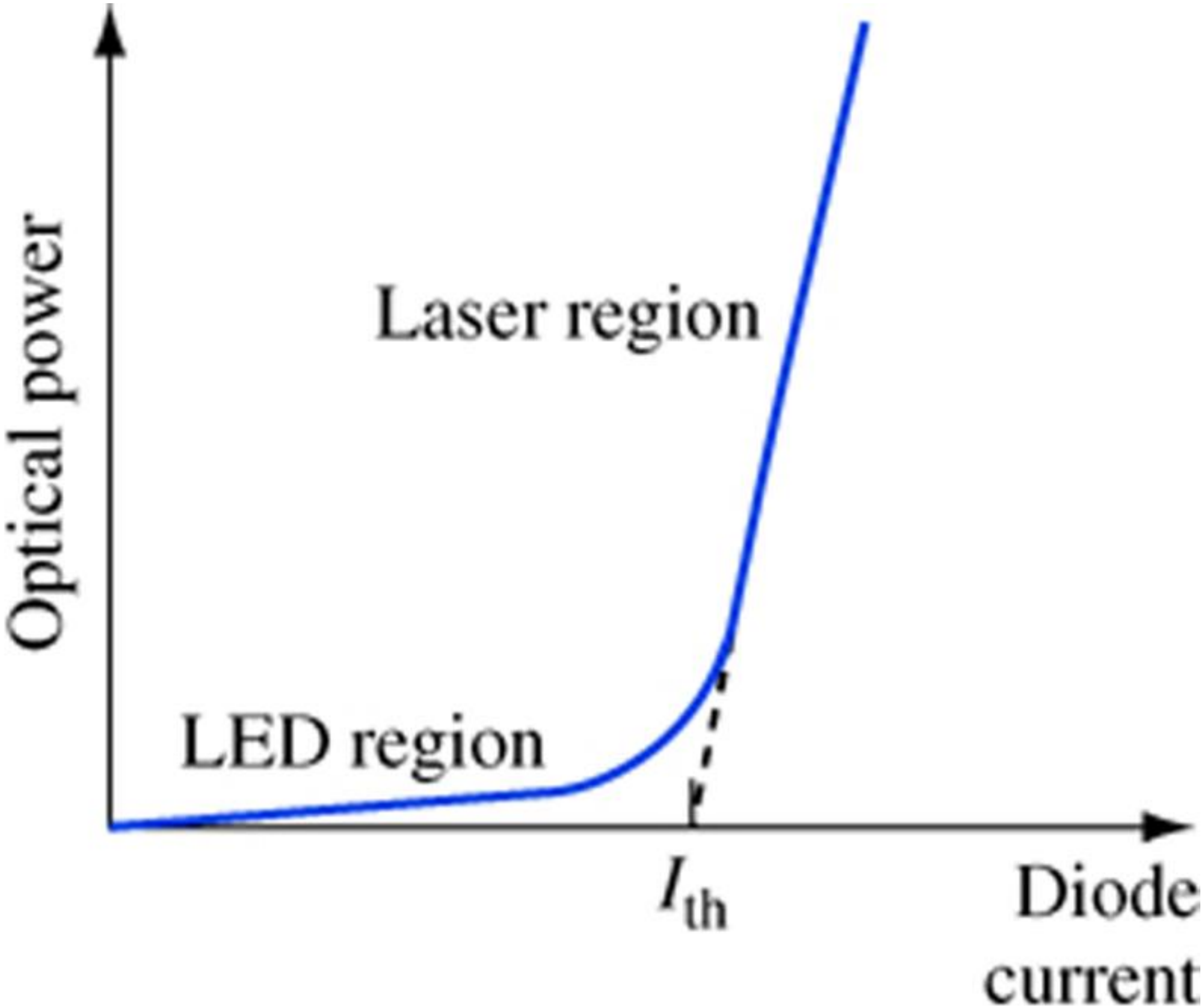
- There is therefore a **<u>population inversion</u>** between energies near E_C and near E_V around the junction.
- This only achieved when degenerately doped p-n junction is forward bias with energy > E_{gap}

- The population inversion region is a layer along the junction → also call inversion layer or active region
- Now consider a photon with $E = E_g$
- Obviously this photon can not excite electrons from E_V since there is NO electrons there
- However the photon CAN STIMULATE electron to fall down from CB to VB.
- Therefore, the incoming photon stimulates emission than absorption
- The active region is then said to have 'optical gain' since the incoming photon has the ability to cause emission rather than being absorbed
- **Pumping**

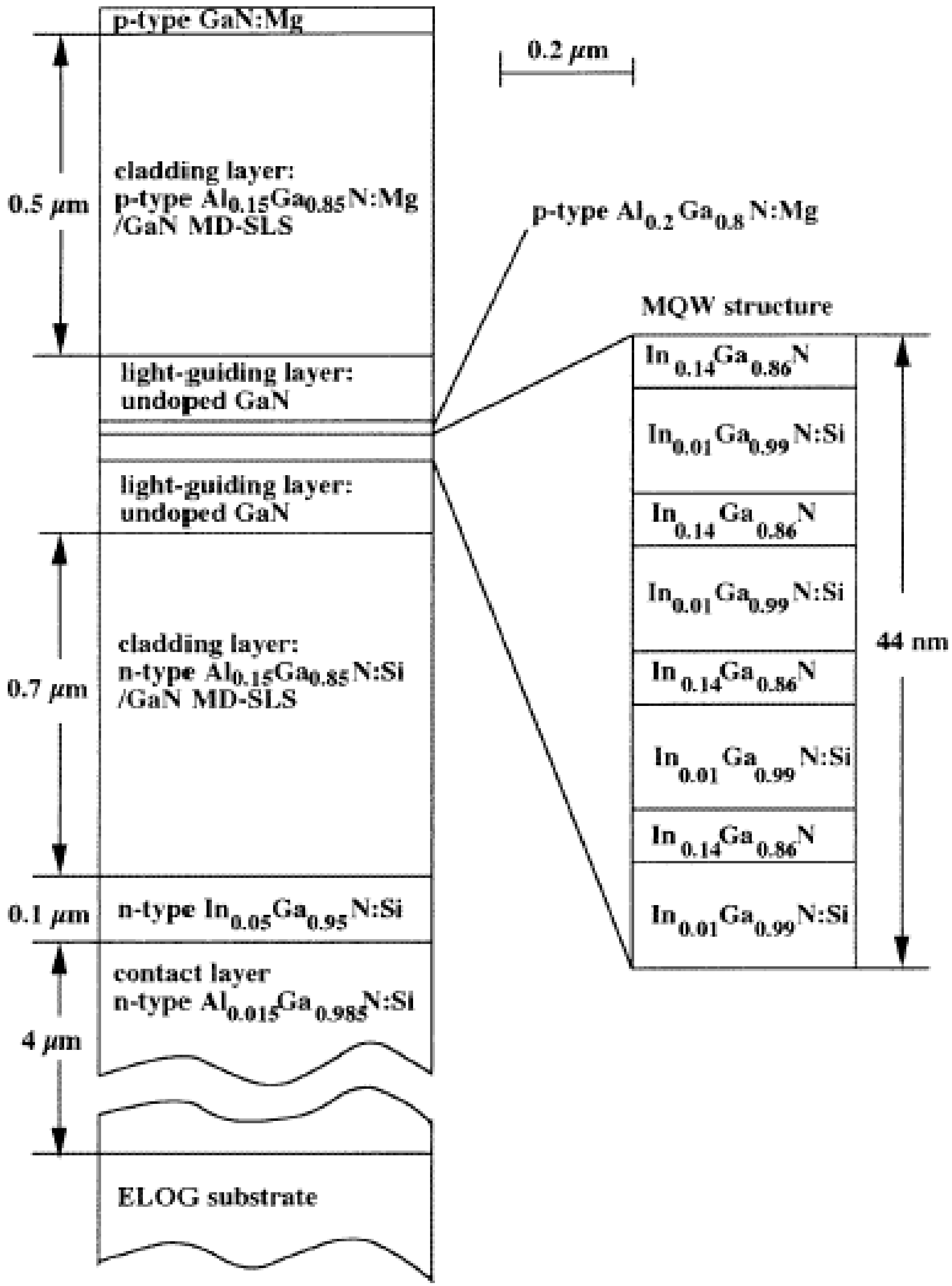
It is obvious that the population inversion between energies near E_C and those near E_V occurs by injection of large charge carrier across the junction by forward biasing the junction.

Therefore the pumping mechanism is FORWARD DIODE CURRENT → Injection pumping

In diode laser it is not necessary to use external mirrors to provide positive feedback. The high refractive index normally ensure that the reflectance at the air/material interface is sufficiently high



Threshold current density



p-type GaN:Mg
0.2 μm
0.5 μm
cladding layer:
p-type Al0.15Ga0.85N:Mg
/GaN MD-SLS
p-type Al0.2 Ga0.8 N:Mg
MQW structure
light-guiding layer:
undoped GaN
In 0.14Ga 0.86N
In0.01Ga0.99N:Si
In 0.14Ga 0.86N
In0.01Ga0.99N:Si
light-guiding layer:
undoped GaN
44 nm
0.7 μm
cladding layer:
n-type Al0.15Ga0.85N:Si
/GaN MD-SLS
In 0.14Ga 0.86N
In 0.01Ga 0.99N:Si
In 0.14Ga 0.86N
In0.01Ga0.99N:Si
0.1 μm
n-type In0.05Ga0.95N:Si
contact layer
n-type Al0.015Ga 0.985N:Si
4 μm
ELOG substrate