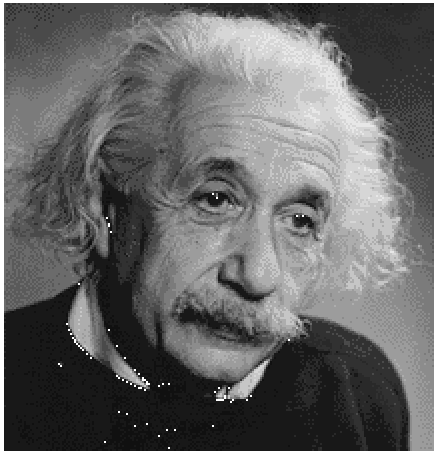
LASER

Light Amplification by Stimulated Emission of Radiation

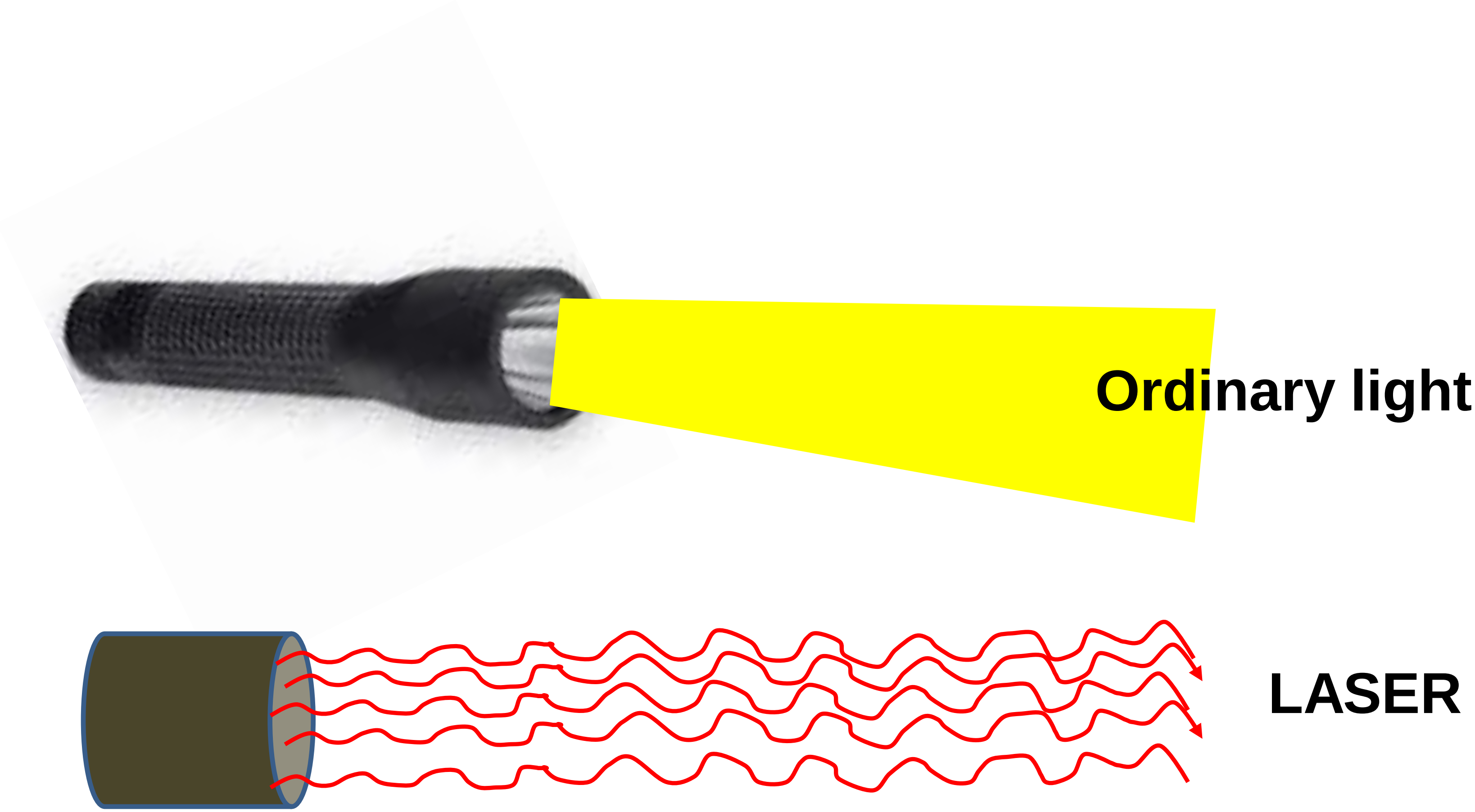
Principle and applications



Stimulated Emission process which makes lasers possible, 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

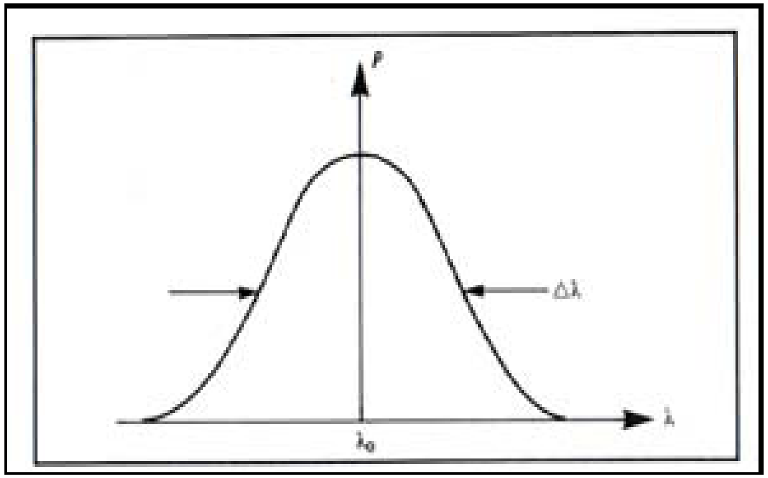
Ordinary Light



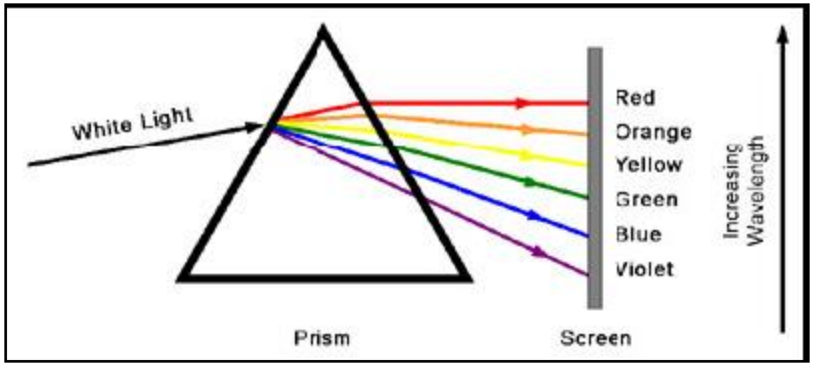
Laser :- 1. Monochromatic 2.Directional

3. High intensity 4. Coherent

Properties of LASER light



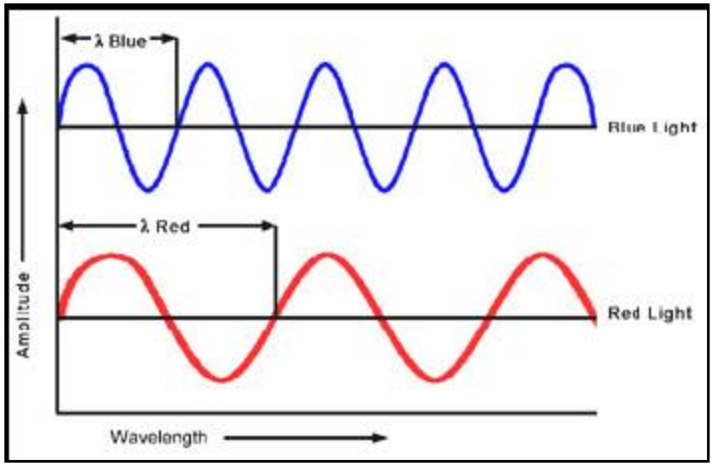
LASER



Ordinary light

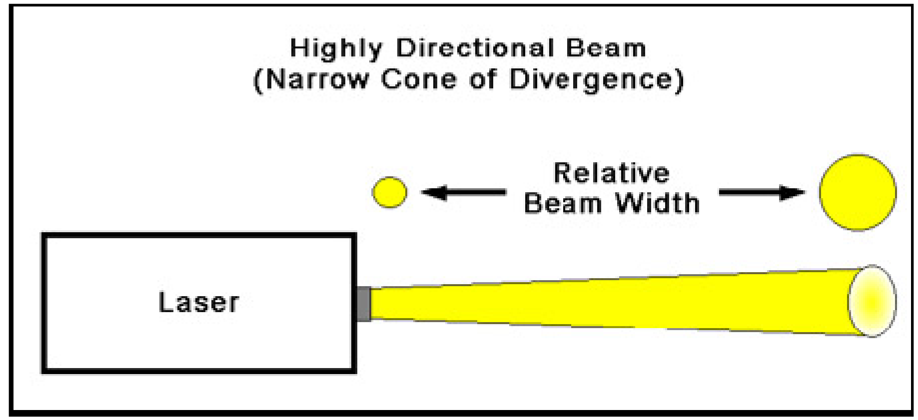
[A] Monochromacity:

- A light emitted from a source has a distribution of wavelengths since the energy levels of atoms are not sharp.
- If white light has a wavelength spread of 30 nm, a laser light will have a wavelength spread of 0.001nm.
- Laser light is highly monochromatic.



Properties of LASER light

[B] Directionality:



LASER

Conventional light source

Beam Divergence angle (θ_d)

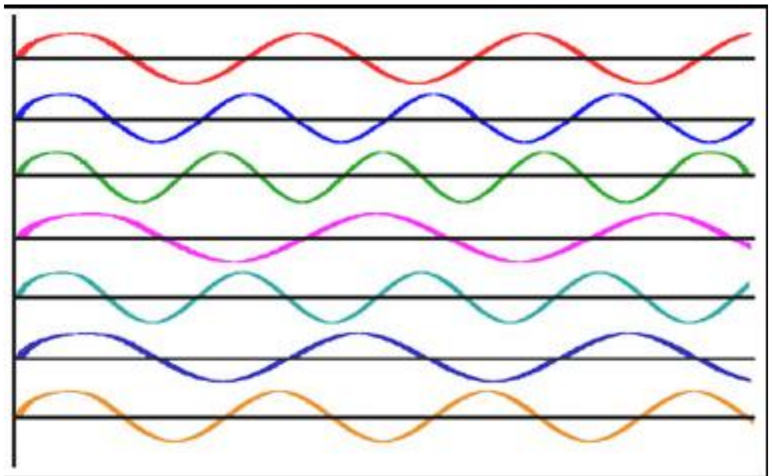
[C] Highly Intense: since highly directional, coherent entire output is concentrated in a small region and intensity becomes very high

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

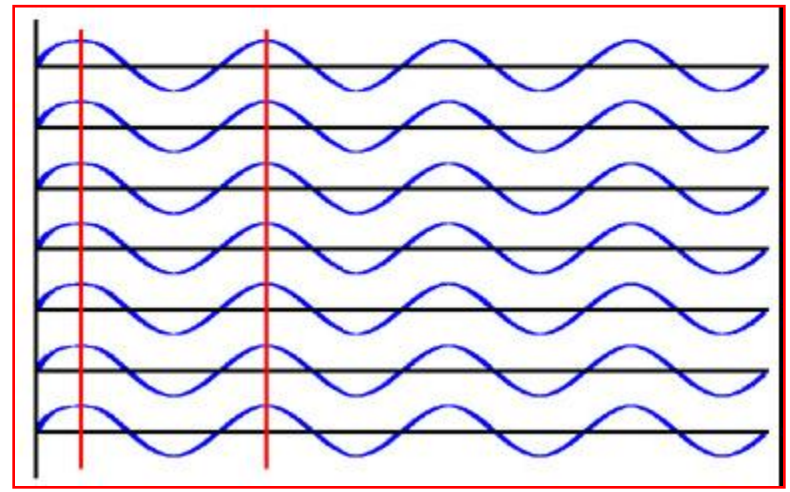
P= power radiated by laser

Properties of LASER light

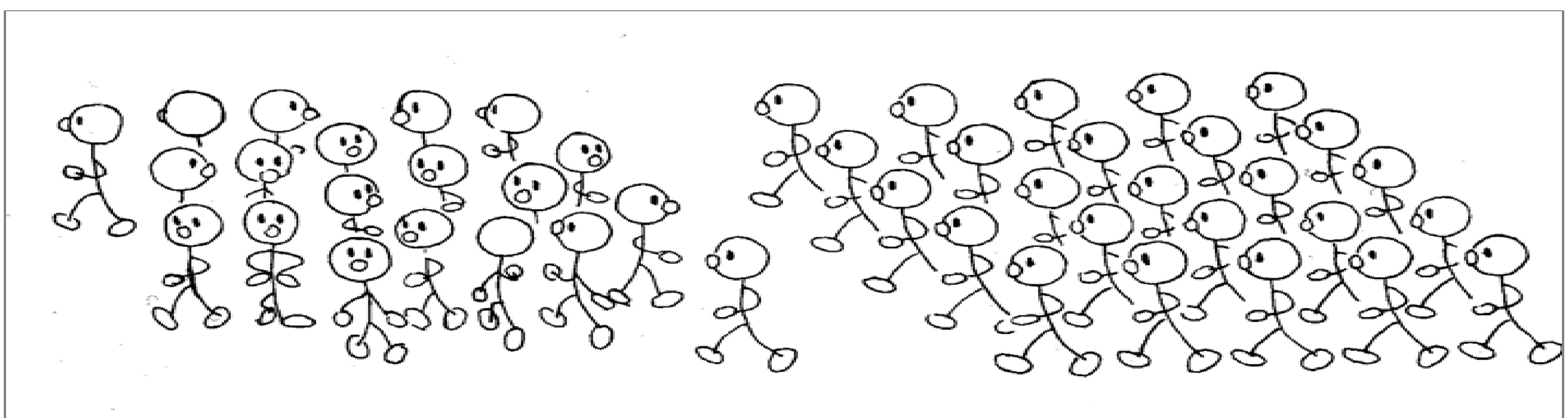
[D] Coherent:



Light: Incoherent light waves



Laser: coherent light waves



Incoherent

Coherent

Temporal Coherence:

- A light wave has temporal coherence, if phase difference between the electric field remains same during a given time interval.
- A source emits continuous light for a short duration only and this duration is called the coherence time. Distance traveled by light in coherence time is called the coherence length that is large for lasers.

$$\ell_{coh} = t_{coh} c$$

$$\ell_{coh} = \frac{\lambda^2}{\Delta\lambda} \; where \; \Delta\lambda = spread \; in \; light \; wavelegth = bandwidth$$

Spatial Coherence:

- A light wave has spatial coherence, if phase difference between the waves remains zero or constant for all times.
- A source is a point so that phases on any two points on any wave front are same. This can not happen for an extended source. Laser source has spatial coherence since it is a small size source.
- Maximum dimension of the source, for which the emitted waves have the same phase, is called the lateral coherence length.

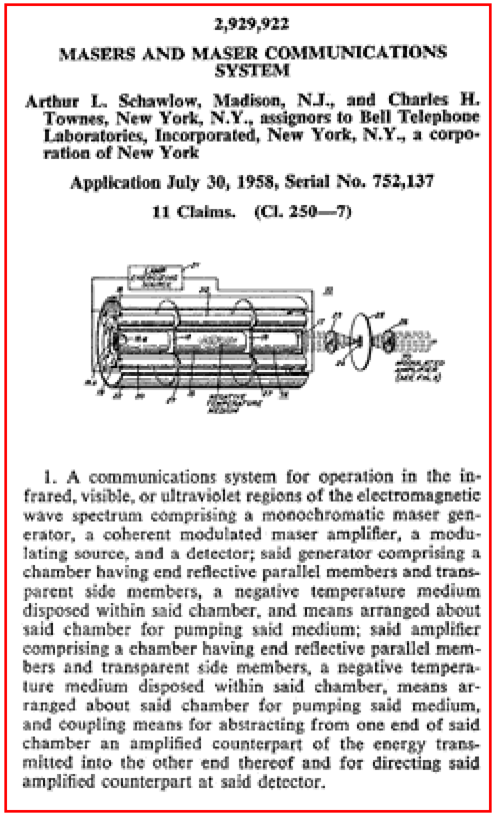
Laser History

- 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 L
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).

2005

ROY J. GLAUBER for his contribution to the quantum theory of optical coherence and **JOHN L. HALL** and **THEODOR W. HÄNSCH** for their contributions to the development of laser-based precision spectroscopy, including the optical frequency comb technique

1997

STEVEN CHU, **CLAUDE COHEN-TANNOUDJI** and **WILLIAM D. PHILLIPS** for development of methods to cool and trap atoms with laser light.

1981

NICOLAAS BLOEMBERGEN and **ARTHUR L. SCHAWLOW** for their contribution to the development of laser spectroscopy

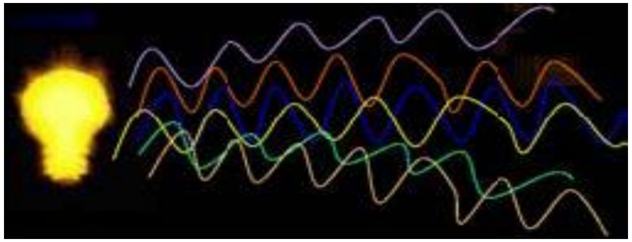
1971

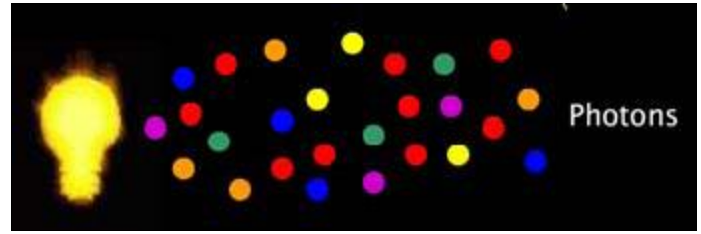
DENNIS GABOR for his invention and development of the laser holographic method

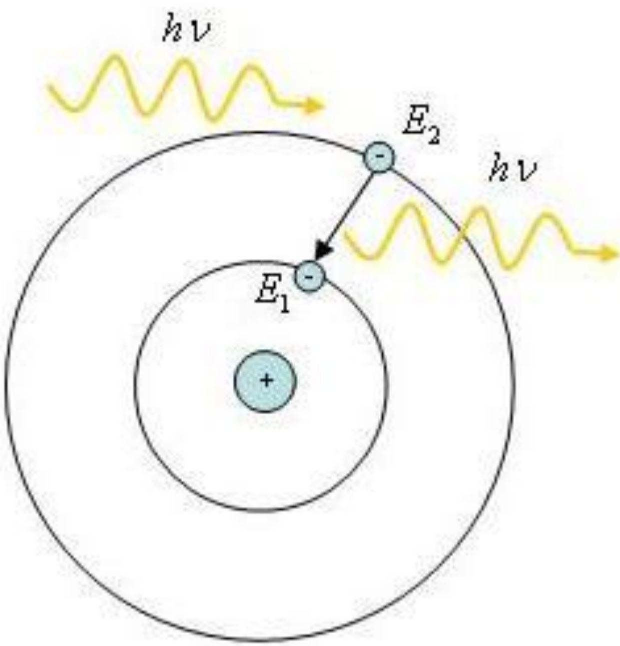
1964

CHARLES H. TOWNES and **NICOLAY GENNADIYEVICH BASOV** and **ALEKSANDR MIKHAILOVICH PROKHOROV** for fundamental work in the field of quantum electronics, which has led to the construction of oscillators and amplifiers based on the maser-laser principle.

Principle of Laser: the wave-particle-duality



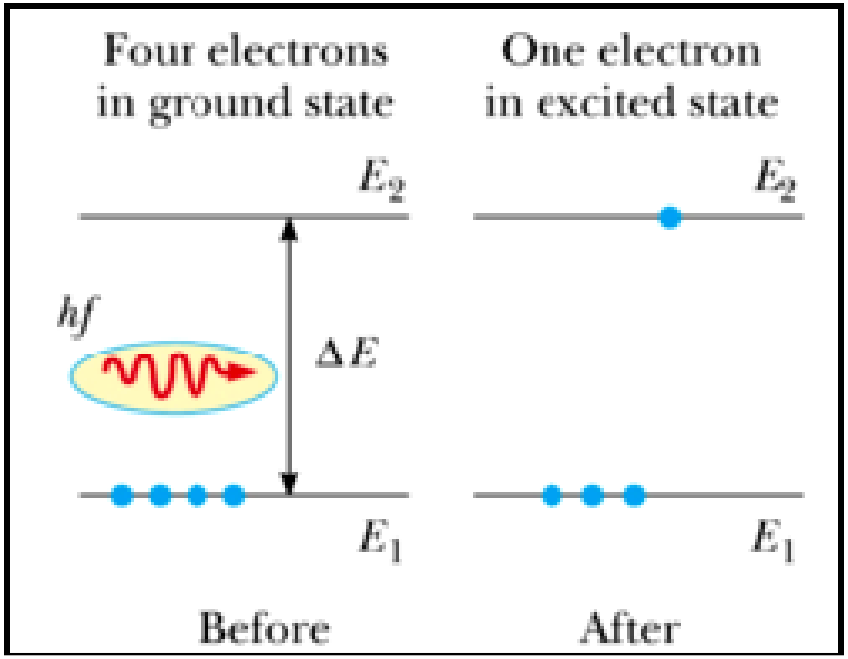




- To raise an electron from one energy level to another, “input“ energy is required
- When falling from one energy level to another, there will be an energy Output By Plank’s law **E = hν**

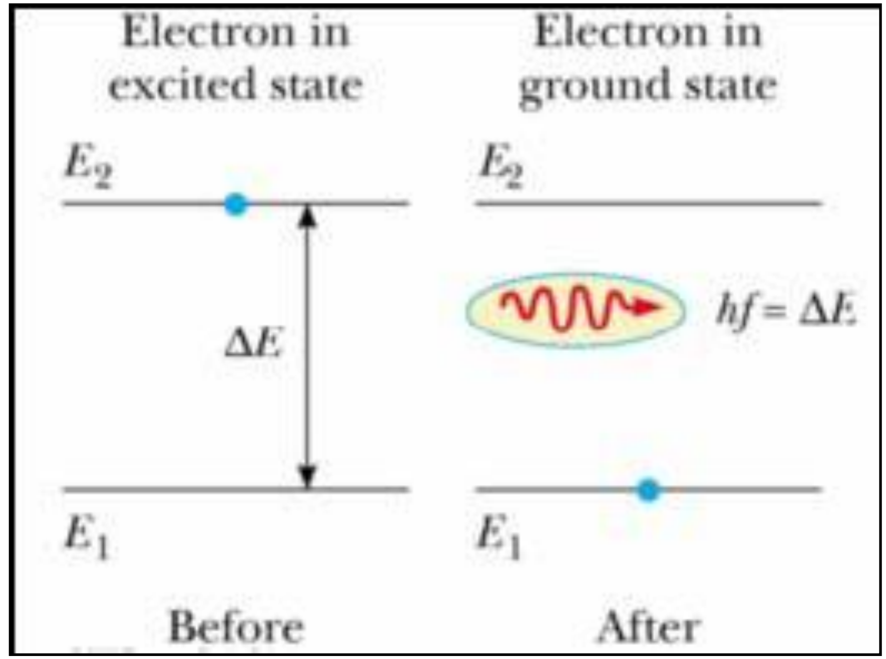
Atomic transitions

- ***Stimulated absorption***



When light (or photon) of frequency, ν, falls on a medium, electrons of the atoms in the medium gets excited to the excited state E_2 from ground state E_1, if $h\nu > E_2 - E_1$

Spontaneous emission



due to short (10^{-9}s) Lifetime of excited atoms

Energy of the photon emitted

$h\nu = \Delta E$

emitted freq. $\nu = (E2-E1) / h$

Or, $\lambda = hc / (E_2 - E_1)$

Population of atoms & normal distribution

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

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

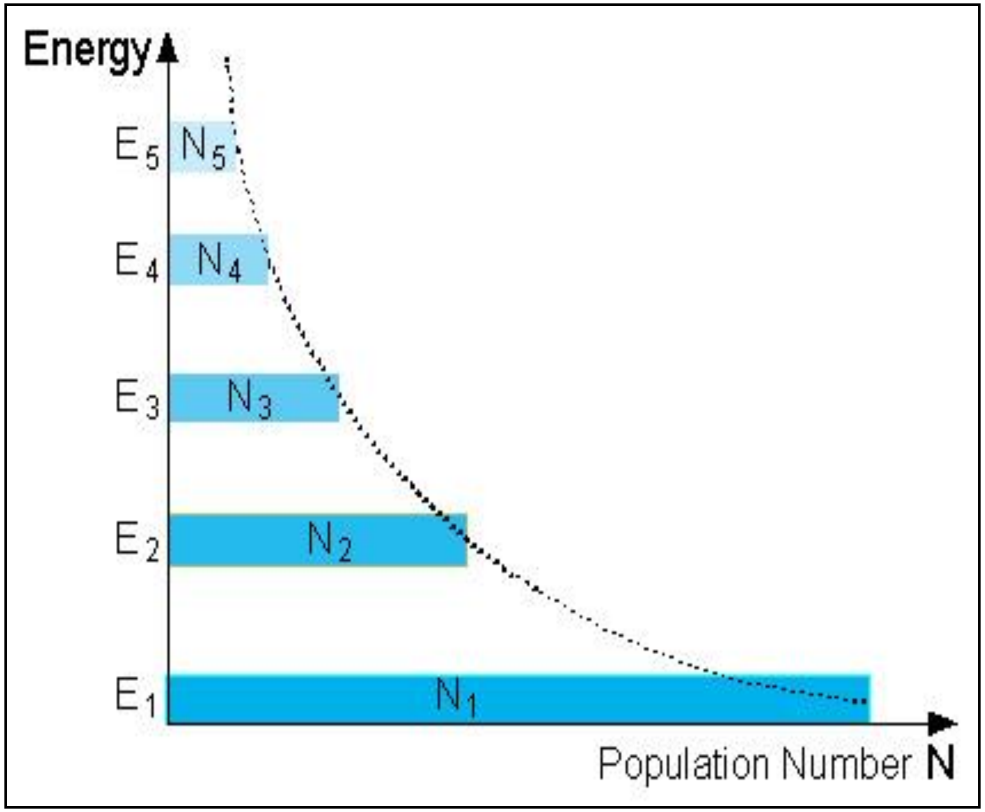
For two energy levels E_1 and E_2

Such that $E_2 > E_1$ the

Relative population :

$N_2 / N_1 = \exp[-(E_2 - E_1)/ k_\beta T]$

With **$\Delta E = E_2 - E_1$**

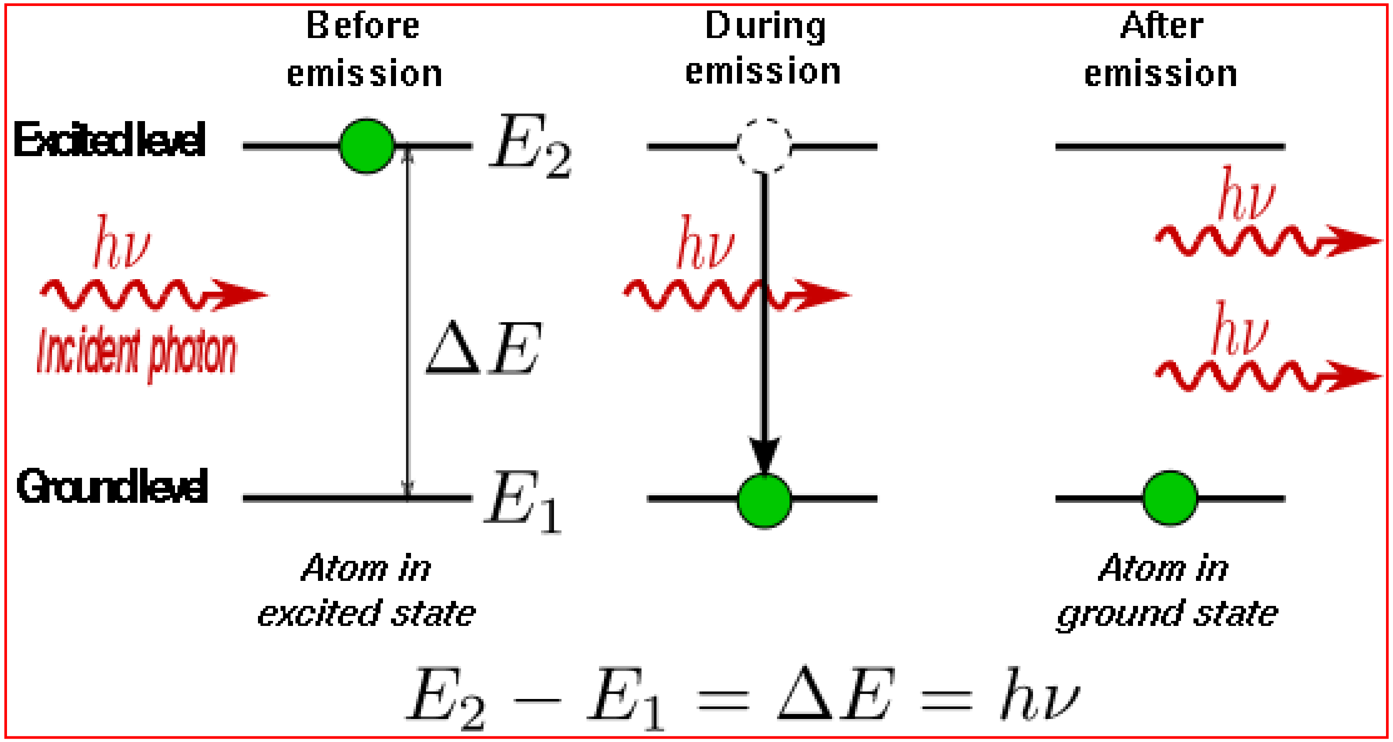


$N_1 > N_2$

Or, $N_1 > N_2 > N_3 > N_4 > N_5$

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

- If spontaneous emission is the only emission process, Then thermal equilibrium will be destroyed,
- since $N_1 > N_2$ probability of induced absorption is more, giving rise to $N_2 > N_1$
- According to Einstein another emission process is possible which is induced by the incident light called stimulated emission



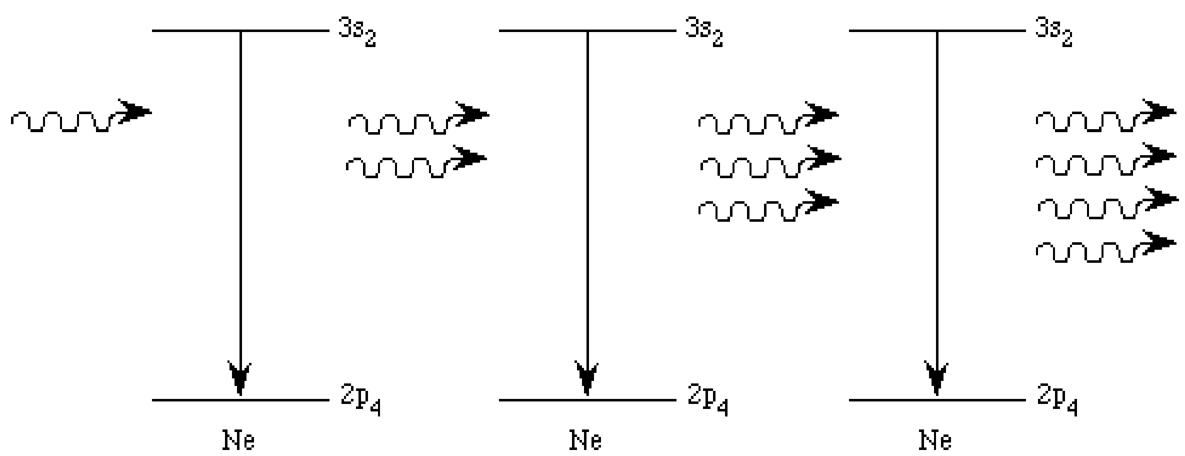
Stimulated Emission

- **<u>Principle of detailed balance:-</u>**

At equilibrium, the total no. of particles leaving a certain quantum state per unit time is equal to the no. arriving in that state per unit time.

So, if a photon can stimulate an atom from lower energy state to higher energy state , then a photon can also be able to stimulate an atom from higher energy state to lower energy state with equal probability. In the first case the photon disappears, whereas in the second case, an additional photon is created, **which has the same energy as that of the incident one to conserve energy and in phase to conserve the momentum.**

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. This is called **lasing action.**



(a)

Spontaneous emission	Stimulated emission
1.Can not be controlled from outside	1. Is controlled from outside
2. Probabilistic or random process	2. Energy transition takes place between definite selected energy levels
3. Emitted photons are random in direction, phase and state of polarisation	3. Emitted photons are same in direction, phase and state of polarisation
4. Not monochromatic	4. Are monochromatic
5. Not coherent	5. Are coherent
6. Output is broad and less intense	6. Output narrow and highly intense.
7. In the output photons are not multiplied.	7. In the output photons are 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 ---$N_2 > N_1$, 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., $N_2 > N_1$,

'T' must be negative in the expression:

$$N_2 / N_1 = \exp [- (E_2 - E_1)/ k_\beta T]$$

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

- For absorption from lower level ‘1’ to higher level ‘2’

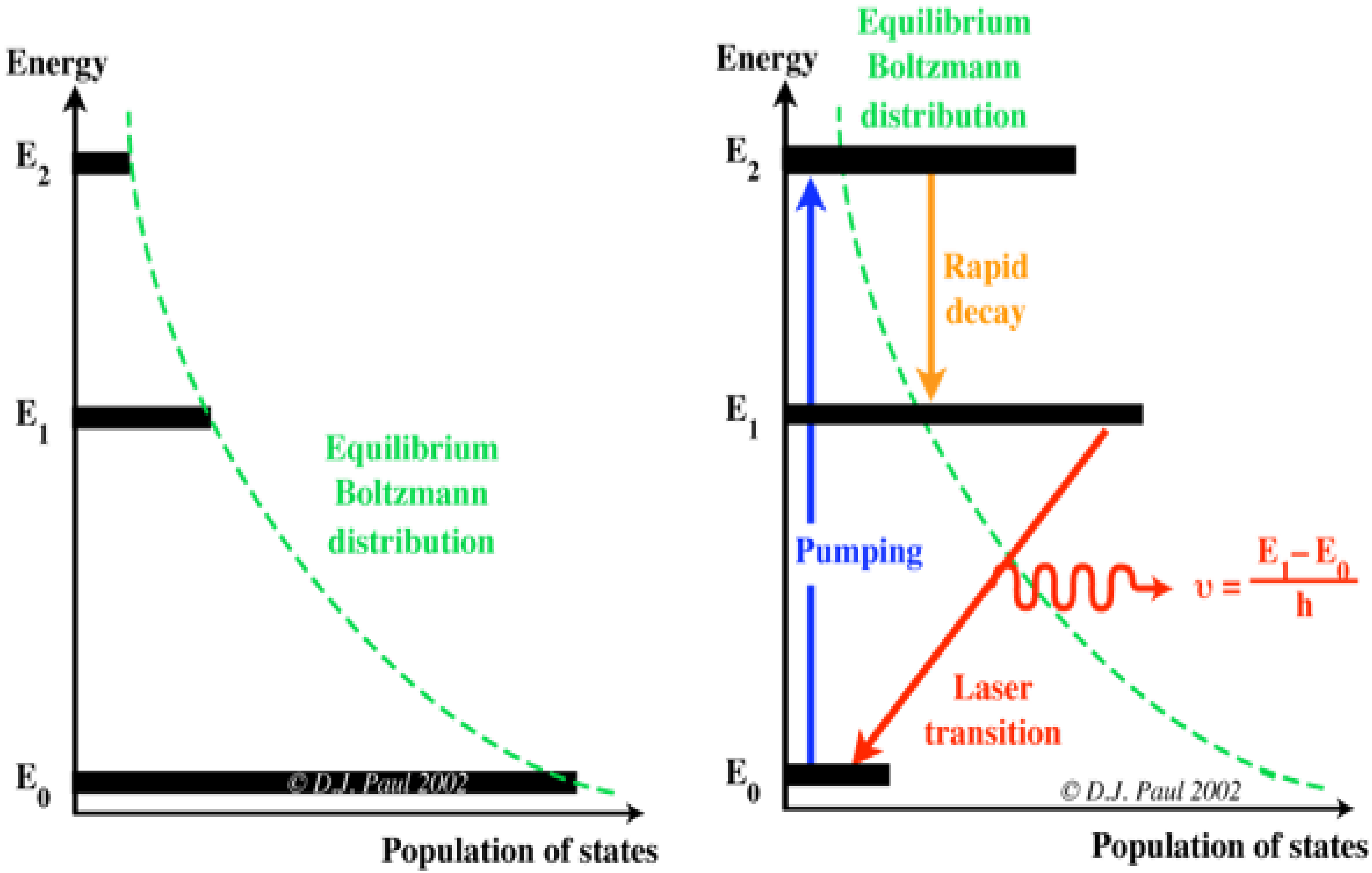
- $I = I_0 \exp\{-\sigma_{21}(N_2 - N_1)z\}$, ‘σ’ depends on transition probability between the two states.

- But for amplification, $I > I_0$ so exponential should be positive,

  Or, $I = I_0 \exp\{\sigma_{21}(N_2 - N_1)z\}$

  For amplification, $N_2 > N_1$

Which is the necessary condition for lasing action, but not the sufficient condition


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

- 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.
- to achieve population inversion i.e. to have larger population in the upper levels than in the lower ones, excitation may be done.
- Usually for population inversion ground state is subjected to excitation as it has a vast store of atoms.
- Various types of excitation processes are called **'pumping'**
- Different pumping mechanisms are

optical, electrical, thermal, direct introduction or chemical techniques,

which depends on the type of the medium employed

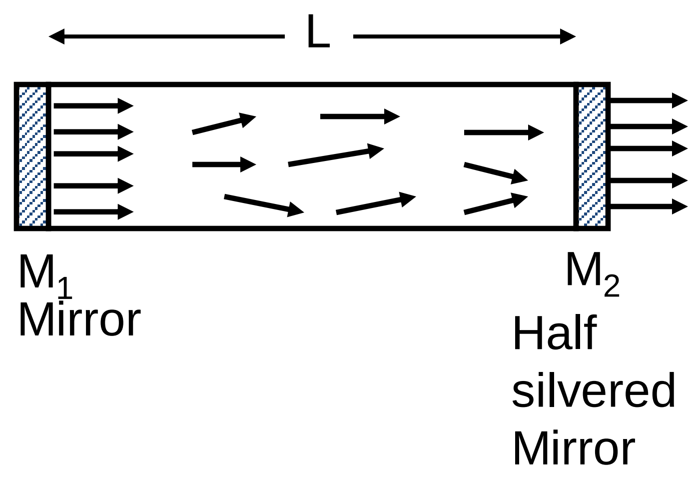
Metastable states:- sufficient condition for lasing action

- 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.
- The energy levels, which has the spontaneous lifetime of the order of microseconds to a few milliseconds, are known as **METASTABLE** levels. The probability of transitions involving metastable levels is relatively low.
- Metastable states available or introduced helps for lasing action, which is the sufficient condition. Besides this lasing threshold energy is required, which give rise to sustained lasing action.
- **Active medium :-** A medium **which supports lasing action with** suitable **metastable states**, and 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 Cavity :

$$I = I_0 \exp[\alpha(N_2 - N_1)z]$$

For good amplification of intensity during pumping, z should be large. This is done by using an optical cavity with two mirrors M_1 and M_2 – M_1 fully silvered (fully reflecting) and M_2 half silvered (partially reflecting).



- The stimulated light is reflected back and forth increasing its intensity.
- Photons traveling off axis will die down due to absorption.
- Photon traveling parallel to axis due to multiple reflection will build up in intensity. These photon then become highly coherent.

Optical resonator

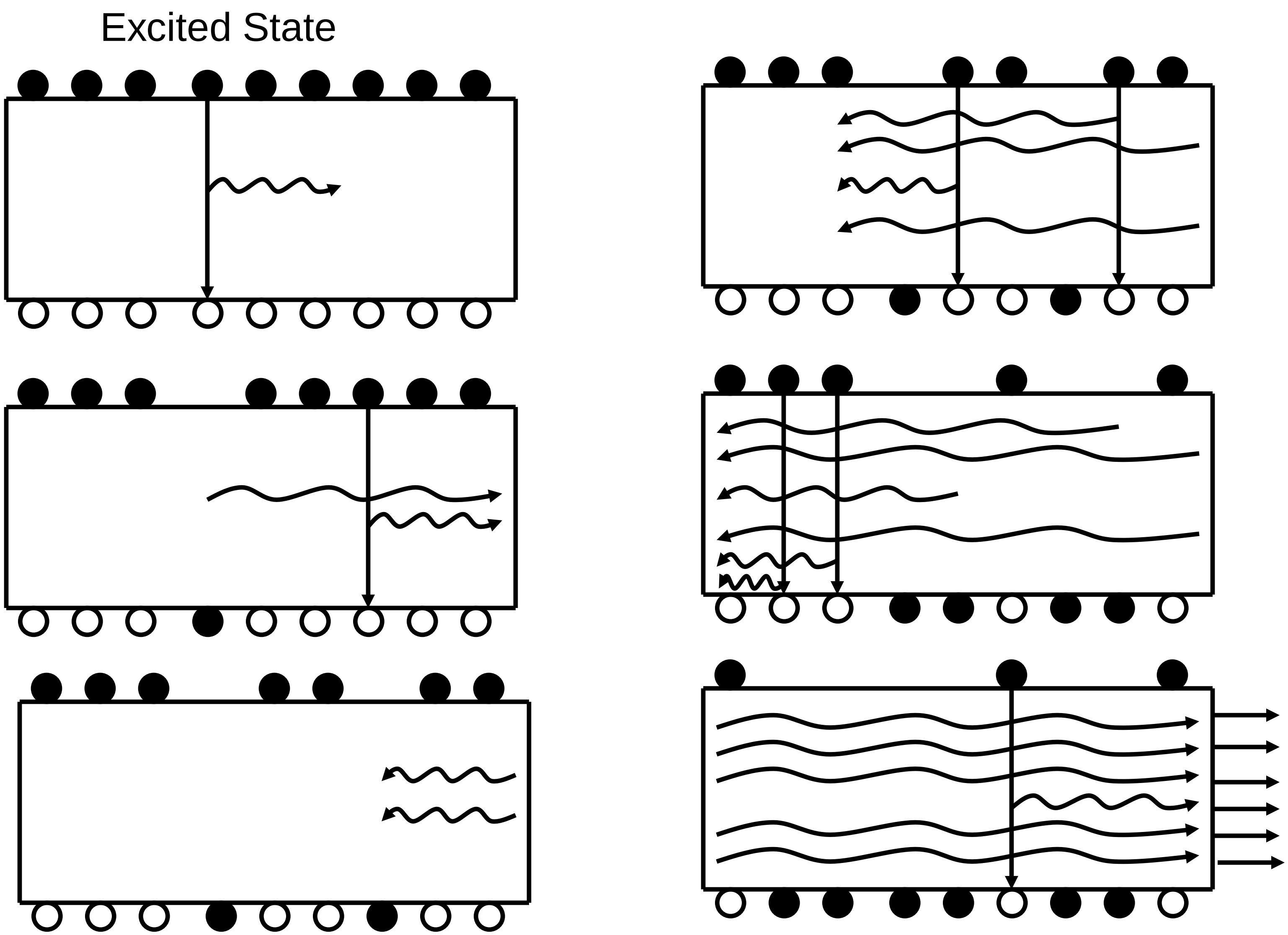
- If one of the atoms emitted spontaneously, then the emitted photon would stimulate other atoms to emit. These emitted photons would, in turn, stimulate further emission. The result would be an intense burst of coherent radiation

- **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**.

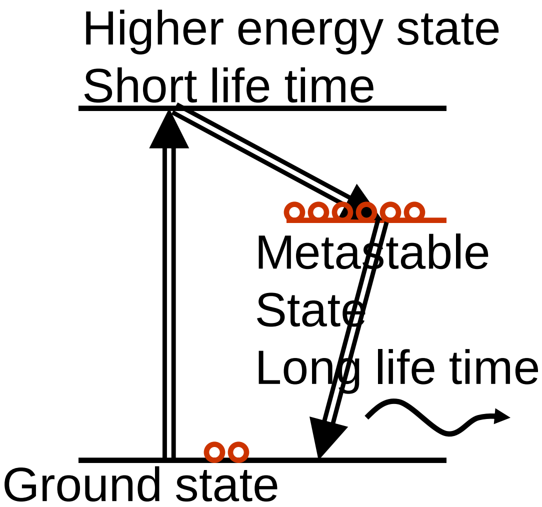
In the process, **any photons which are either not of the correct frequency or do not travel along the optical axis are lost.**

Lasing action

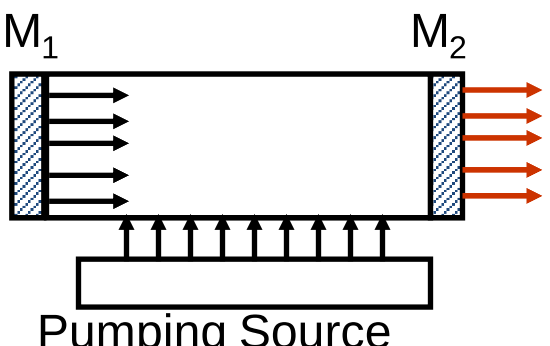


Basic Requirement for Lasing Action :

1. Active medium for amplification: solid, liquid or gaseous – with three or more levels
2. Pumping mechanism for Population Inversion.
   - Optical pumping – using light source like xenon lamp
   - Electrical pumping – high voltage pulse used for gas lasers
   - Direct conversion – pn diode used in semiconductor lasers



3. Stimulating agent
4. Optical Cavity or Resonator
5. Cooling Mechanism – to cool down the active medium
6. Brewstor's Windows: Inclined mirror set for polarized laser beam



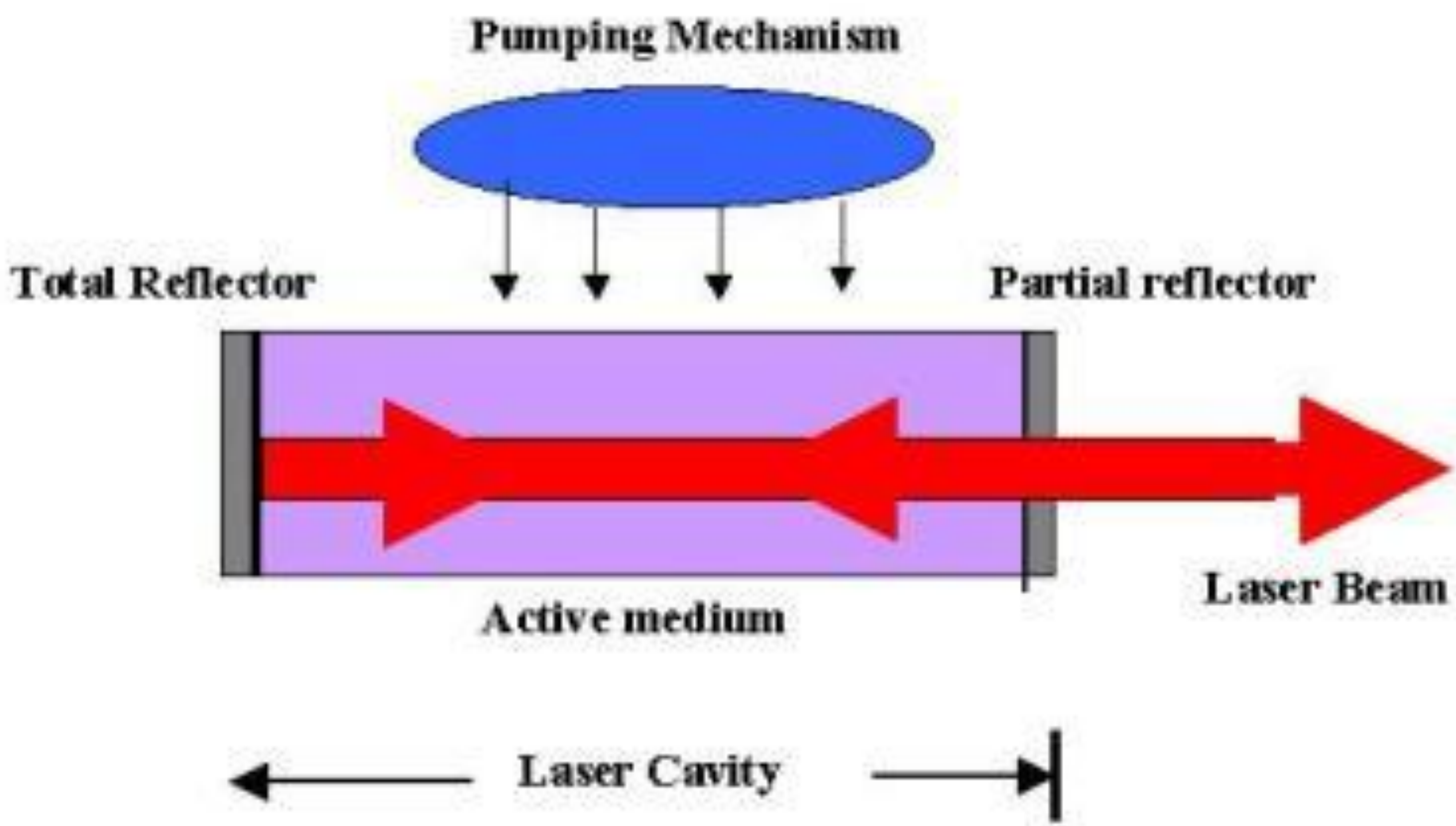


Fig. 2: *Basic Laser System*

Pumping schemes

Two level pumping Scheme

A two level laser is not possible

Let us consider a system with two energy state – excited energy E_2 and ground energy state E_1. Intensity of absorbed light will be:

$$I = I_0 \exp\left[\alpha(N_2 - N_1)z\right] = I_0 \exp\left[\alpha N\left(1 - \frac{2N_1}{N}\right)z\right]$$

$$\begin{aligned} where\ N_2 &= no.\ of\ \ atoms\ in\ E_2 \\ N_1 &= no.\ of\ \ atoms\ in\ E_1 \\ N &= N_1 + N_2 \end{aligned}$$

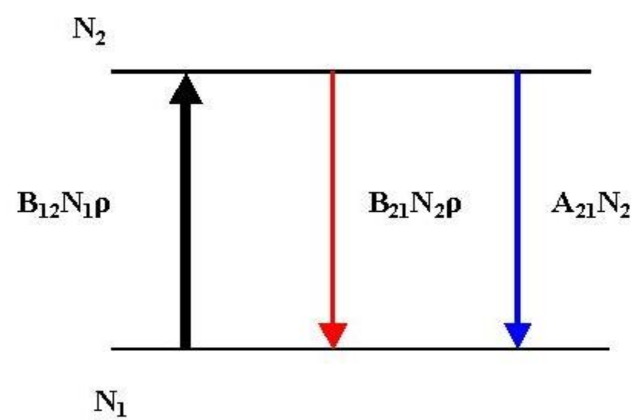


Fig 1: *Spontaneous and stimulated processes in a two-level system*

Initially, N_1 /N=1, I(z)<I_0 & there is absorption
As absorption continues N_1/N decreases from 1.
When N_1/N=1/2, I(z) = I_0 and no further absorption is possible.
So for a two level system, population inversion (N_1/N < ½) is not possible.
For population inversion, at least three level system with one metastable level with large life time is needed.

Three level pumping Scheme

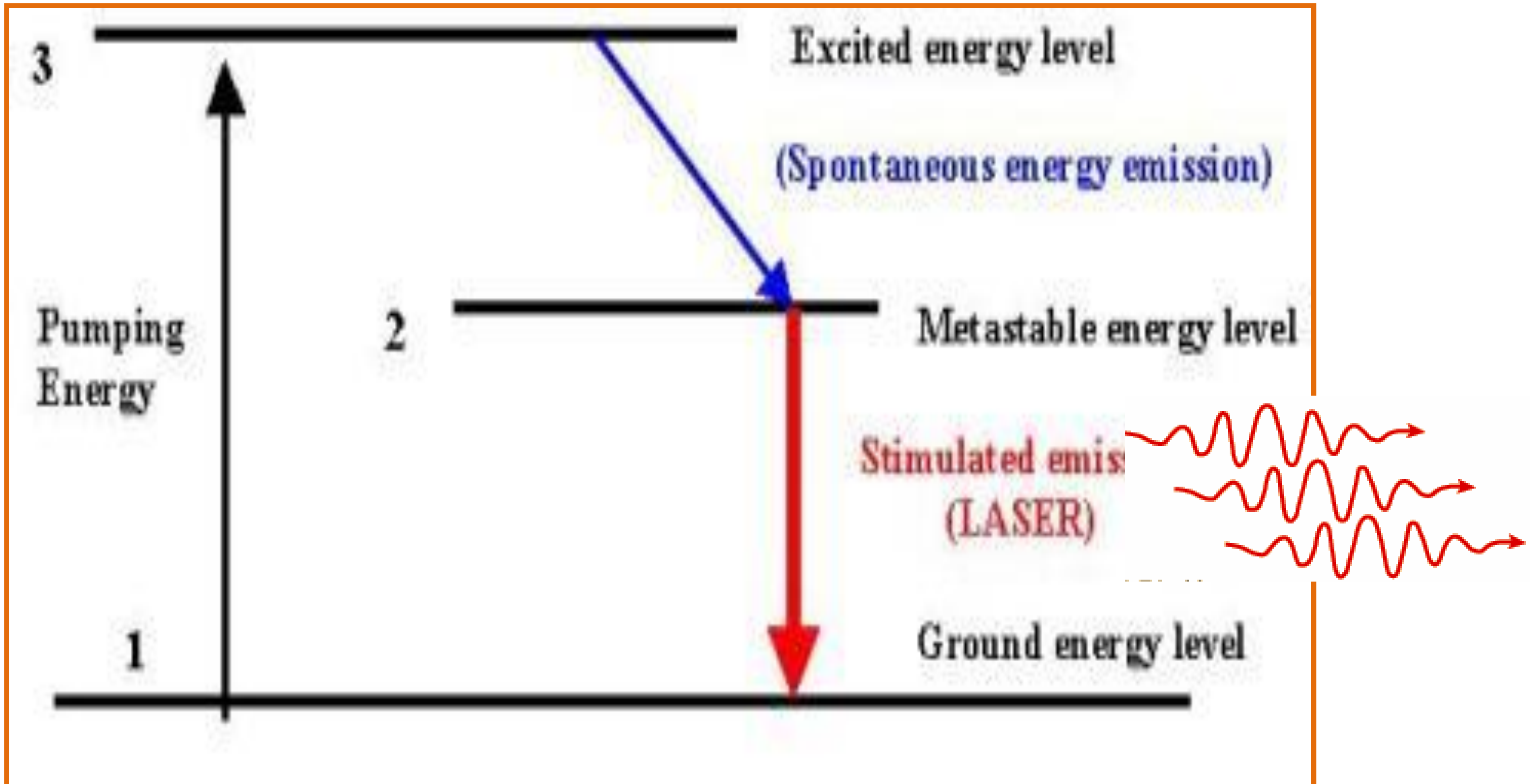


Fig. 3a: *Energy States of Three – level Active Medium*

E_2-E_1≈ k_β T
1- Ground state and lower laser level
2- Upper laser level and metastable state
3- Pump level

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

Four level pumping Scheme

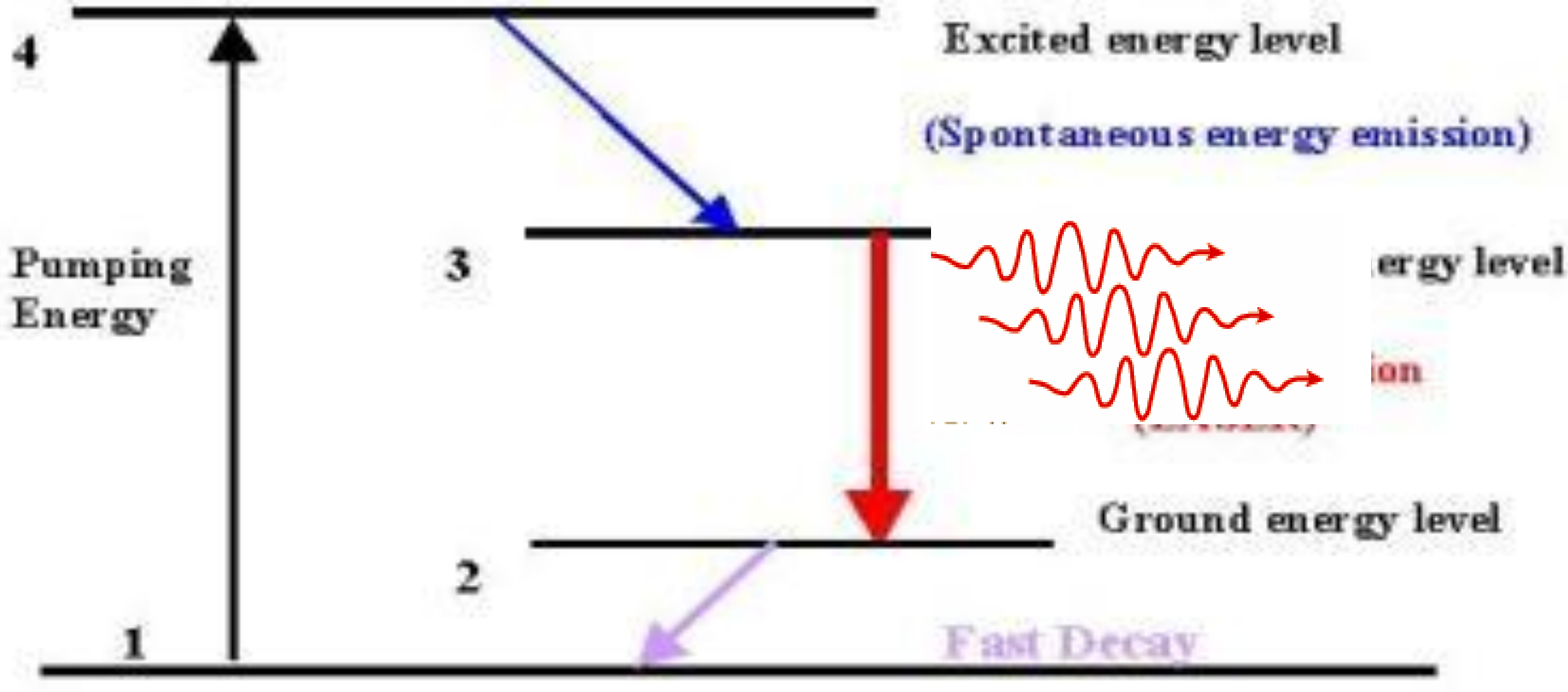


Fig. 3b: *Energy States of Four – level Active Medium*

E_2-E_1 >>> k_β 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,

1) **Pumping energy is less**

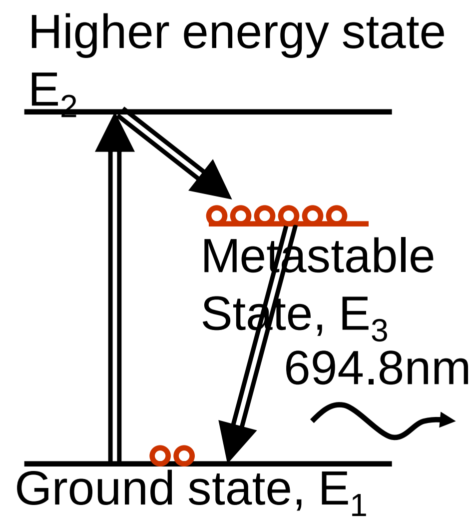
&

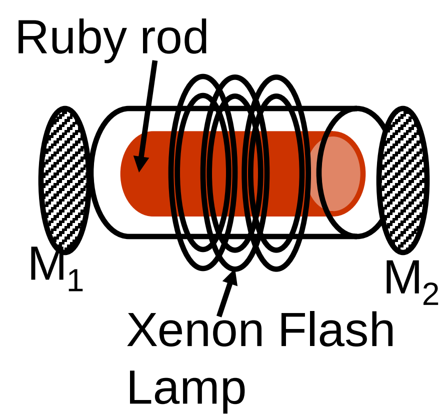
2) **output in continous mode (CW)**

Ruby Laser: **(1960)**

Medium: Cr^{3+} doped Al_2O_3 crystal
Pumping: Helical Xenon flash lamp (optical pumping)
Optical Cavity: M_1 – 100%, M_2 – 90%

- Optical pumping takes electrons to the metastable state causing population inversion.
- Photons (λ = 694.8nm) produced by stimulation travels in the optical cavity causing further stimulated emission increasing the number of photons.
- When number of photons reach a threshold value, laser beam comes out of M_2.





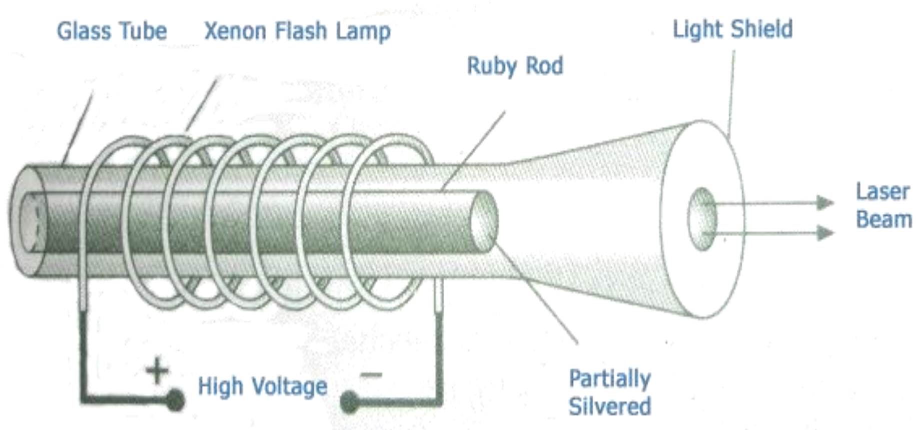
Laser Power:

Pulsed laser – Energy ~ 1MW (P),

Duration -10-100 nsec

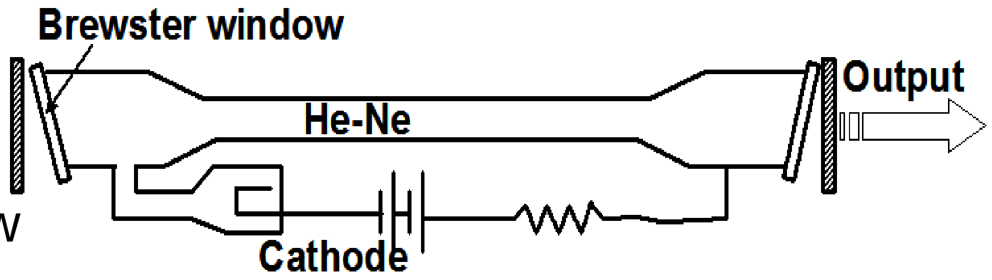
Application:

- Distance measurement using pulse echo technique
- Drilling
- Pulse holography
- Plasma production in fluoresence spectroscopy



He-Ne Laser:

Medium: He-Ne (10:1 ratio) gas
Pumping: DC or RF discharge
Optical Cavity & Brewster window



Ne atoms get excited to E_3 due to collision with He atoms.
Different transition in the Ne atom energy states produce light at 632.8nm, 1.15μm and 3.39μm.
Since the gas container is glass or quartz, only light of 632.8nm wavelength comes out.

Output Power : 0.5 – 100 mW Continuous Wave (CW)

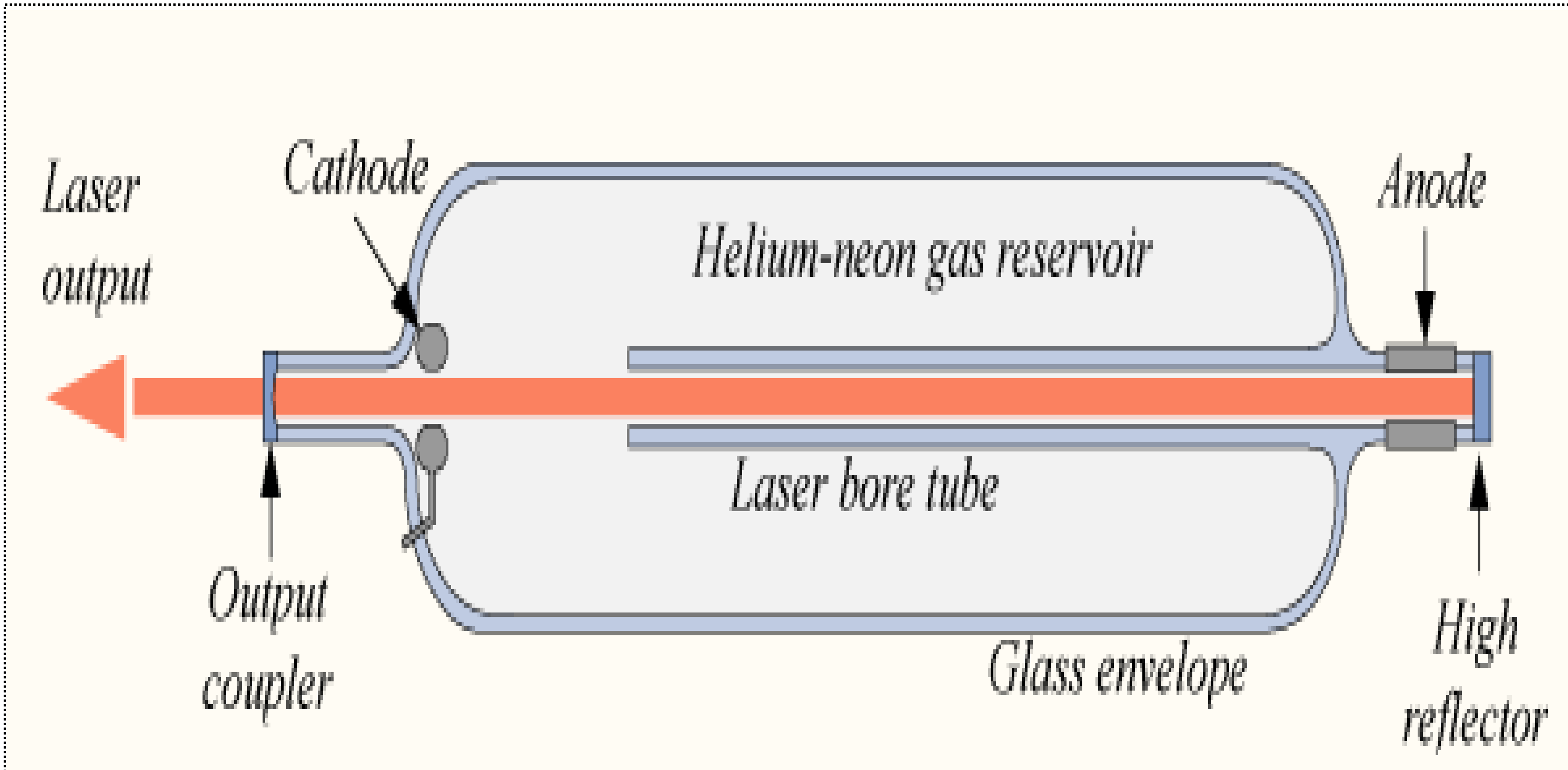
<u>Application:</u>
Barcode reading, Laser interferometry, Holography, Metrology

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.

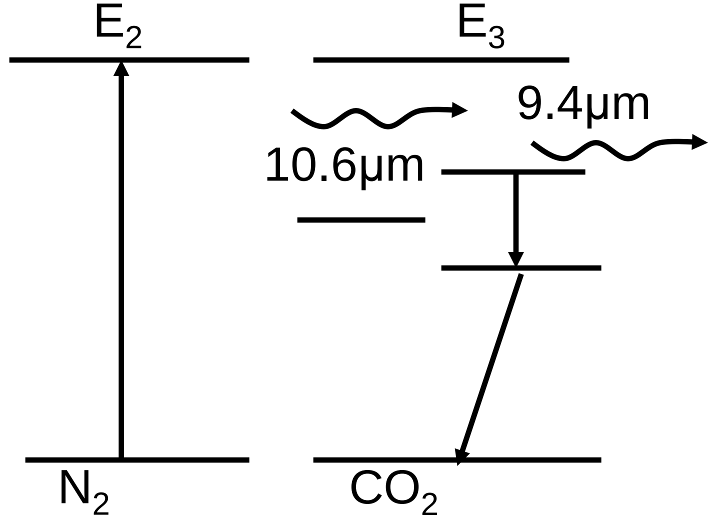
•HeNe lasers are normally small, with cavity lengths of around 15 cm up to 0.5 m, and optical output powers ranging from 1 mW to 100 mW.



CO_2 Laser: (C K N Patel, Bell Lab, 1964)

Medium: CO_2 gas mixed with small amounts of N_2 and He (1:4:5 ratio)
Pumping: Electric discharge (optical pumping)
Optical Cavity: With Brewster window

Energy levels are due to various modes of vibration of CO_2 molecule.
N_2 excites the CO_2 to excited state.
He increases efficiency of 10.6μm emission.
Output Power :
100 W Continuous Wave Mode (CW)
A few KW in Pulsed mode (P)



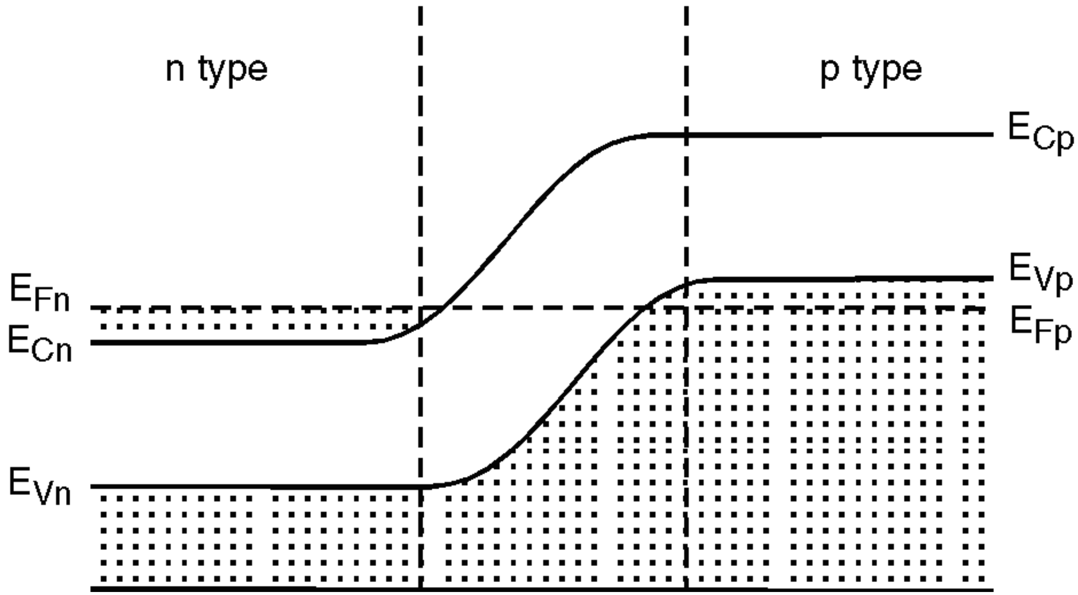
Application:
Material Processing (Melting, welding, etc.)
Bloodless surgery

Semiconductor laser

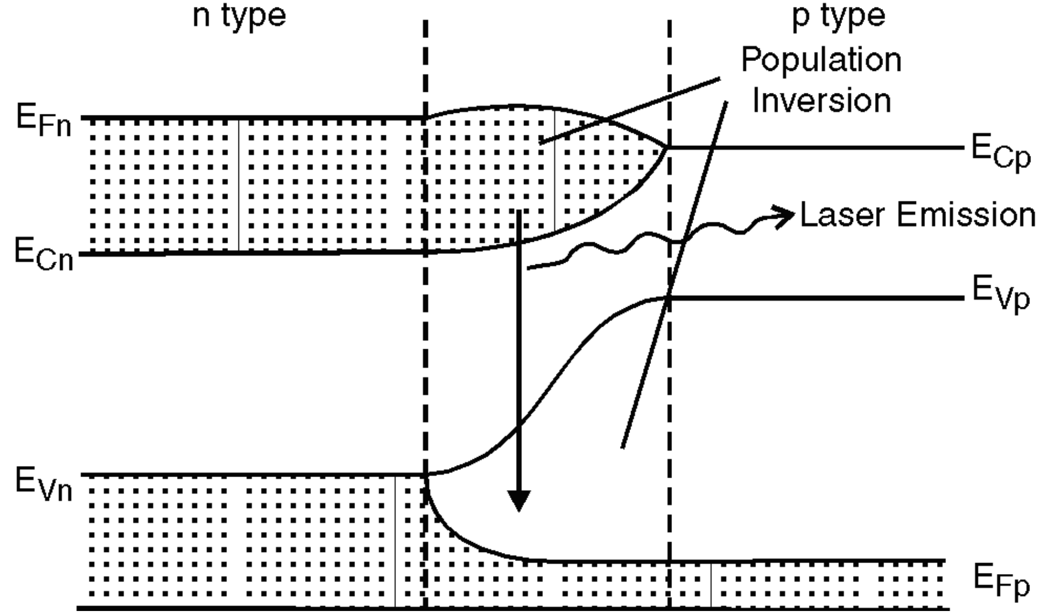
- Small size, so portable
- Inexpensive
- Driven by electrical current and less power requirement
- Efficient

Used in

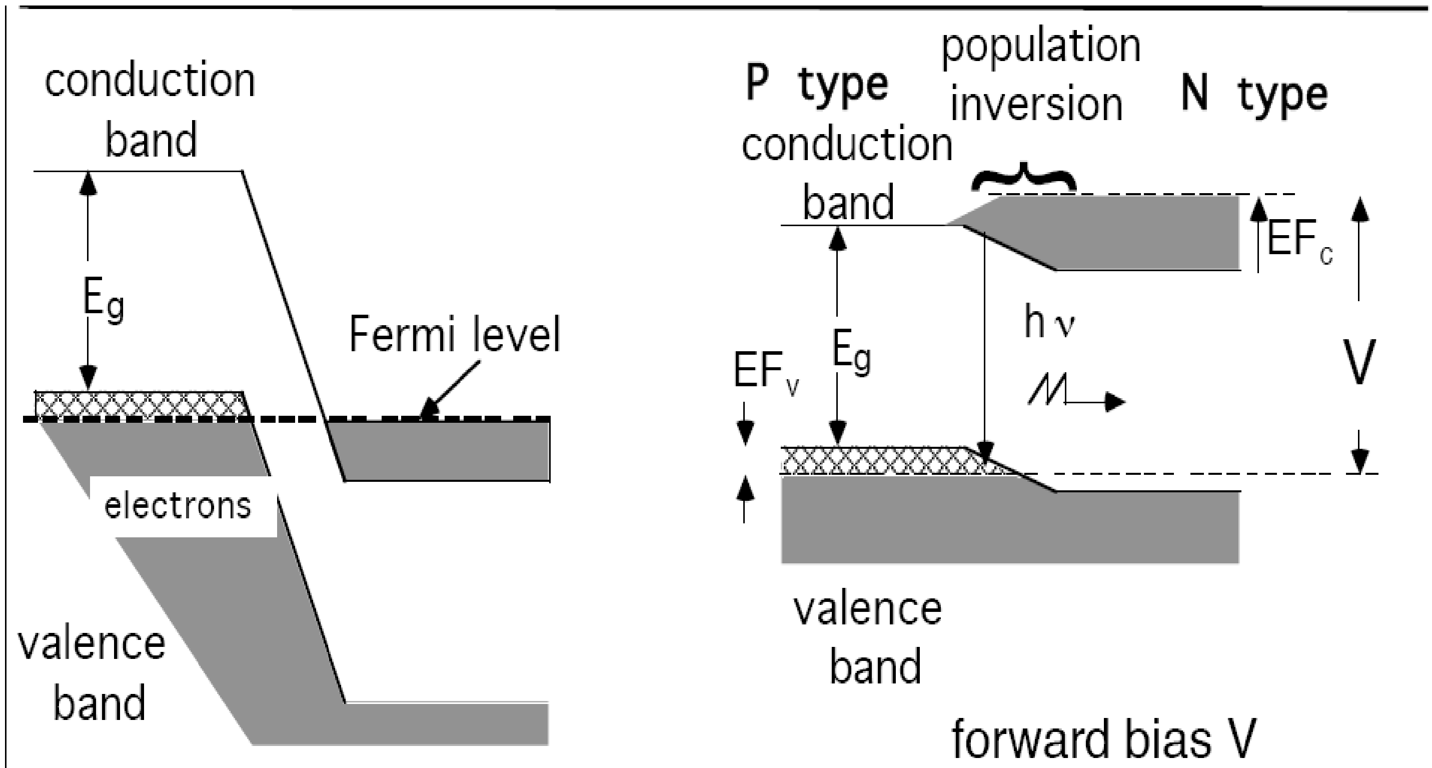
- ➢ Information transmission:- optical fibre communication system
- ➢ Information storage:- audio, video, optical disk data storage
- ➢ Information collection & processing:- scanner, laser printer



NO BIASING

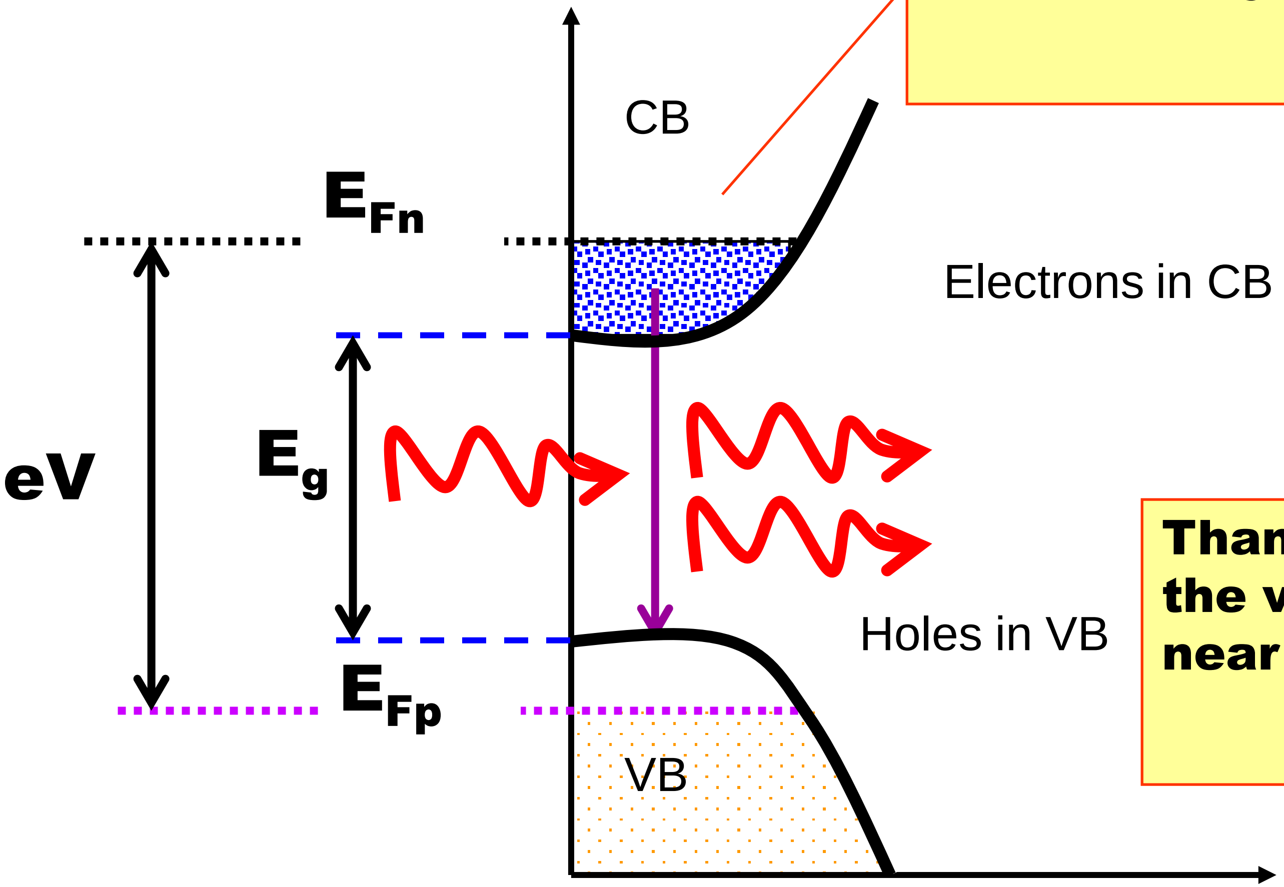


FORWARD BIASING



no bias, V=0

Carriers can diffuse and are poorly confined

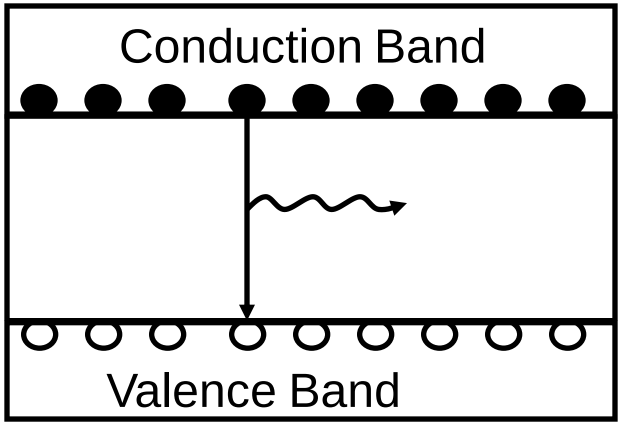


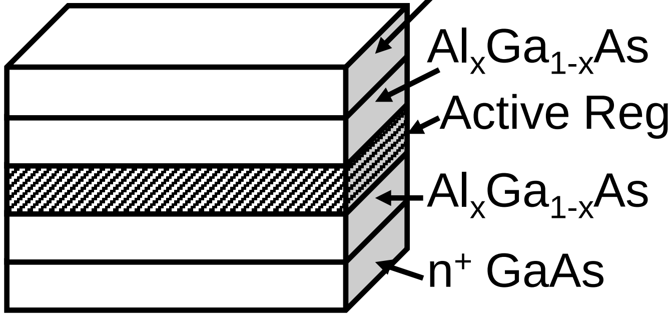
More electrons in the conduction band near E_c

Than electrons in the valance band near E_v

Semiconductor Laser:(R.Hall,1962)

Medium: $Ga_{1-x}Al_xAs$
Pumping: p-n junction

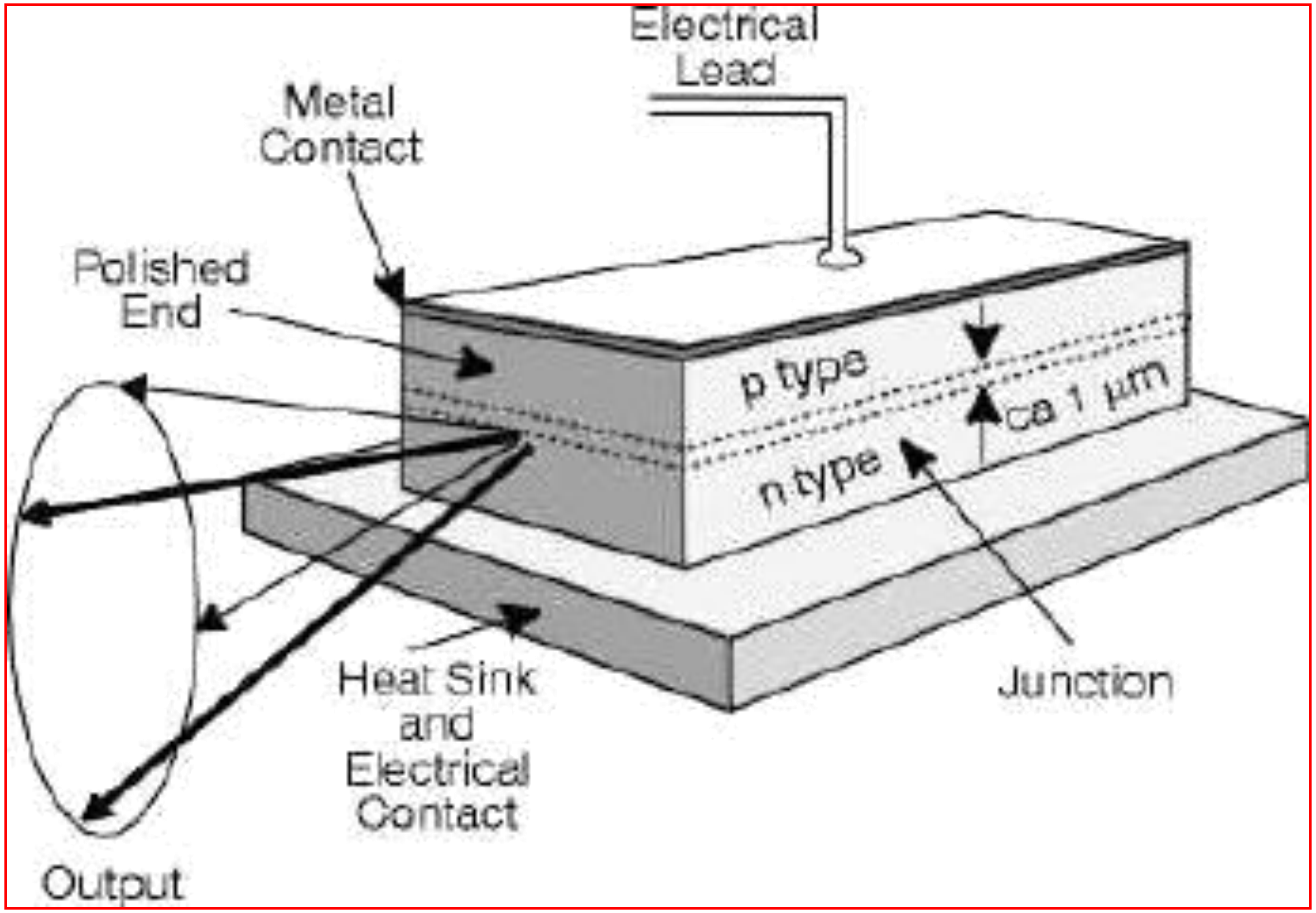




Multi-layered p-n junction laser diode structure

Population inversion is achieved through the p-n junction by applying a voltage across the junction.
Mirrors are present on the two faces of the active region.
AlGaAs laser – 650-900 nm, 1-10 mW (CW)
Application : CDROM, Video disk, Optical Communication

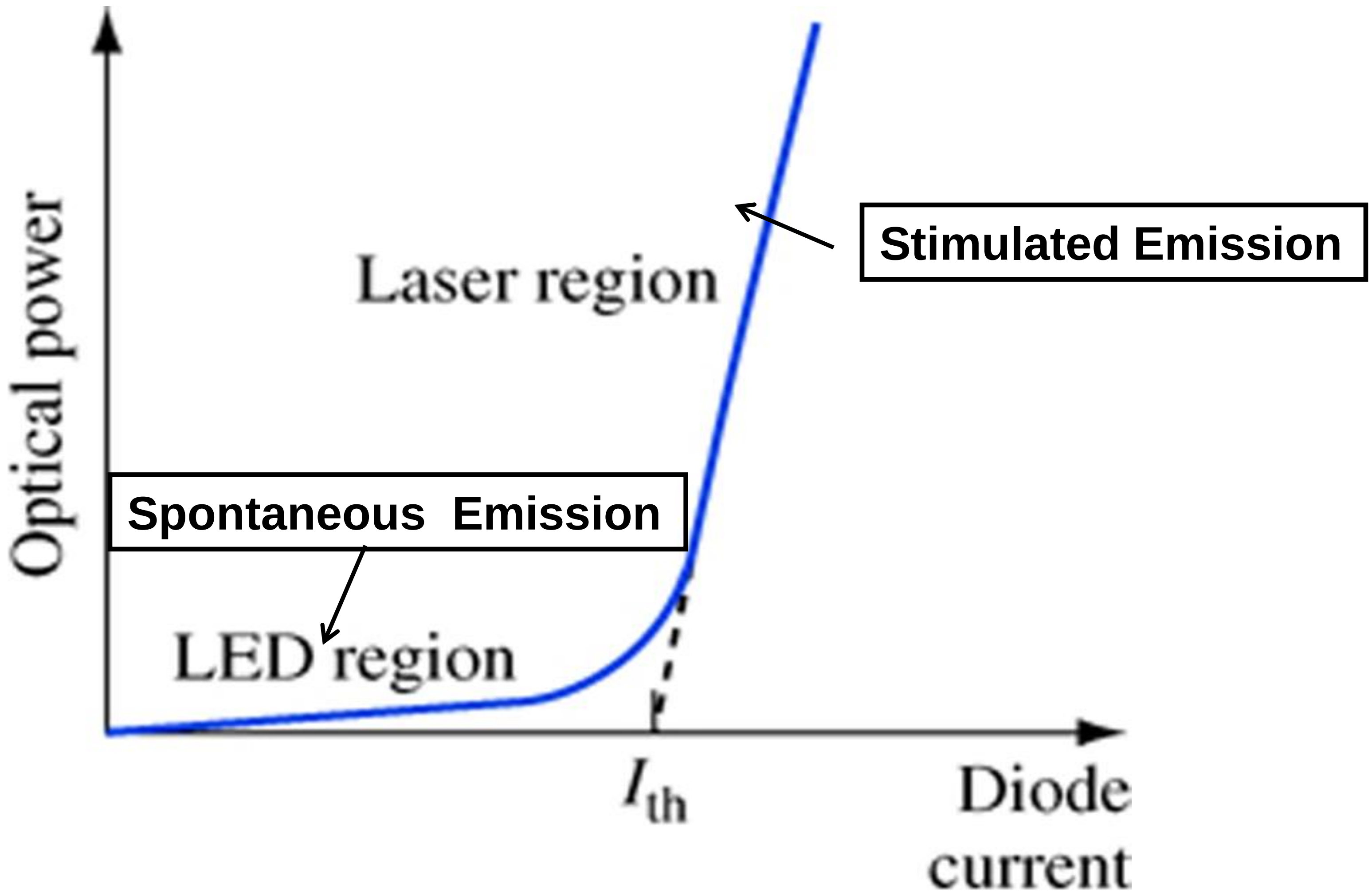
- Suppose that the degenerately doped p-n junction is forward biased by a voltage greater than the band gap; $eV > E_g$
- The separation between E_{Fn} and E_{Fp} is now the applied potential energy
- The applied voltage diminished the built-in potential barrier, eV_o to almost zero.
- Electrons can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



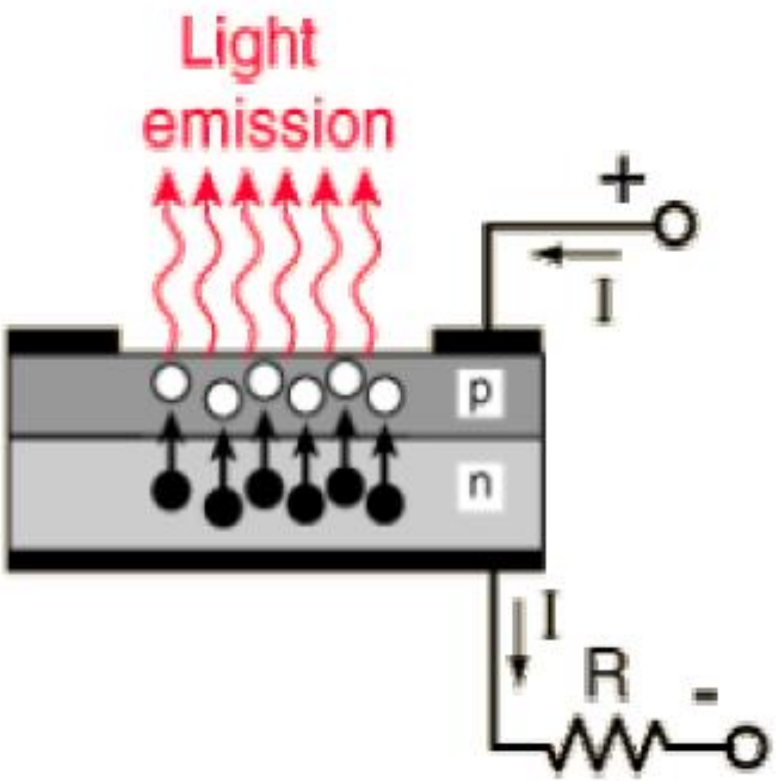
Condition for emitted radiation:- $h\nu \geq E_g = E_c - E_v$

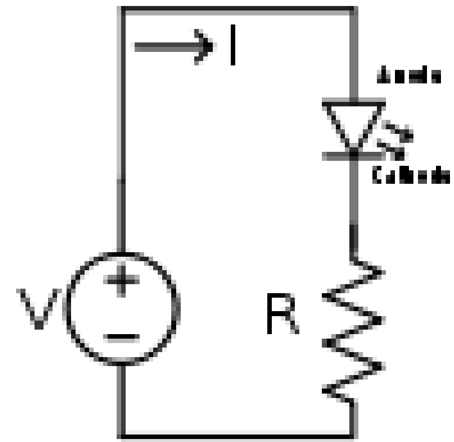
For driving (forward biasing) current < I_{th} :- spontaneous emission ---- LED(light emitting diode)

For driving (forward biasing) current >I_{th} :- stimulated emission ---- LD(laser diode)



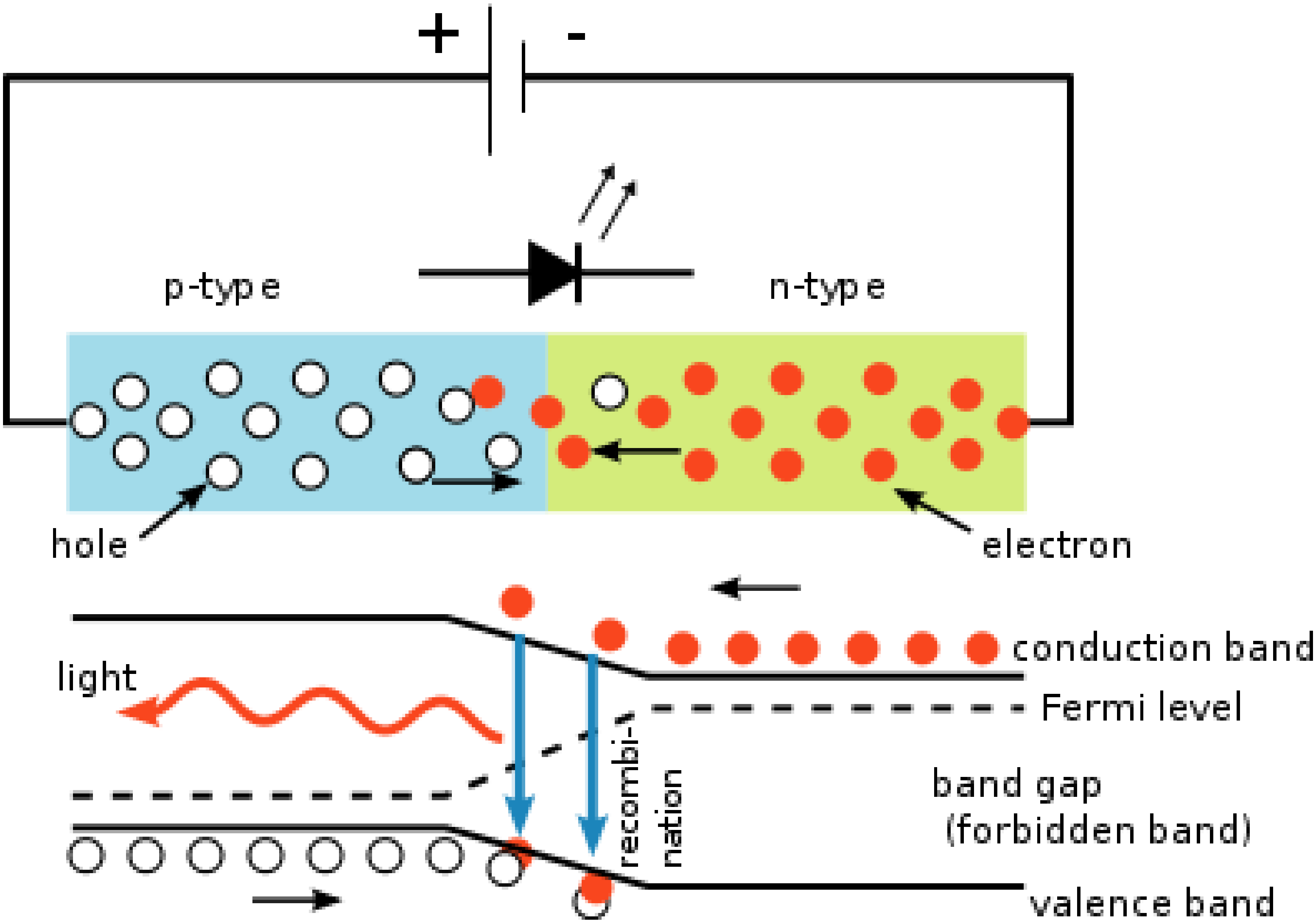
LIGHT EMITTING DIODE





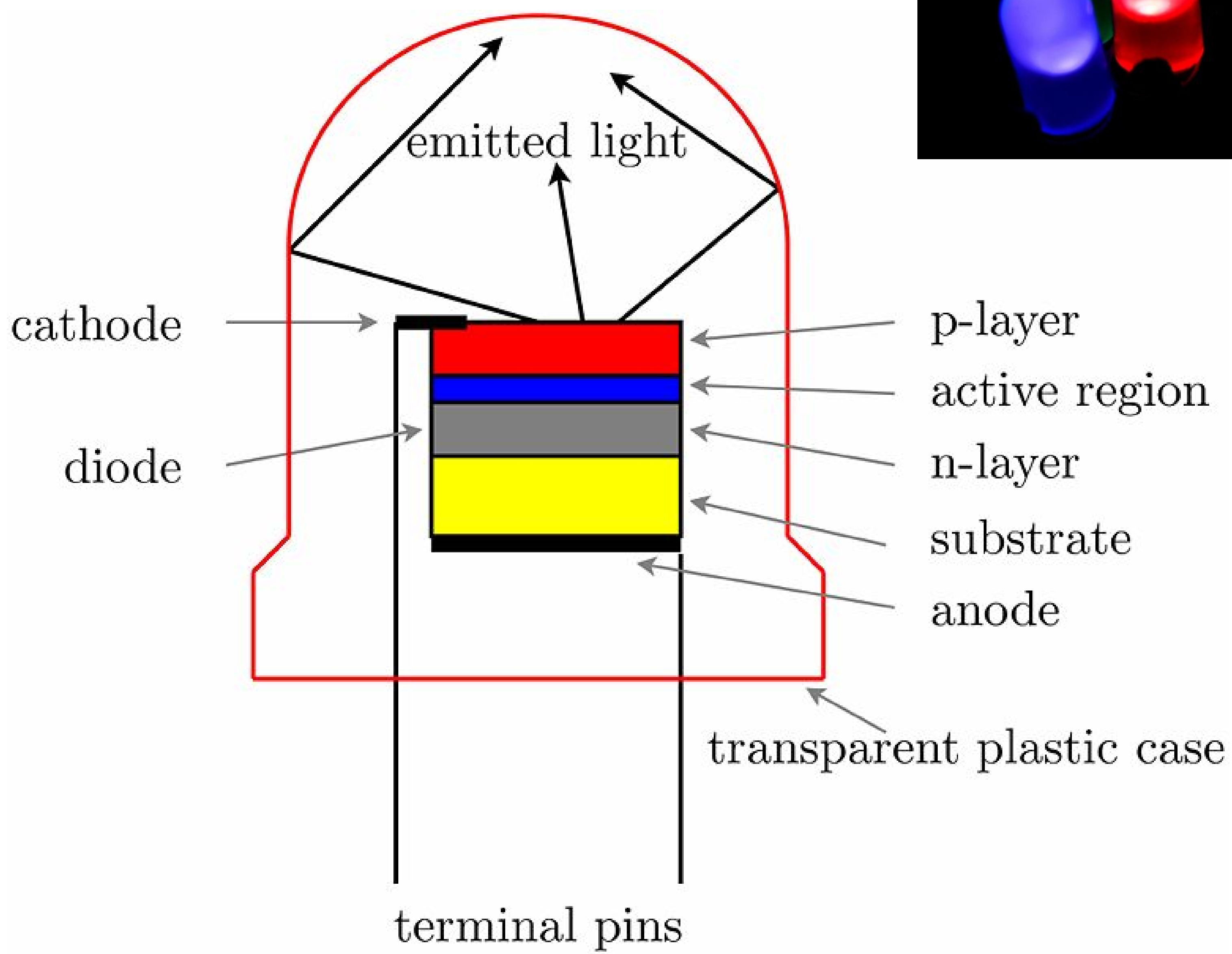
As $\lambda = hc / E_g$

GaAs—IR
GaAsP—Red / Yellow
GaP--- Green
GaN---Blue



+
-
p-type
n-type
hole
electron
light
conduction band
Fermi level
recombi-
nation
band gap
(forbidden band)
valence band

LED


emitted light
cathode
diode
p-layer
active region
n-layer
substrate
anode
transparent plastic case
terminal pins

Lased diode (LD)	Light Emitting Diode (LED)
1. Forward biased p-n junction	1. Forward biased p-n junction
2. Drive current > threshold current	2. Drive current < threshold current
3. Stimulated emission	3. Spontaneous emission
4. Population inversion and positive feedback provided	4. Population inversion and positive feedback not required
5. Output coherent	5. Output incoherent
6. Directional and less bandwidth	6. Not perfect directional and bandwidth more
7. Costly	7. Less costly
8. Small lifetime	8. Long lifetime

Applications

Laser	Type	λ (μm)	Max. Power Output (W)	Application
He-Ne	Gas	0.6328	0.0005-0.05 (CW)	Communication, recording, playback, holography, metrology
CO_2	Gas	9.6, 10.6	500 – 15000 (CW)	Material processing, Cutting, Scribing, Marking
Ar	Gas	0.488, 0.5145	0.005 – 20 (CW)	Surgery, distance measurement, holography
Dye	Liquid	0.38 – 1.0	0.01 (CW) 10^6 (P)	Spectroscopy
Ruby	Solid	0.694	10^7 (P)	Hole drillling, Holography
Nd-YAG	Solid	1.06	1000 (CW) 2×10^8 (P)	Welding, Hole drilling, Laser evaporation
Diode	Semiconductor	0.33 - 40	0.6 (CW) 100 (P)	Bar code reading, CD and video disk, optical communication, digital watch, mobile phone, 7 segment display, remote control, switch board