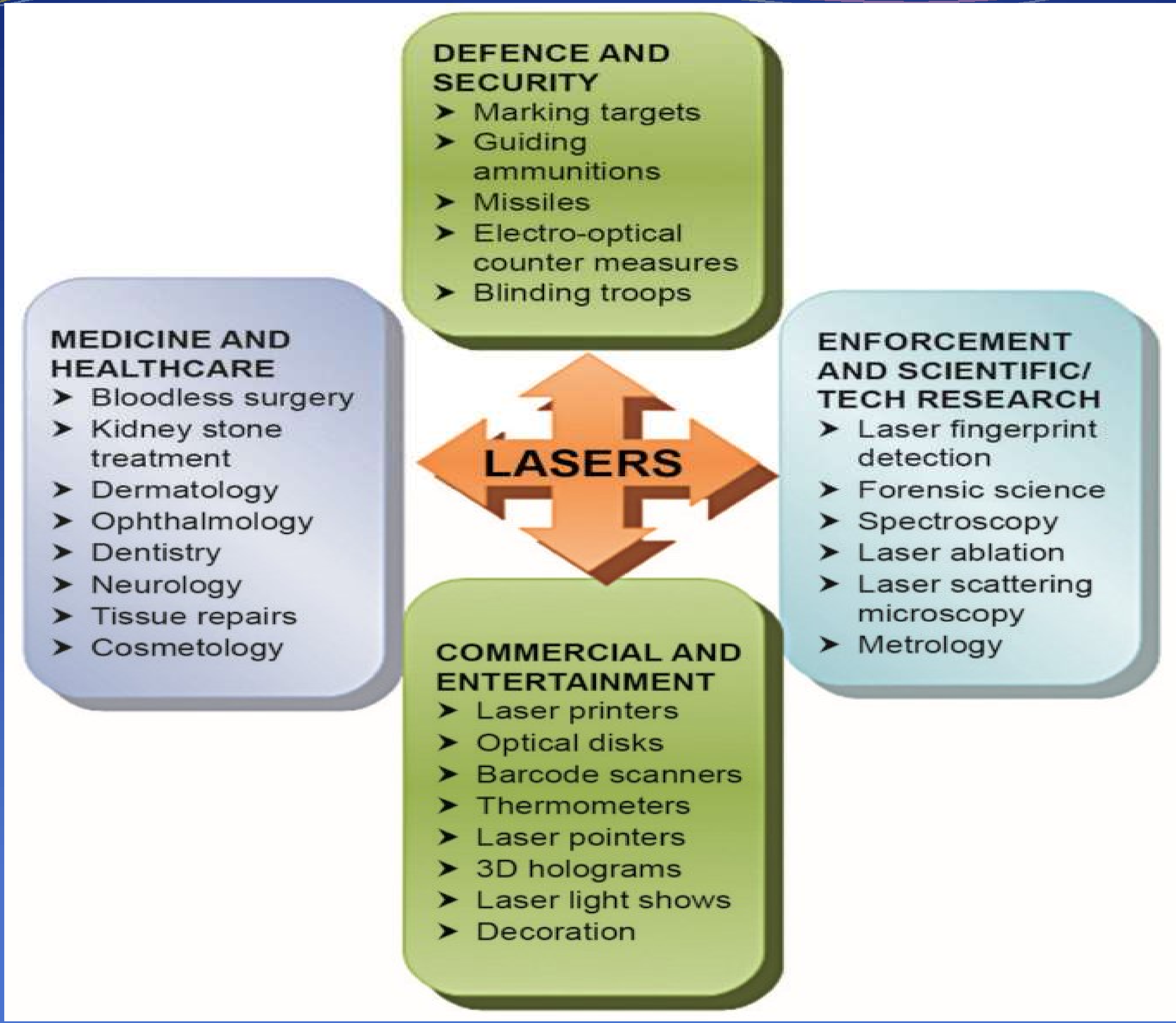
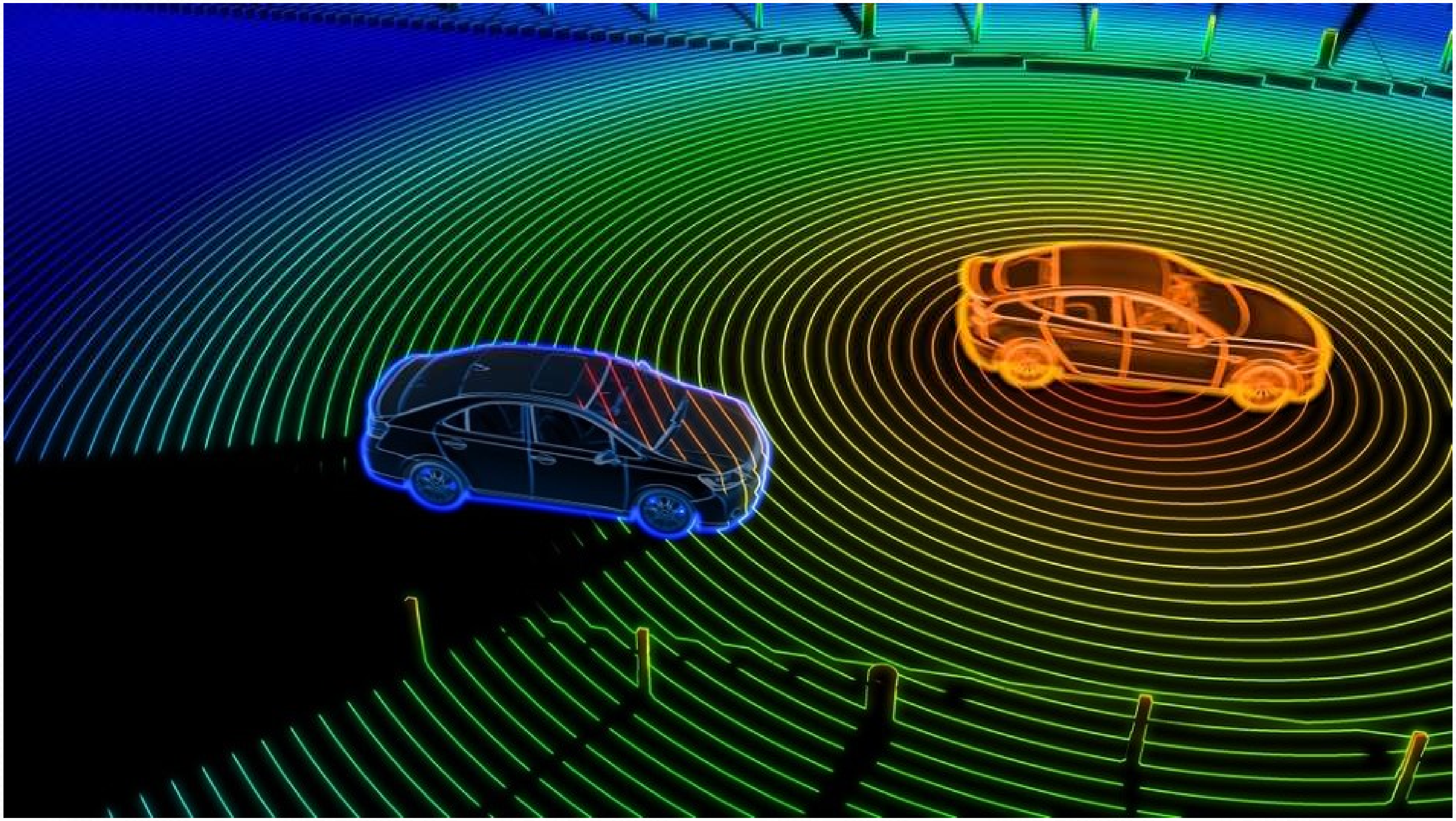
Unit-3

LASER

(Light Amplification due to stimulated emission of Radiations)


DEFENCE AND SECURITY
Marking targets
Guiding ammunitions
Missiles
Electro-optical counter measures
Blinding troops
MEDICINE AND HEALTHCARE
Bloodless surgery
Kidney stone treatment
Dermatology
Ophthalmology
Dentistry
Neurology
Tissue repairs
Cosmetology
LASERS
ENFORCEMENT AND SCIENTIFIC/ TECH RESEARCH
Laser fingerprint detection
Forensic science
Spectroscopy
Laser ablation
Laser scattering microscopy
Metrology
COMMERCIAL AND ENTERTAINMENT
Laser printers
Optical disks
Barcode scanners
Thermometers
Laser pointers
3D holograms
Laser light shows
Decoration



Interaction of Radiation with Mattar

1)Absorption

2) Spontaneous Emission

3) Stimulated Emission

Thermal Equilibrium

❖Material medium can be considered as composed of identical atoms characterized by specific system of energy levels

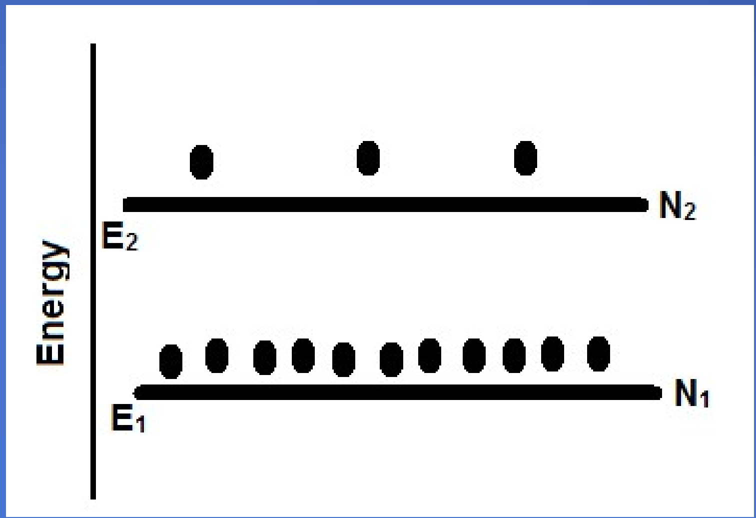
❖These energy levels are identical for all atoms in the medium.

❖**Population** : The number of atoms per unit volume that occupy a given energy level is called the population of that energy level.

➢ Assumption: Particular medium has atoms, which are characterized by only two energy levels.

➢E_1 be ground level with population N_1

➢E_2 be Exited level with population N_2



At thermal Equilibrium, the population at the energy levels can be found with Boltzmann Law

$$N_1 = e^{\frac{-E_1}{KT}}$$

$$N_2 = e^{\frac{-E_2}{KT}}$$

Relative population N_2 / N_1 is given by

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

✓ N_2 / N_1 depends on

a) Temperature

b) $(E_2 - E_1)$

Effect of Temperature

$(E_2 - E_1)$=10.21 eV

T= 300K

$$\frac{N_2}{N_1} = e^{\frac{-(10.21)}{0.025}} \cong 0$$

T= 6000K

$$\frac{N_2}{N_1} = e^{\frac{-(10.21)}{0.516}} \cong \frac{4}{10^{10}}$$

<u>Even at very high temperatures the fraction of excited atoms is very small</u>

❖ <u>Under normal conditions(at Thermal Equilibrium)</u>

$N_1 >> N_2$

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Even at very high temperatures the fraction of excited atoms is very small

❖ Under normal conditions(at Thermal Equilibrium)

$N_1 >> N_2$

As $T \rightarrow \infty$

$N_2 / N_1 = e^0 = 1$

$N_1 = N_2$

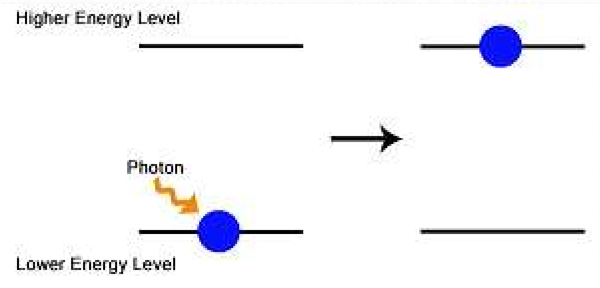
As Long As System is in Thermal Equilibrium the population of higher energy level cannot exceed the population of lower energy level.

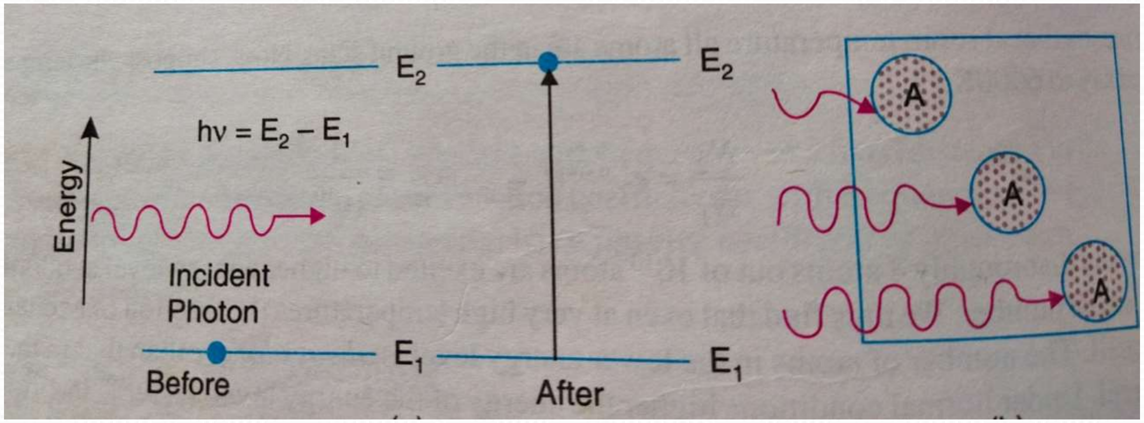
Interaction of Light with Mattar

When Photons travel through medium three different optical processess are likely to occur:

1) Absorption
2) Spontaneous Emission
3) Stimulated emission

Absorption





- When Photon of energy hν is incident on an atom. It may impart its energy to the atom.

- The atom residing in the lower energy state E_1 may absorb the incident photon and make transition to higher energy state E_2

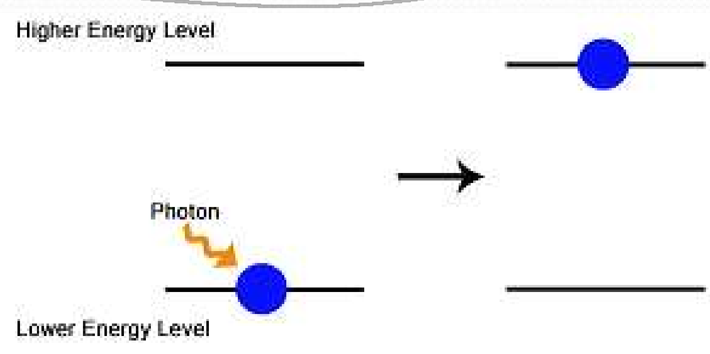
- Transition is called absorption transition or induced absorption.

$$A + h\nu \rightarrow A^*$$

A is atom in lower energy state

A* is atom in excited state

Absorption



Probability of absorption transition is P_{12}

a) Directly proportional to number of atoms in ground state (N_1)

b) Photon density $\rho(\nu)$

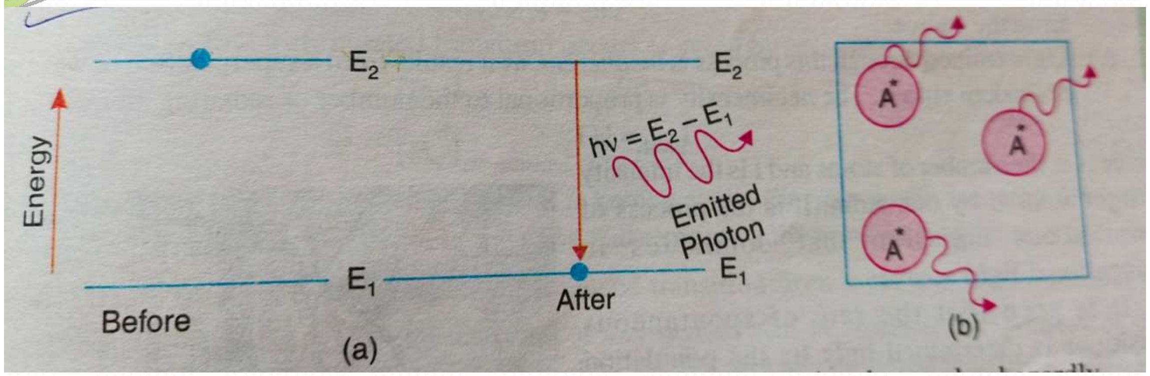
$$P_{12} = B_{12}\ \rho(\nu)$$

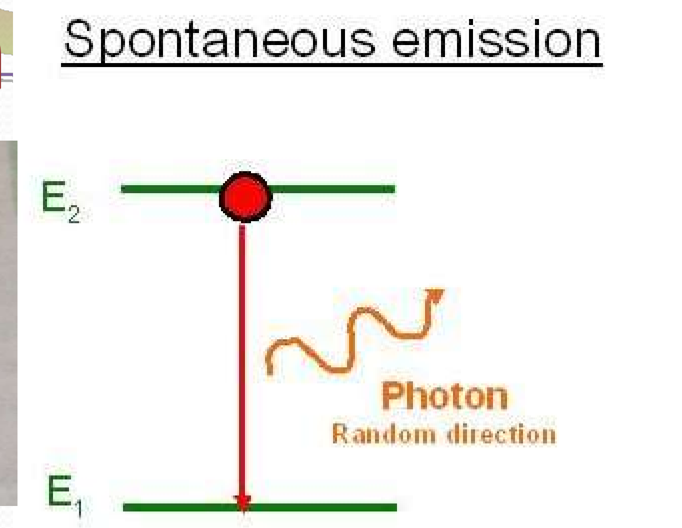
Number of absorption transitions in time Δt

$$N_{ab} = B_{12}\, N_1\, \rho(\nu)\, \Delta t$$

B_{12} = Einstein coefficient for induced absorption (it indicates the probablity of occurrence of induced transition from level $1 \rightarrow 2$

Spontaneous Emission





- ❖An atom in excited state (E_2)make transition to Lower energy state (E_1) by emitting a photon.
- ❖The excited atom in the state E may return to lower energy state E on its own out of natural tendency to attain minimum potential condition.
- ❖During transition the excess energy is released as a photon of energy .

$$h\nu = E_2 - E_1$$

- ❖ This process in which photon emission occurs without any external impetus is called spontaneous emission.
- ❖$A^* \rightarrow A + h\nu$

A is atom in lower energy state

A^* is atom in excited state

Probability of spontaneous emission transition is P_{21}

a) Depends only on properties of energy states E_2 and E_1

$$P_{12} = A_{21}$$

- **Number of spontaneous transitions in time Δt**

$$N_{sp} = A_{21} N_2 \Delta t$$

A_{21} = Einstein coefficient of spontaneous emission (it indicates the probablity of occurrence of spontaneous transition from level $2 \rightarrow 1$

A_{21} is a Characterstics of energy states of an atom

1/ A_{21} represents the lifetime of upper state against spontaneous transition to lower state.

Characterstics of Spontaneous transitions

- **The process of spontaneous emission is essentially probabilistic in nature and is not ameable to control from outside**

- **The instant of transition, direction of propagation, the initial phase and plane of polarization of each photon are all random.**

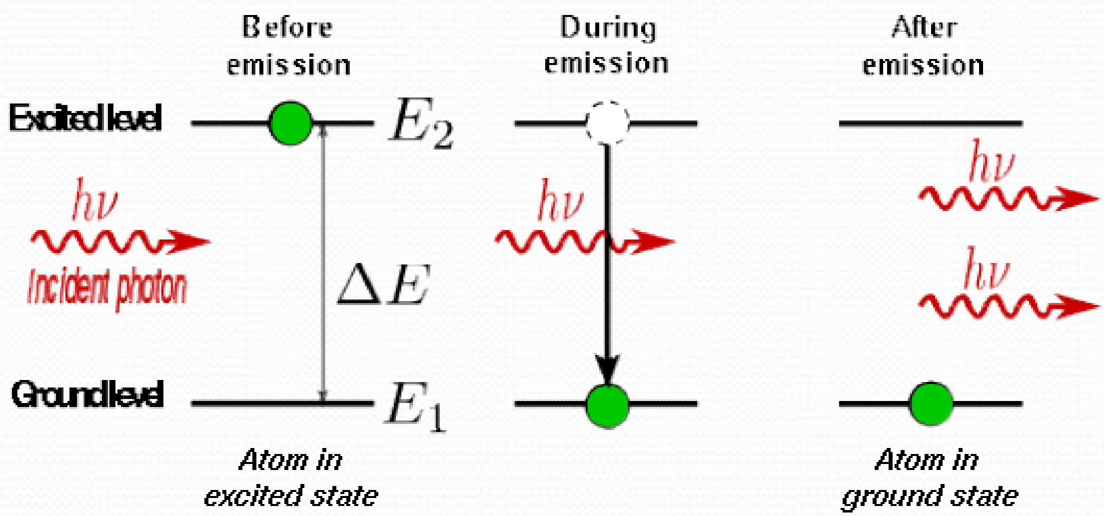
- **The light resulting from this process is not monochromatic**

- **Different atoms in source emits photons in all different directions, the light spreads in all directions around the source. Light intensity goes on decreasing rapidly with distance from the source**

- **Light emitted through this process is incoherent.**

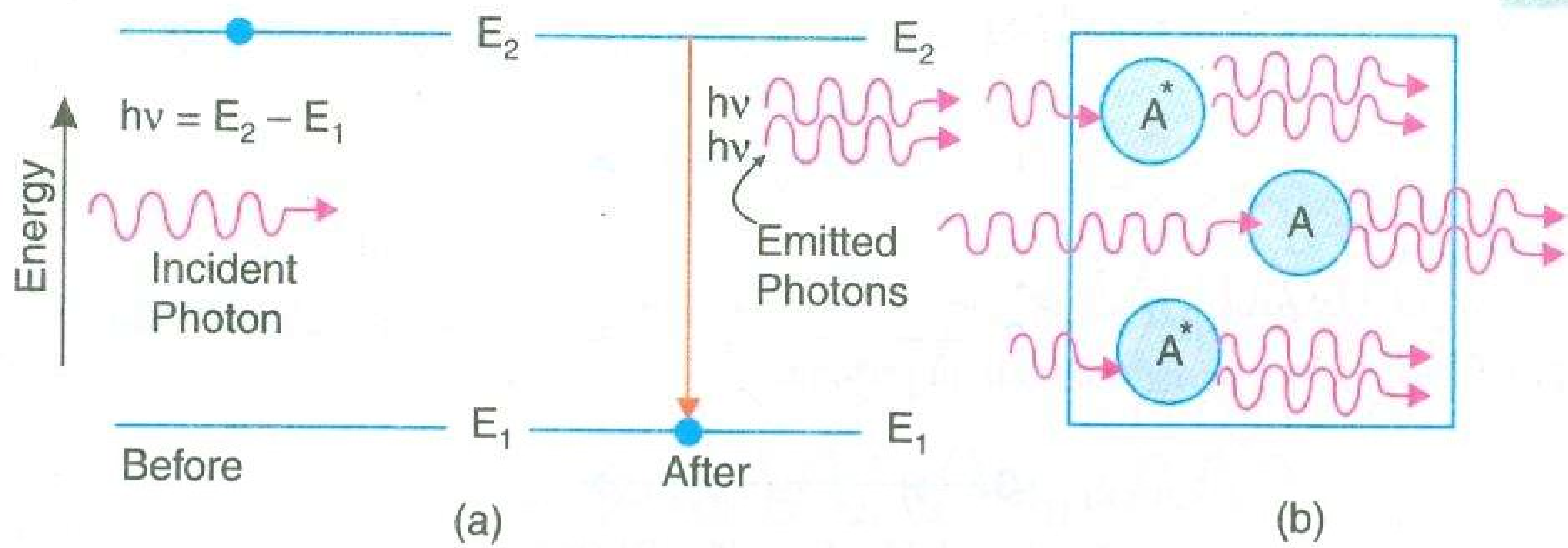
- **Net Intensity is Proportional to number of radiating atoms**
  $I_{net} = NI$

Stimulated Emission



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

The Phenomenon of forced photon emission by an exited atom due to the action of an external agency is called stimulated emission or induced emission.



Stimulated emission (*a*) emission process.
(*b*) Material emits photons in a coordinated manner.

Stimulated Emission

stimulated transition may be represented as

$A^* + h\nu \rightarrow A + 2\,h\nu$

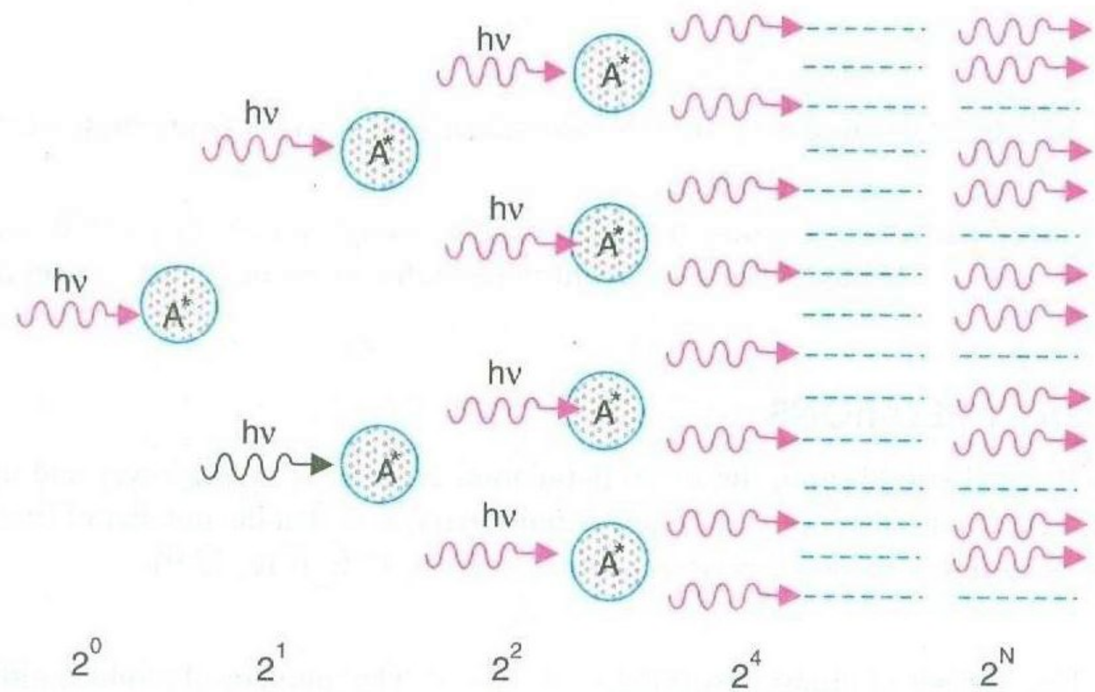
A= an atom in lower state

A^*= excited atom

The number of stimulated transitions N_{st} occurring in the material during the Δt may be given by

$N_{st}=B_{21}N_2\rho(\nu)\Delta t$

Multiplication of stimulated photons

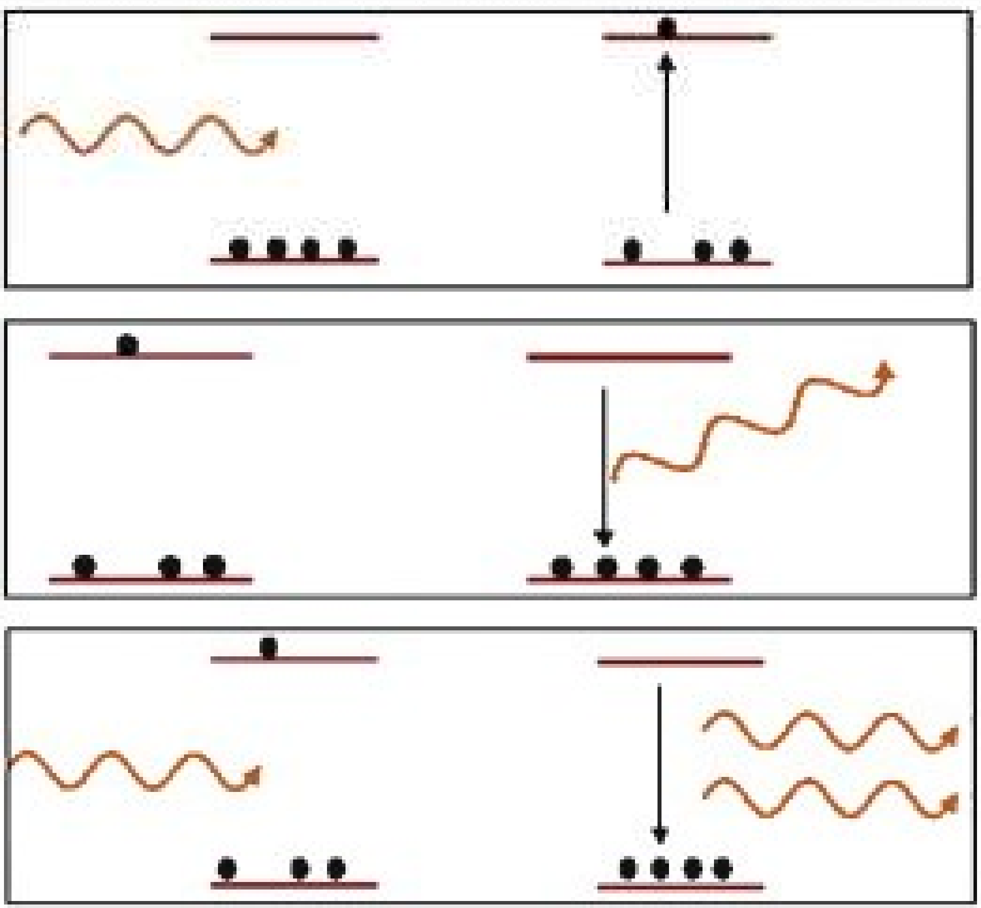


Multiplication of stimulated photons into an avalanche

$I_{total} = 2^N I$

Characterstics of Stimulated transitions

1. Not a Random Process
2. Amenable to control from outside
3. The photons emitted in the process travel in same direction as that of stimulating photon.
4. The emitted photon has same frequency, phase and plane of polarization as that of stimulating photon.
5. Multiplication of photon takes place.
6. electromagnetic waves of extremely high amplitude could be generated by the combined stimulated emmisions from a large samples of atoms leading to amplification of light
7. The process of stimulated emission is the key to the operation of a laser.



Absorption

Spontanous Emission

Stimulated Emission

Conditions for Light Amplification

Light Amplification requires stimulated emission to dominate spontaneous emission.

$$\frac{Stimulated\ emission}{Spontaneous\ emission} = \frac{B_{21} N_2 \rho(\nu)}{A_{21} N_2} = \frac{B_{21}}{A_{21}} \rho(\nu)$$

For Stimulated emissions to dominate Spontaneous Transition

a) Lifetime of energy state should be high

b) ρ (ν) is very large

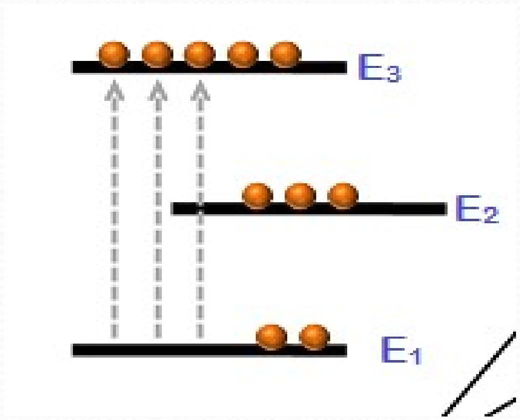
Condition for stimulated emission to dominate absorption transition

$$\frac{Stimulated\ emission}{Absorption\ transition} = \frac{B_{21} N_2 \rho(\nu)}{B_{12} N_1 \rho(\nu)} = \frac{N_2}{N_1}$$

$B_{12} = B_{21}$

For Stimulated emission to dominate Absorption transition

$N_2 >> N_1$



Meeting Requirements for Stimulated emission

- Existence of Metastable state
- Population Inversion
- High Radiation density

Meeting Requirements for Stimulated emission

Existence of Metastable States: Exited state with large lifetime of the order millisecond to microsecond duration.

- **In order to establish the condition of population inversion, the excited atoms are required to 'wait' at the upper energy level till a large number of atoms accumulate at that level, it is necessary that the excited state has a longer lifetime.** ***A metastable state is such a state with lifetime of the order of 10^{-3}s to 10^{-6}s.***
- *There could be no population inversion and hence no laser action, if metastable states do not exists*

Metastable States

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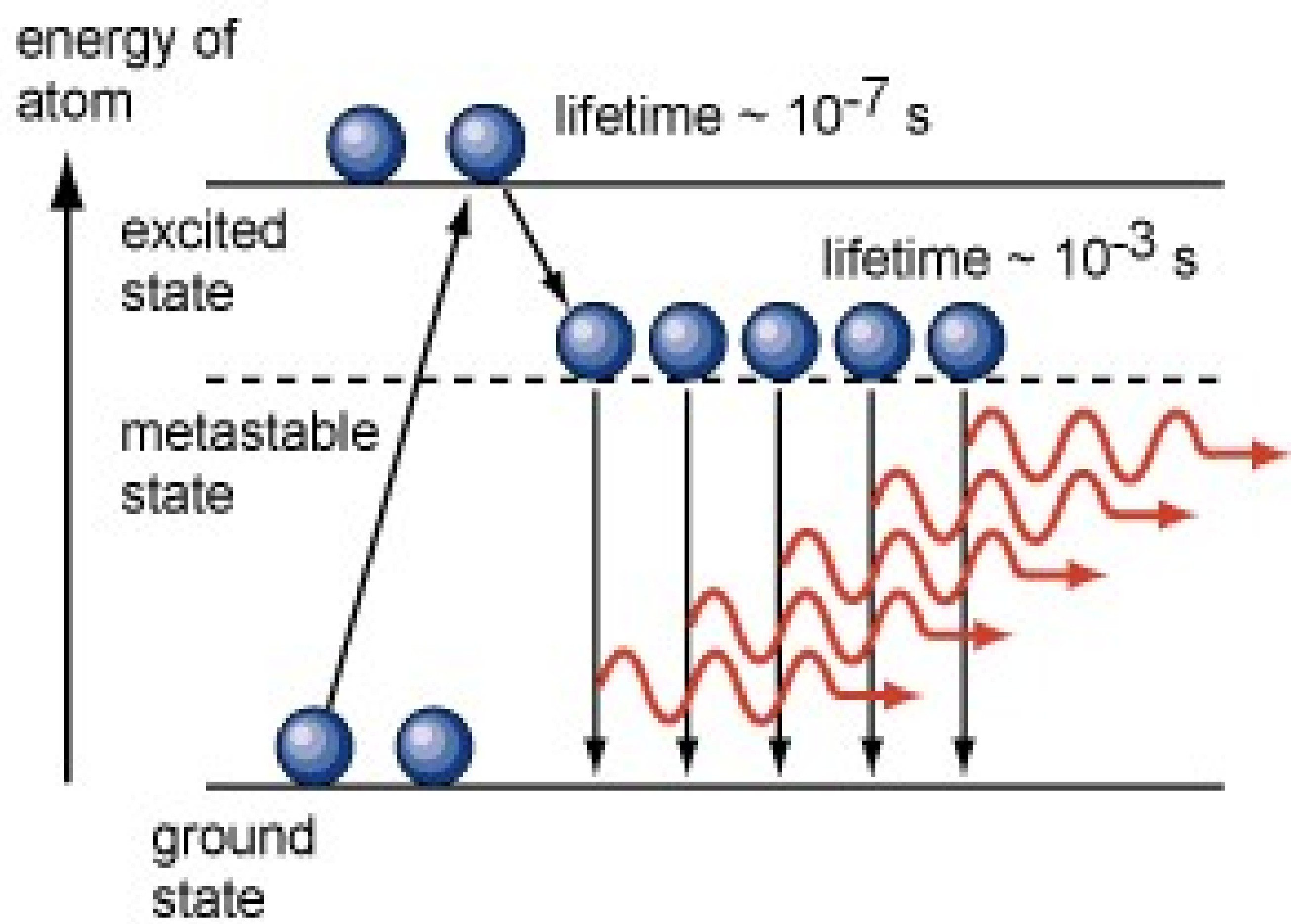

energy of atom
lifetime ~ 10-7 s
excited state
lifetime ~ 10-3 s
metastable state
ground state

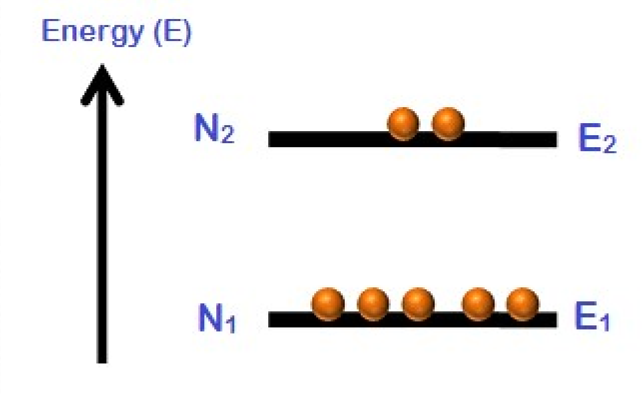
Conditions for Stimulated emission

Population Inversion

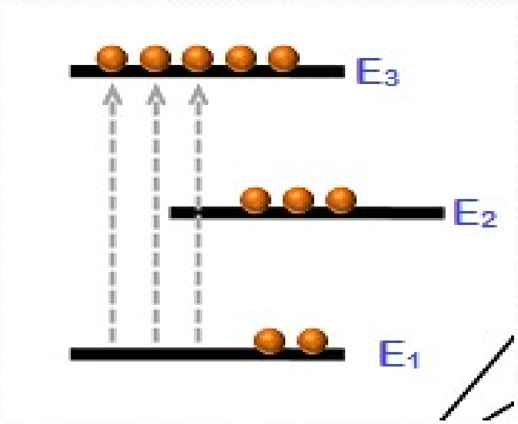
- $N_2 > N_1$ N_2- no. of atoms in E_2
  N_1- no. of atoms in E_1

The condition in which there are more number of atoms in exited state as compared to lower energy state is called population inversion.

This is non equilibrium state and exists for short time.



Normal Energy State
Equilibrium State



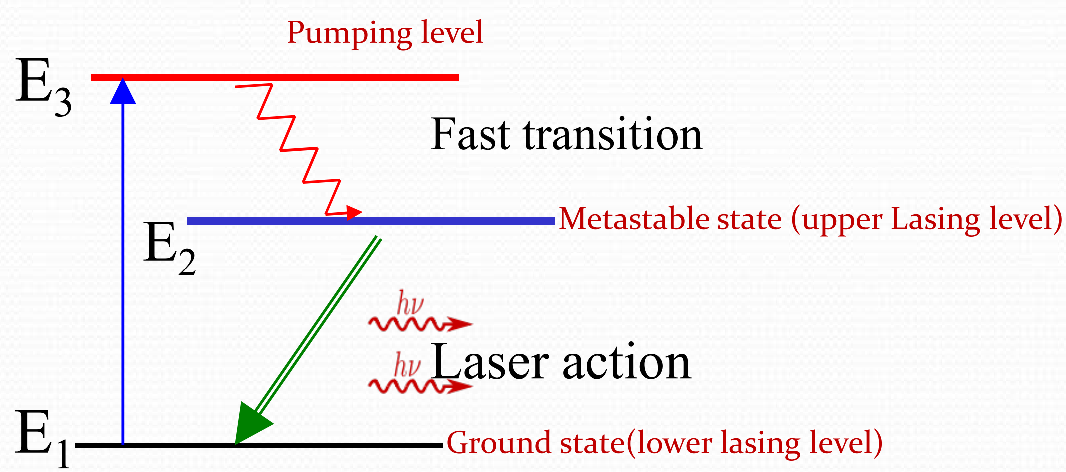
Population Inversion

Population Inversion

- The population Inversion is non equilibrium condition of material in which population of upper energy level N_2 momentarily exceeds population of lower energy level N_1
- It is also referred to as negative temperature state.
- Population inversion is negative temperature state.

The principal Pumping Schemes: Laser Operation

Three level system

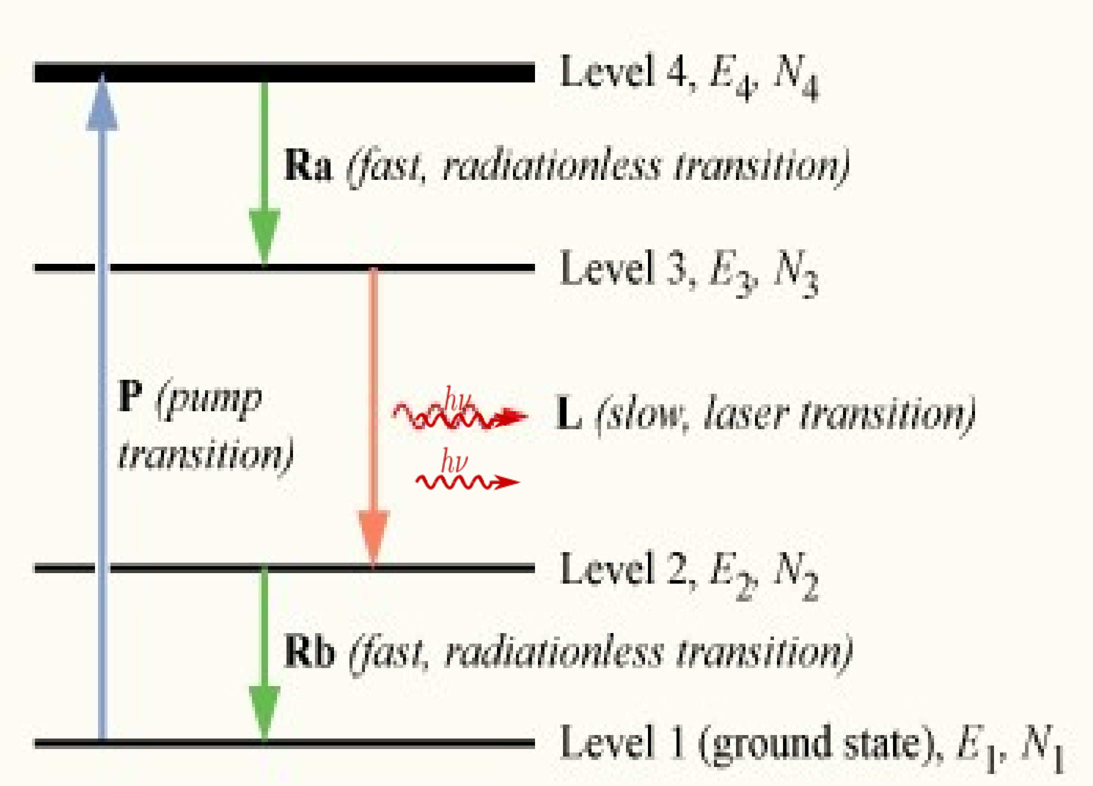


Possible Transitions

- $E_1 \rightarrow E_3$ Pumping
- $E_3 \rightarrow E_2$ Spontaneous emission.
- $E_2 \rightarrow E_1$ Stimulated emission.
- Population inversion between states E_2 and E_1
- State E_2 is a metastable state

The principal Pumping Schemes: Laser Operation

Four level system



Possible Transitions

- $E_1 \rightarrow E_4$ Pumping
- $E_4 \rightarrow E_3$, $E_2 \rightarrow E_1$ spontaneous emission.
- $E_3 \rightarrow E_2$ Stimulated emission.
- Population inversion between states E_3 and E_2
- State E_3 is a metastable state

Two Level System

In a simple two-level system, it is not possible to obtain a population inversion with optical pumping because the rate of absorption becomes equal to rate of

TWO LEVEL LASER NOT POSSIBLE

Optical pumping will at most only achieve equal population of a two-level system. This is because the probabilities for raising an electron to the upper level and inducing the decay of an electron to the lower level (simulated emission) *are exactly the same*! In other words, when both levels are equally populated, the numbers of electrons "going up" and "down" will be the same, so you cannot achieve population inversion which is required for lasers.

The solution is to use a *third metastable level*. The pumping will be between the other two, but electrons in the upper energy level will quickly decay into the metastable level, leaving the upper level practically unpopulated at all times. The transition from the metastable level to the ground level has a different frequency: the laser frequency. The pumping frequency is between upper level and the ground level, so the pumping is off-resonant to the laser transition and will, thus, not trigger stimulated emission.

Two level Pumping Scheme

According to Heisenbergs Uncertainty Principle

$\Delta E \, \Delta t \geq h/2\pi$

ΔE is band width

Δt is time span for which atom stays in upper energy state

Δt should be longer for achieving population inversion and if Δt is longer ΔE is smaller that is E_2 is narrow, enough atoms cannot be raised to level E_2 and hence population inversion cannot be achieved.

Components Of Laser

<u>The essential components of laser</u>

- ✓ Active Medium
- ✓ Pump
- ✓ Optical Resonator Cavity

Active Medium

Active Medium is medium in which light amplification takes place

Active Medium= Active Centers + Host Atoms

Active Centers when exited reaches the state of population inversion and promotes stimulated emissions leading to light amplification

Host Atoms supports active centers. Active centres are dispersed in host atoms(bulk)

Pump

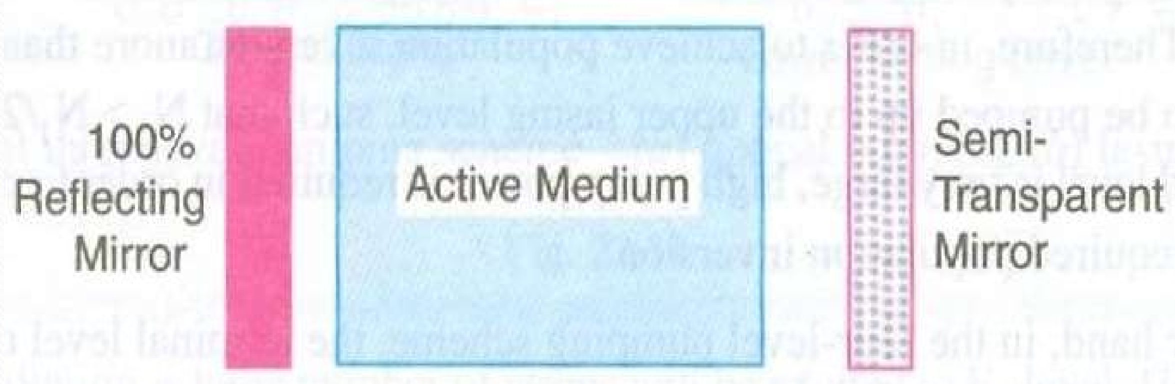
Pumping is the process of supplying energy to the laser medium with the view to transfer it into the state of population inversion.

Pump is agency which supplies energy

Different types of Pumping:

- Optical Pumping (Light Source, such Flash Discharge tube)--------employed in solid state lasers
- Electric Discharge methods(Electric field causes ionization of medium and raises it to exited state)---------employed in gas lasers
- Direct Conversion of electrical energy into light energy------Employed in semiconductor lasers

Optical Resonator Cavity

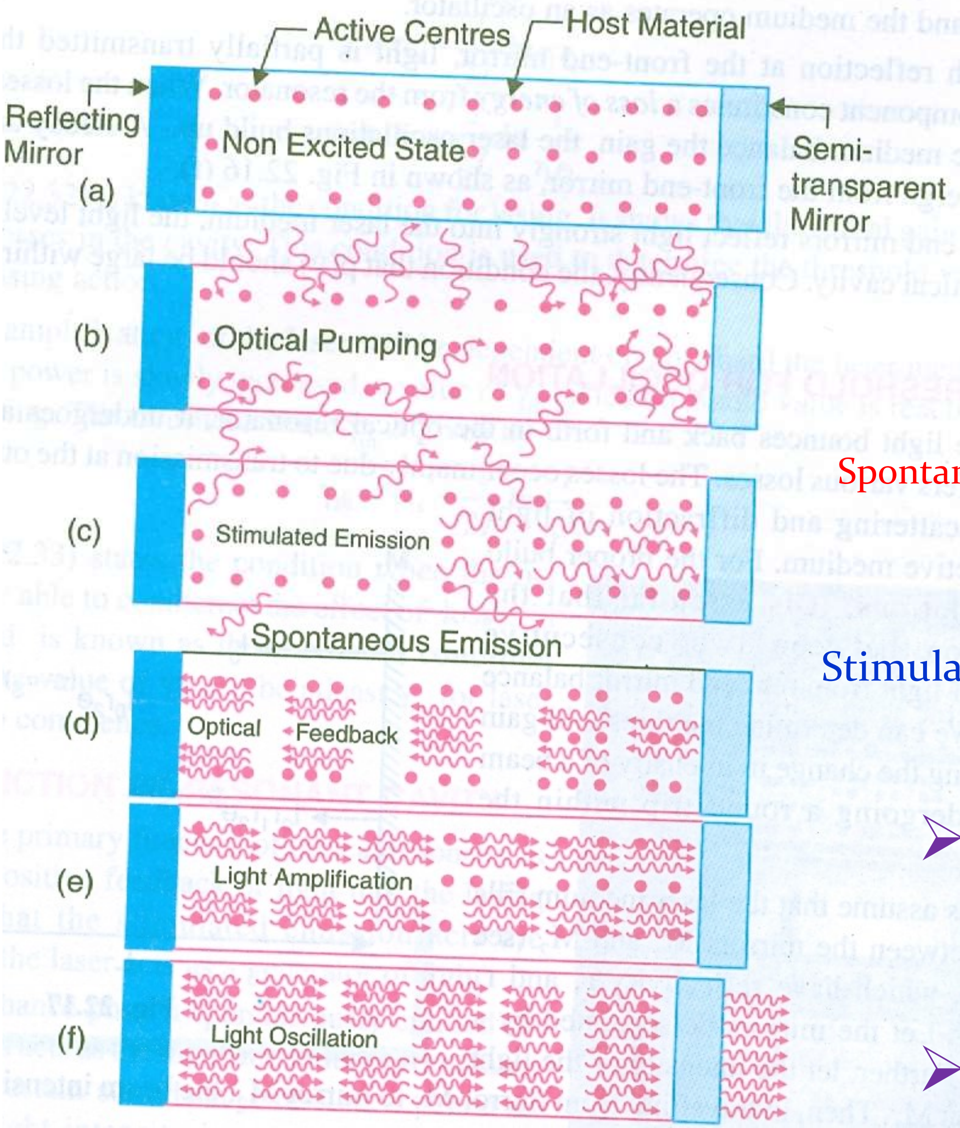


Fabry-Perot optical resonator

- A pair of optically plane parallel mirrors , enclosing laser medium in between them is known as an optically resonator cavity.
- One mirror is partially reflecting other mirror is fully reflecting

Optical Resonator

- Optical Resonator provide positive feedback of photons into the medium
- Optical resonator selects direction in which the light is to be amplified (makes light beam directional), The direction of photons is along optic axis of the pair of mirror.
- Optical cavity builts up photon density to high value through repeated reflections of photons and confines them within the medium.
- Optical cavity selects and amplifies only certain frequencies causing laser output to be highly monochromatic.



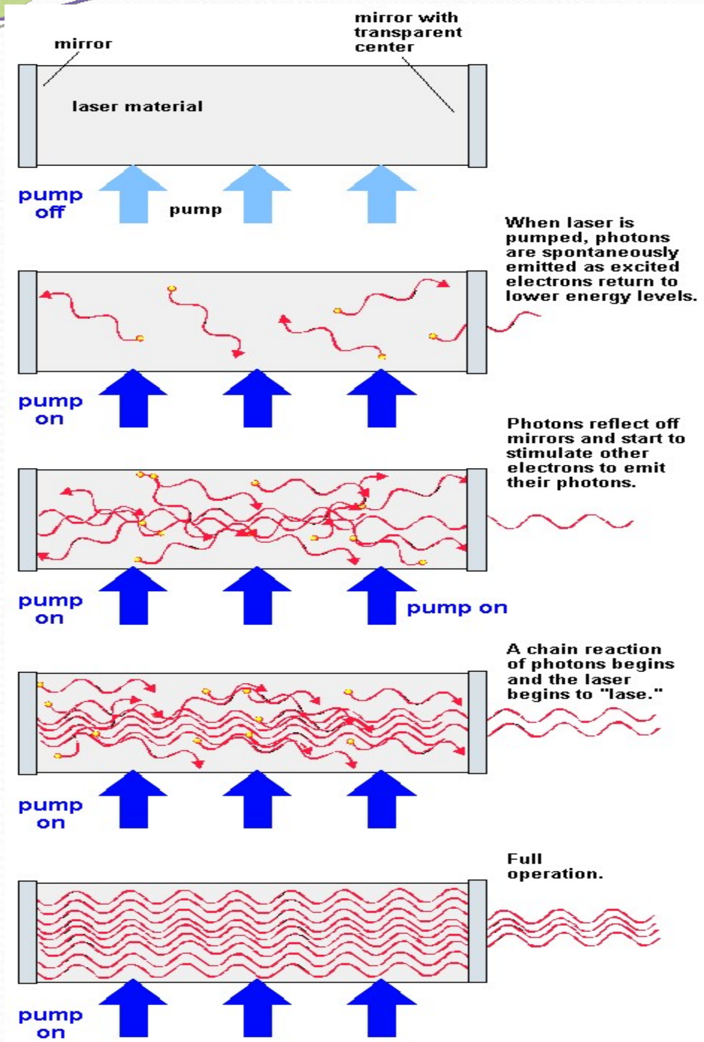
Spontaneously emitted photons

Stimulated emission

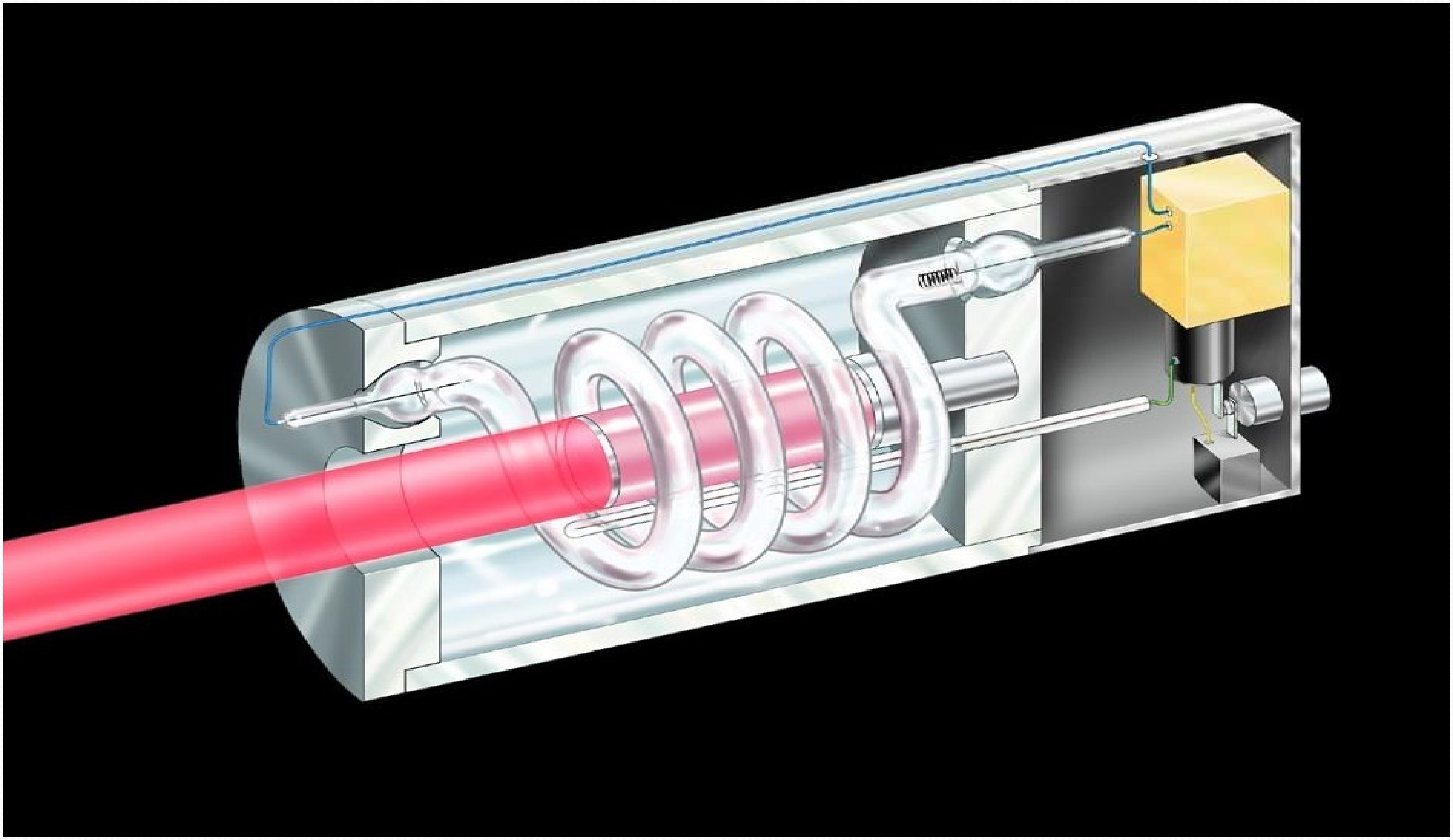
- **Standing Wave Formation**

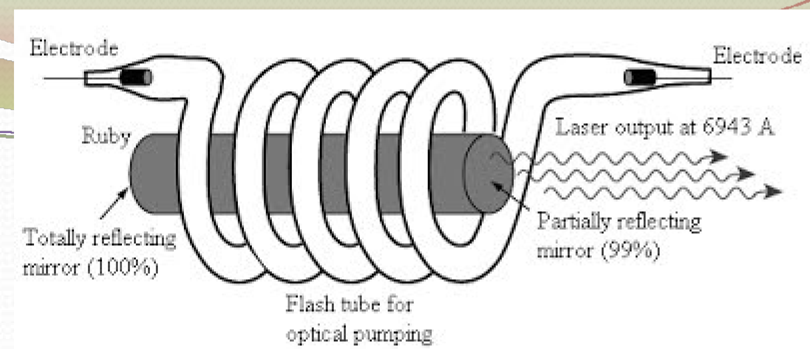
  $2L=n\lambda$

- **$L=n\lambda/2$**


mirror
mirror with transparent center
laser material
pump off
pump
When laser is pumped, photons are spontaneously emitted as excited electrons return to lower energy levels.
pump on
Photons reflect off mirrors and start to stimulate other electrons to emit their photons.
pump on
pump on
A chain reaction of photons begins and the laser begins to "lase."
pump on
Full operation.
pump on

SOLID STATE LASER: RUBY LASER



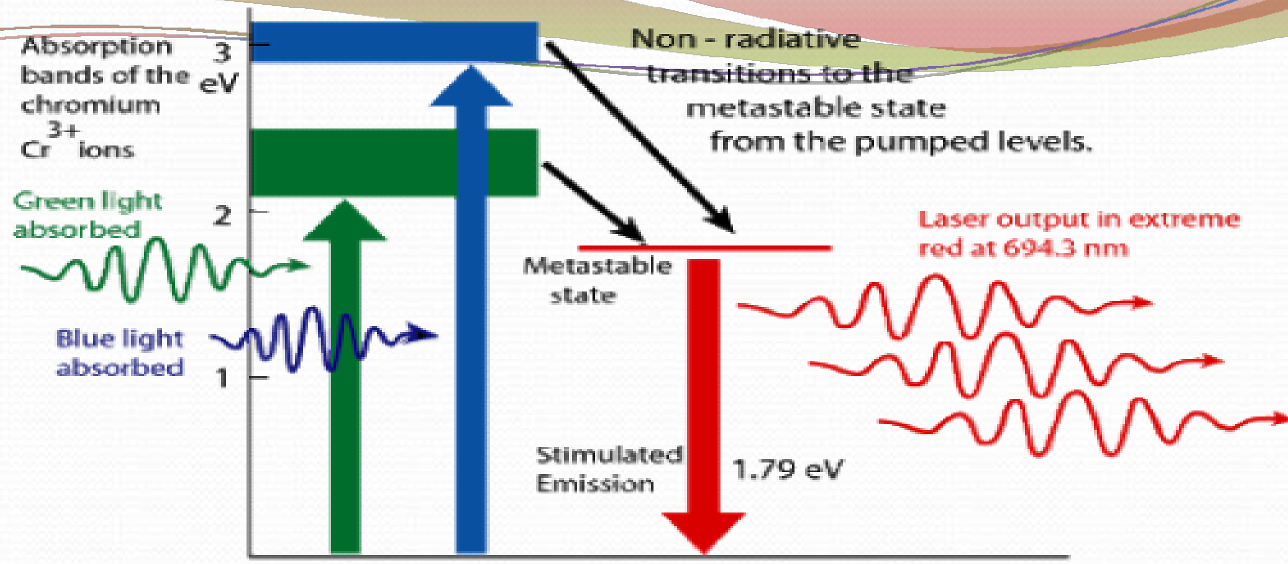


Ruby Laser

- Solid State laser
- Ruby: Al_2O_3 Crystal containing 0.05% chromium atoms.
- Al^{3+} ions in the crystal lattics are substituted by Cr^{3+}
- Cr^{3+} are active centers and Al_2O_3 acts as host.
- Chromium ions gives pink colour to ruby crystal.

Construction:

- ✓ Ruby crystal is taken in the form of Cylindrical rod of dimention Length:4cm and Diameter 1cm.
- ✓ Ends of ruby crystal are grounded and polished to make end facets parallel and perpendicular to axis of rod.
- ✓ One face is silvered to make 100% reflecting whereas other face is partically silvered to make semitransparent.
- ✓ Rod is surrounded by helical Flash Lamp filled with Xenon.
- ✓ It produces flashes of white light.
- ✓ System is cooled with the help of coolant.



Working

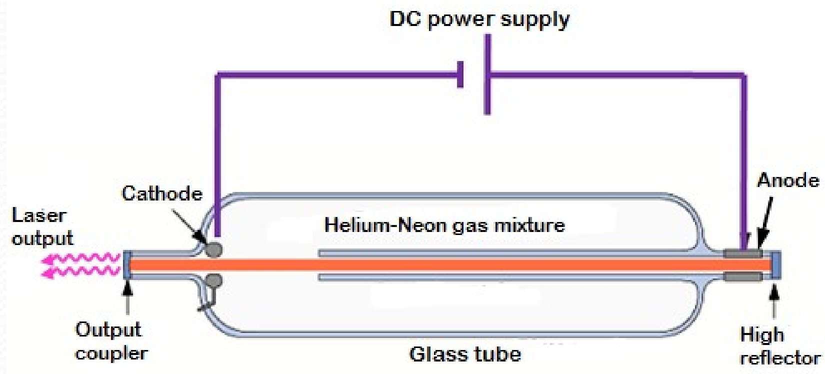
- Ruby Laser Forms three level system
- Xenon Flash lamp generates intense burst of white light for few milliseconds
- The green and blue component of spectrum is absorbed by Cr^{3+} ions making transition to E_3 Bands
- Exited levels are unstable and atoms loose there energy ($E_3 - E_2$) to the crystal lattice and undergo non-radiative transitions.
- E_2 is a metastable state.
- Population inversition is achieved between E_2 and E_1 Energy state.
- Spontaneously emitted photon initiates stimulated emissions.
- Photons travelling along axial directions are repeatedly reflected and amplified.
- The output beam is red in colour and corresponds to wavelength 6943 A.

Problems

Question 1

Find the ratio of population of the two states in helium neon laser that produces wavelength of 6328 A at 27^{o}C.

Helium Neon Laser

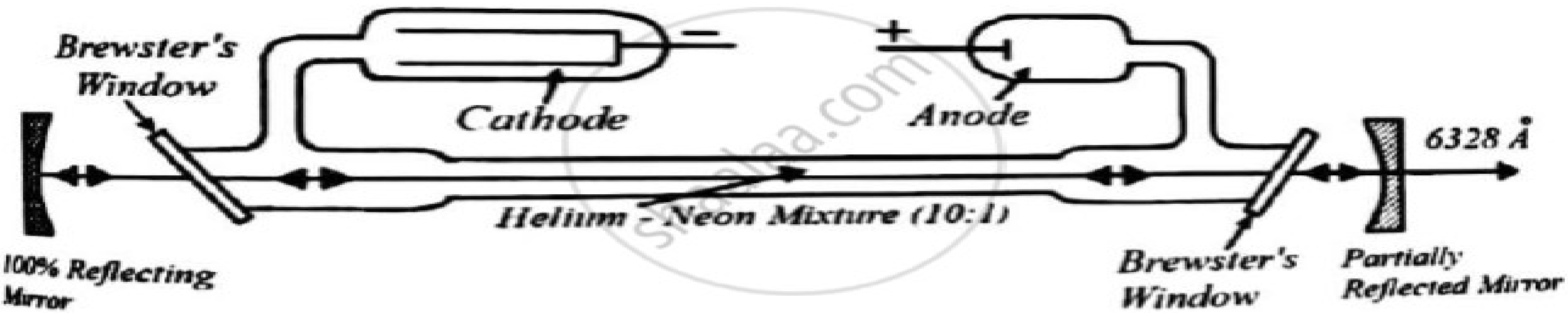


A helium-neon laser, usually called a He-Ne laser, is a type of small gas laser. He-Ne lasers have many industrial and scientific uses, and are often used in laboratory demonstrations of optics.

He-Ne laser is a four-level laser.

Its usual operation wavelength is 632.8 nm, in the red portion of the visible spectrum.

It operates in Continuous Working (CW) mode.



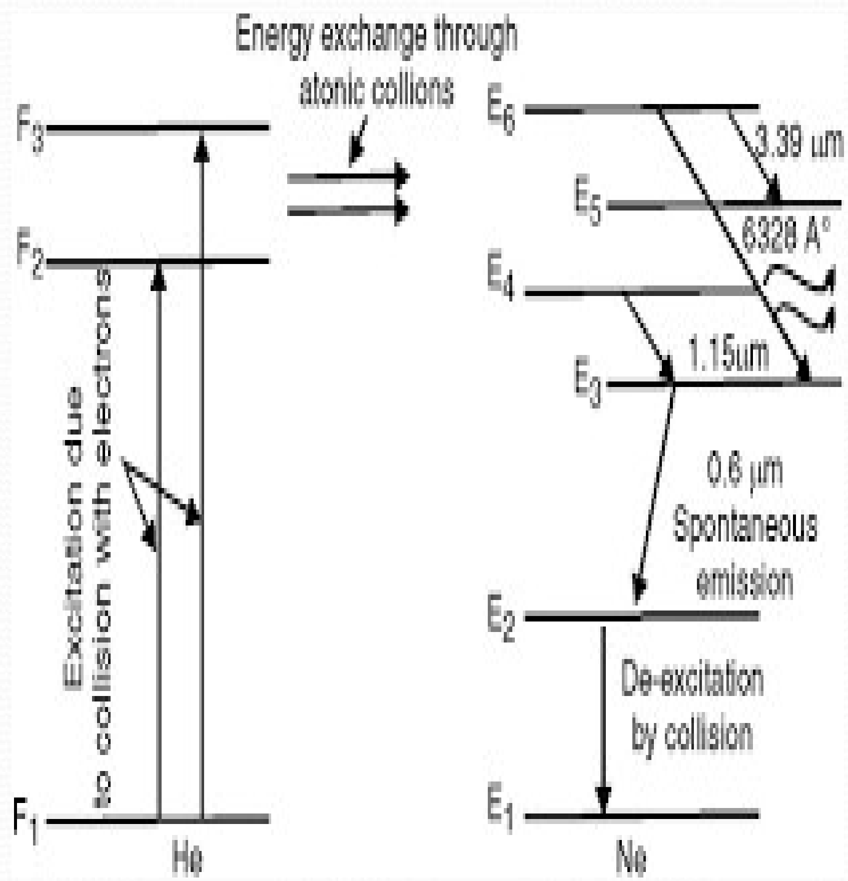
Helium Neon laser is a gas laser.

Construction

- Consist of long discharge tube of length 50cm and diameter 10cm
- The tube is filled with the mixure of helium and neon gas in the ratio 10:1
- Electrodes are connected to high voltage power supply to produce discharge in gas
- The tube is sealed at its two ends
- The distance between two mirrors is adjusted such that $L=m\lambda/2$ and it supports standing wave pattern.

Working

- Employs four level pumping scheme
- Neon atoms are active centers and role of helium atoms is to exite neon atoms too create population inversion.
- When power is switched on electric field ionizes some of the gas atoms.
- Electrons and +vely charged ions moves towards anode and cathode respectively
- Energetic electrons exite helium atoms through collissions to exited levels f2 and f3 which lies 19.81 and 20.61 ev above ground level
- These two states of helium are metastable states and atoms cannot return to ground state spontaneously
- The exited helium atoms transfer there energy to neon atms through collission
- Such energy transfer can take place when colliding atoms have identical energy states.
- The E_6 (20.61eV)energy level E_4 (18.71eV)energy level of neon atoms nearly coincide with F_2 and F_3 of helium atoms
- E_6 and E_4 energy states of neon are metastable states
- Successive collissions increase the population of E_6 and E_4 levels
- E_5 and E_3 levels of neon atoms are sparsely populated.



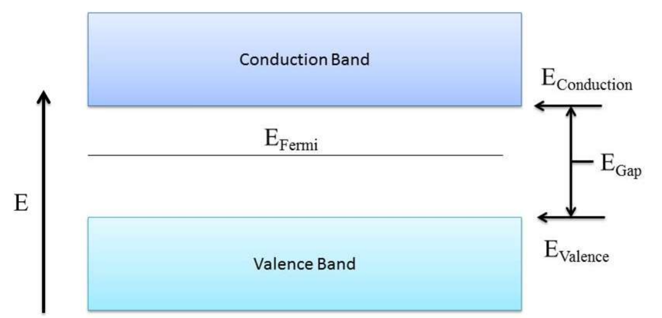
Possible Transitions

$E_6 \longrightarrow E_3$ transition: generates laser beam of red colour of wavelength 6328A

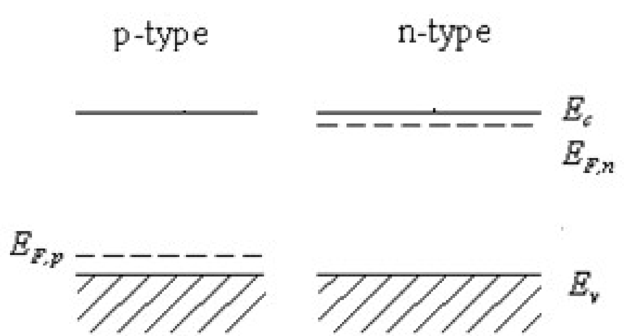
$E_4 \longrightarrow E_3$ transition: Produces infrared laser beam of wavelength 11500A

$E_6 \longrightarrow E_5$ transition : laser beam of wavelength 33900A

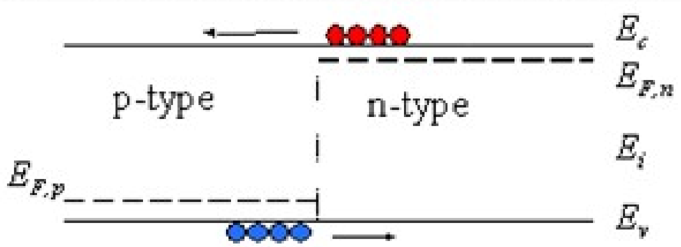
PN Junction Diode (Band Bending)

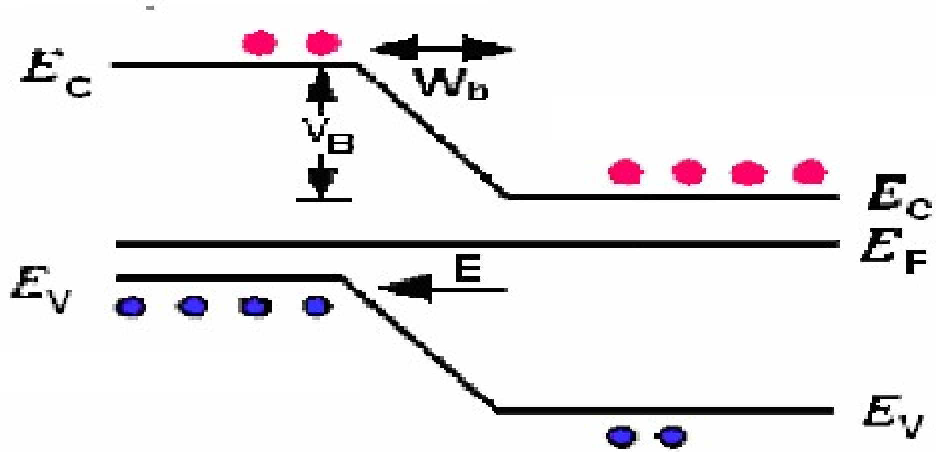


Band structure of Intrinsic Semiconductor

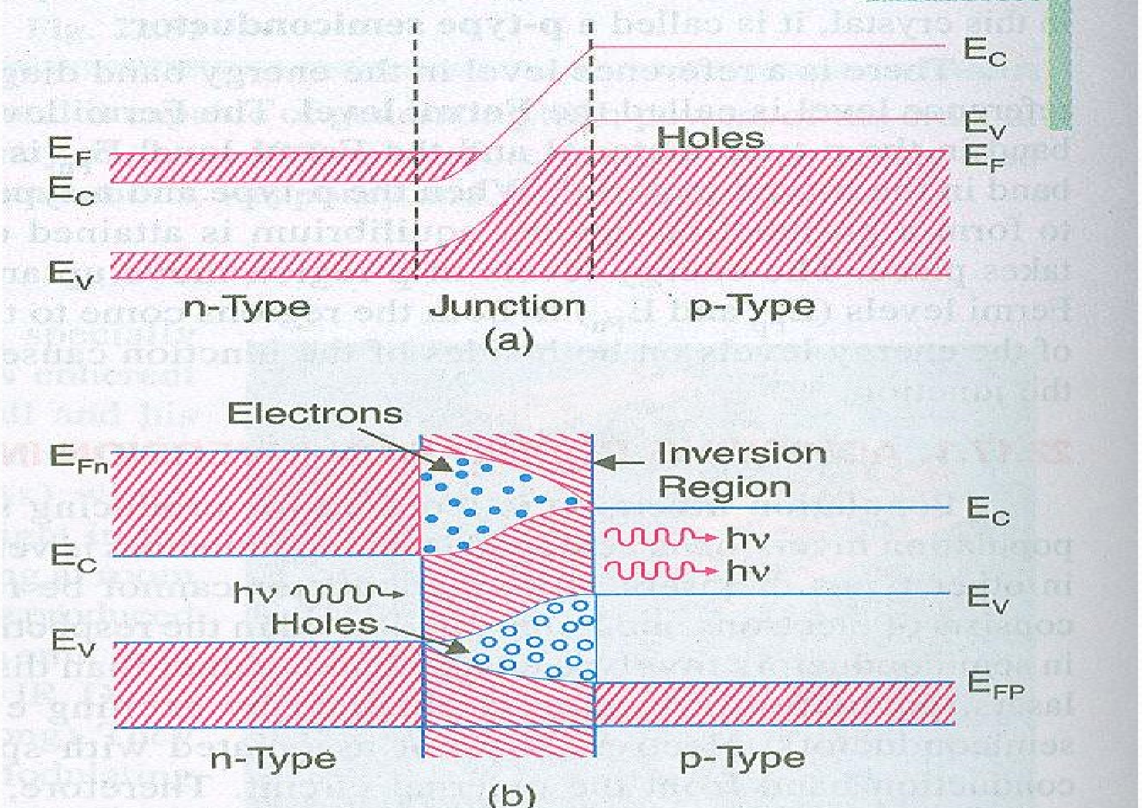


Band structure of P-type and N-type material





Energy band diagram

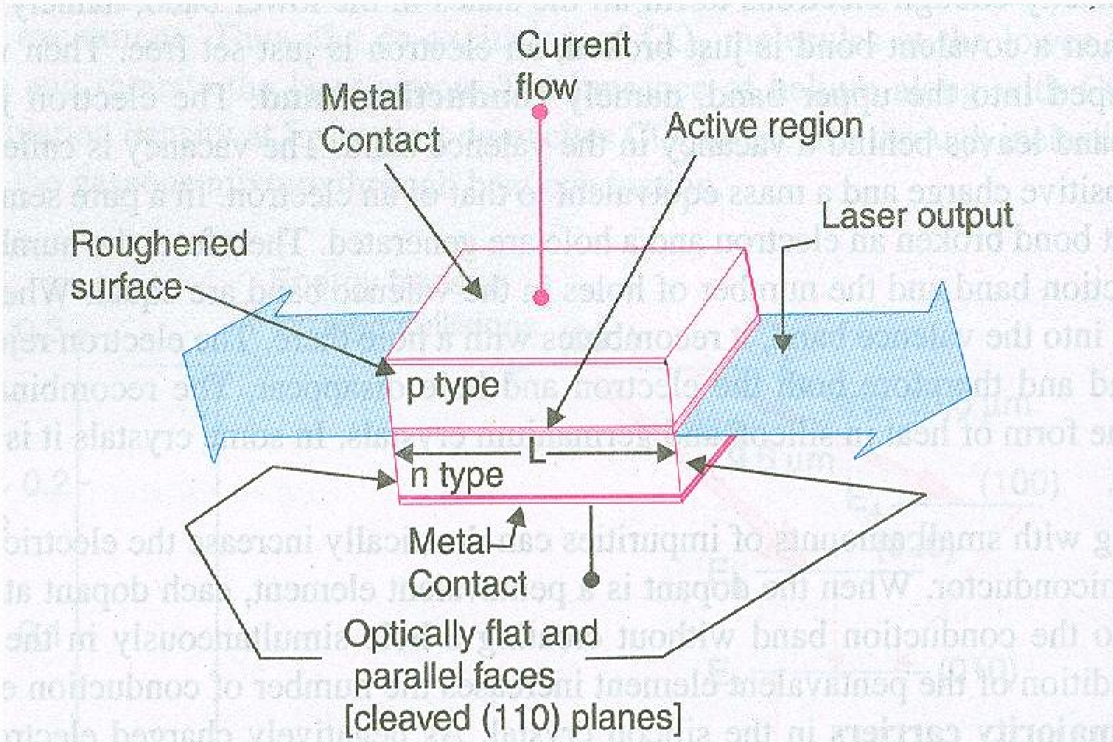


Energy band structure of a semiconductor diode (*a*) Heavily doped pn-junction without bias. (*b*) Heavily doped pn-junction forward biased above threshold value

Introduction

- Laser diode is similar in principle to an LED.
- The most common semiconductor material that has been used in lasers is gallium arsenide(GaAs).
- Stimulated and organized photon emission occurs when two electrons with the same energy and phase meet. The two photons leave with the same frequency and direction.

Construction



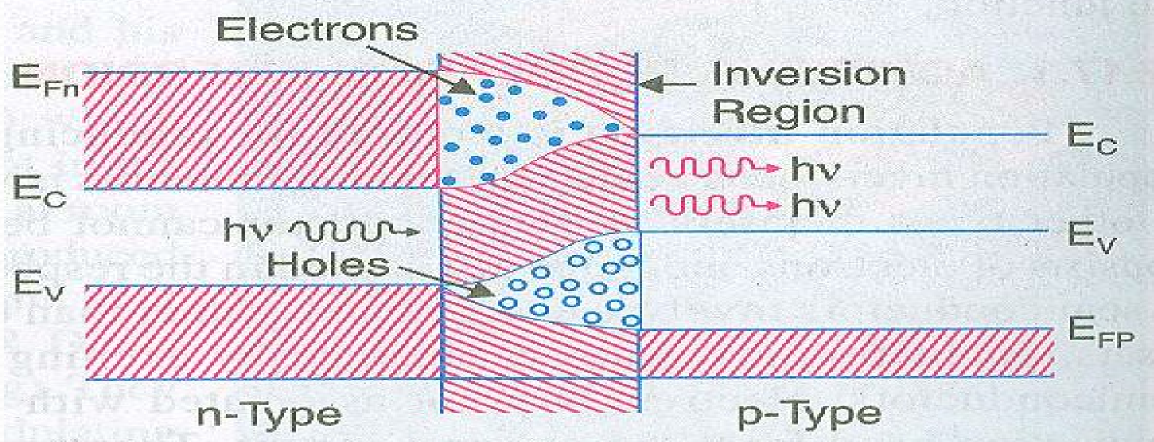
Schematic of a semiconductor diode laser

Laser Diode Working

An adequate forward bias is required to develop injection carriers across a junction to initiate a population inversion between energies at VB and energies at CB.

Pumping: Forward diode current.

The process is called ***injection pumping.***



(b)

Energy band structure of a semiconductor diode (*a*) Heavily doped pn-junction without bias. (*b*) Heavily doped pn-junction forward biased above threshold value

Working

- On P-side E_F is in the valence band (VB)
- On the N-side E_F is in the conduction band (CB).
- Energy levels up to the fermi level are occupied by electrons.
- When there is no applied voltage the fermi level is continuous across the diode.

Pumping Mechanism

- When junction is forward biased, electrons and holes are injected into the junction region in high concentration
- Charge carriers are pumped by DC voltage source
- When diode current reaches threashold value, the carrier conc. In the junction region will rise to very high value

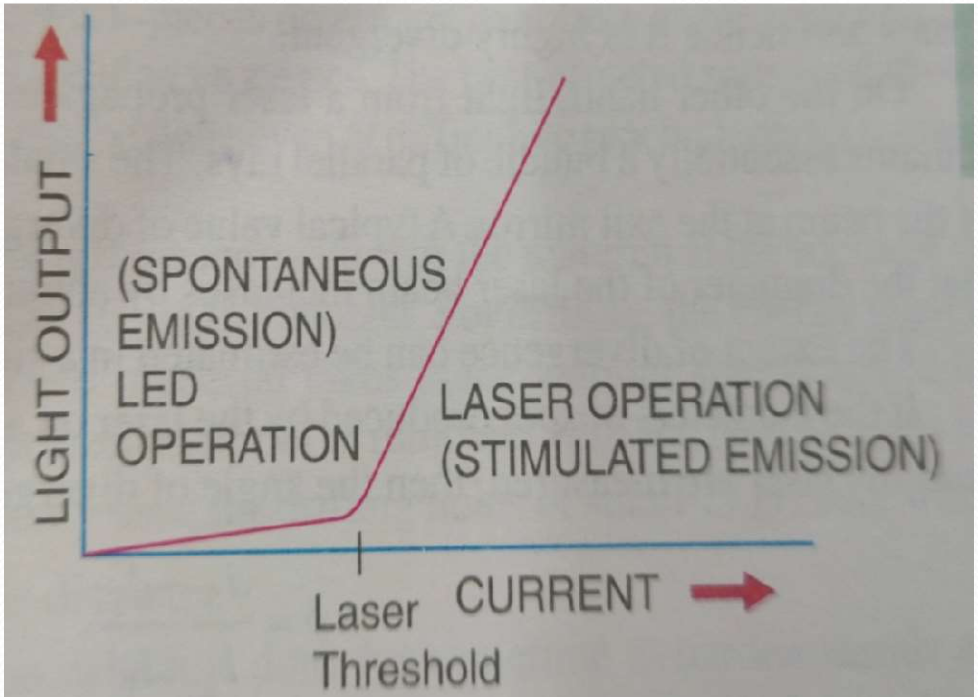
Population Inversion

- When forward biased, the narrow depletion region contains large number of electrons in conduction band and large number of holes in valence band.
- This represents condition of population inversion.
- ***The narrow zone in which population inversion occurs is called as inversion region or active region.***

Lasing

- electron and hole pair recombine to emit photon.
- Spontaneously emitted photon initiates the stimulated emissions
- Stimulated electron hole recombination produces coherent light.

Output characterstics of ideal Laser Diode



Light output-current characterstic of an ideal diode laser.

Energy Band Diagram Of semiconductor diode at equilibrium and forward bias

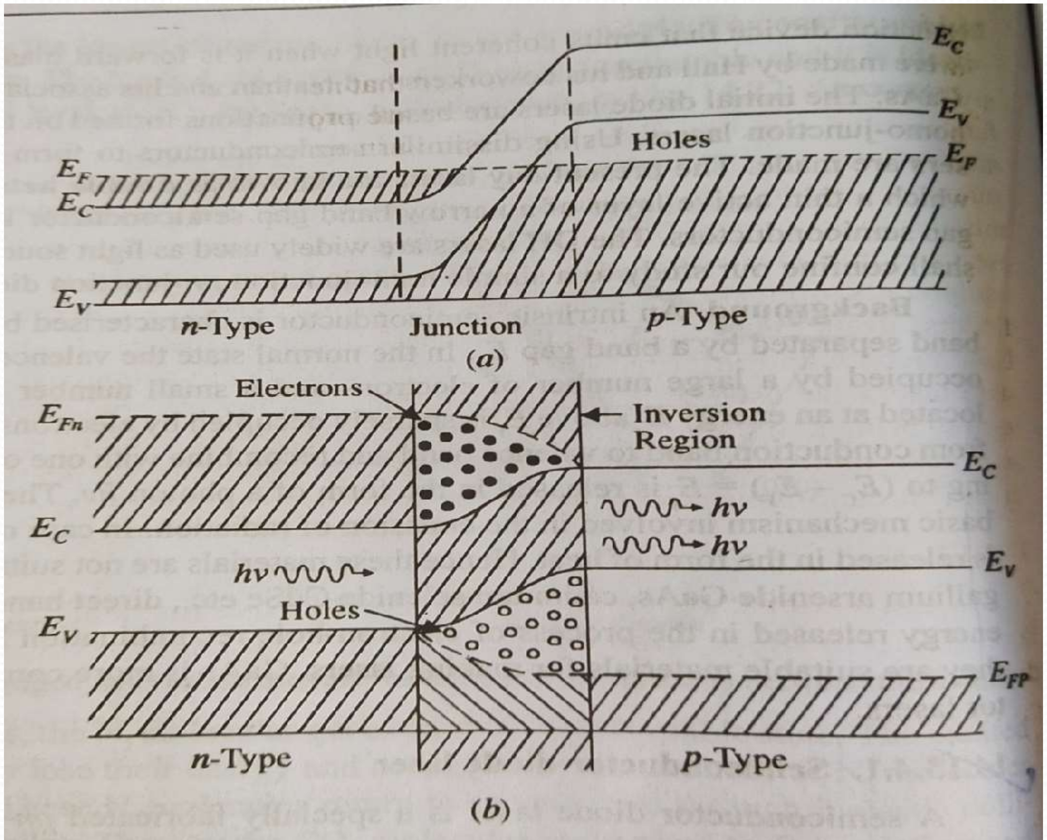


Fig. 14.24. Energy band structure of a semiconductor diode (*a*) Heavily doped *pn*-junction without bias. (*b*) Heavily doped *pn*-junction forward biased above threshold value.

Nd:YAG Laser

- Four level, solid state laser
- Yitrium Aluminium Garnate(YAG) acts as host material
- Y^{3+} ions in the crystal lattics are substituted by Nd^{3+}
- Nd^{3+} are active centers and YAG acts as host.

Construction

- Consist of elliptical cylindrical reflector housing the laser rod.
- Laser rod is placed at one focus and krypton flash lamp is placed at another focus
- The light leaving one focus will pass through another focus after reflection from silvered surface
- Thus entire flash lamp radiation gets focused on the laser rod.
- The two ends of laser rod are silvered and polished to make resonator cavity.

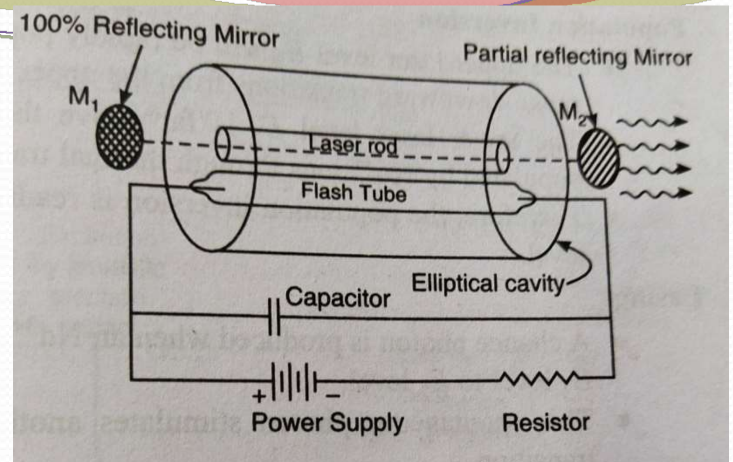
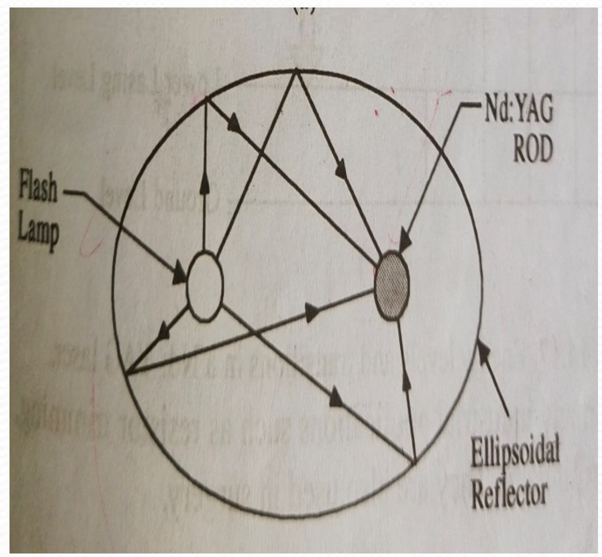


Fig. 24.17. Schematic of a Nd:YAG Laser



Energy level transition

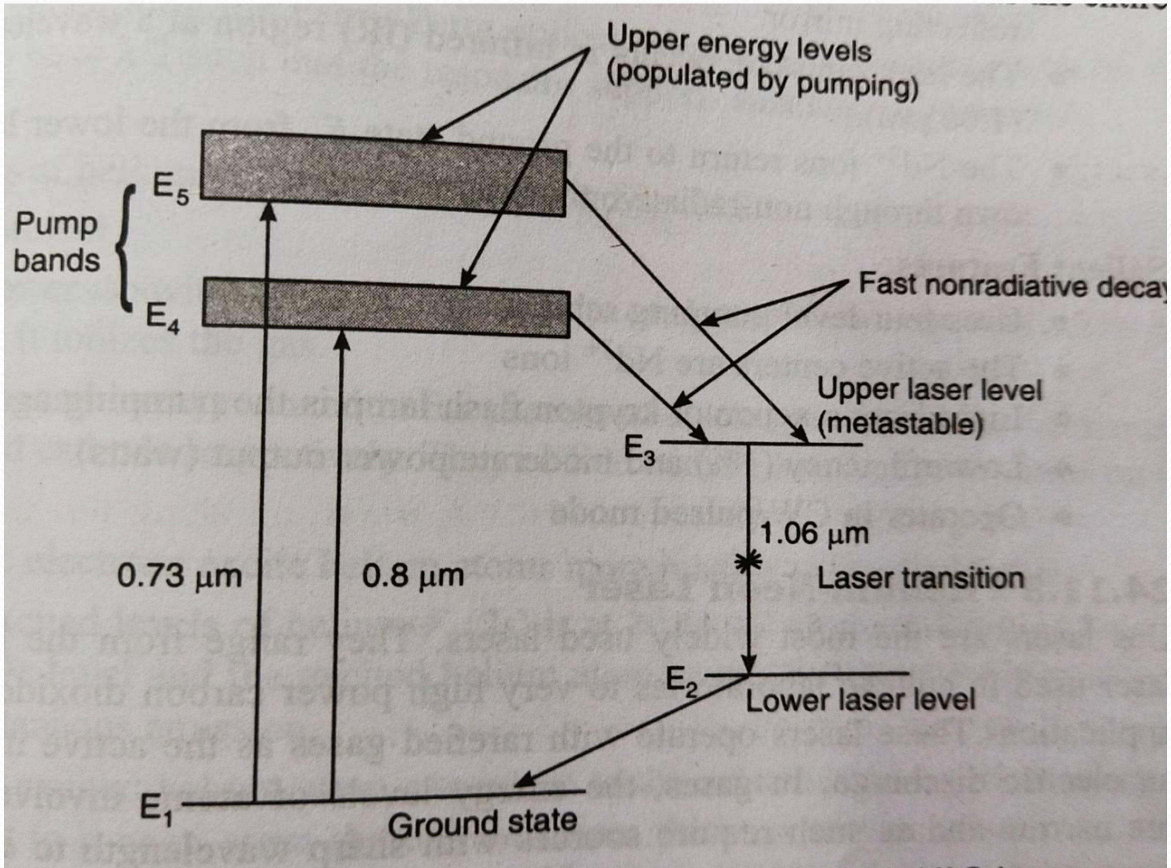


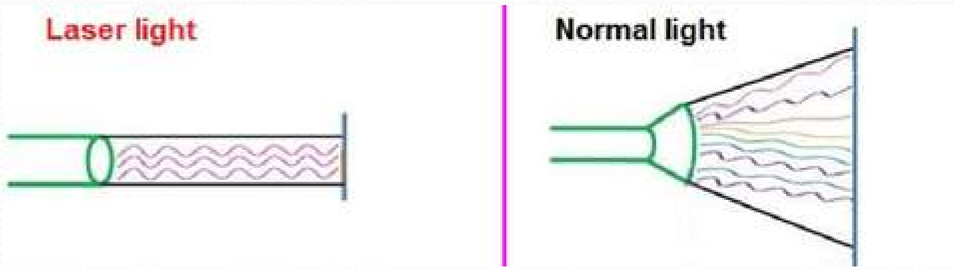
Fig. 24.18. Energy levels and transitions in a Nd : YAG laser.

Pumping Mechanism

- Crypton flash lamp is switched on, the Nd^{3+} ions are exited to the upper energy bands E_4 and E_5
- Nd^{3+} ions make non radiative transitions to energy state E_3 , E_3 is metastable state
- Population inversion is achieved between E_3 and E_2 energy states of neodymium ions.
- The laser emission occurs in infrared region at the wavelength of 10,600 A (1.06 μm)

Laser Beam Characterstics

- Directionality
- Negligible Divergence
- High Intensity
  I=P/A
- High Degree of coherence
- High Monochromaticity



S.No	**Ordinary light**	**Laser beams**
1	In ordinary light the angular spread is more.	In laser beam the angular spread is less.
2	They are not directional.	They are highly directional.
3	It is less intense	It is highly intense
4	It is not a coherent beam and is not in phase.	It is a coherent beam and is in phase
5	The radiation are polychromatic	The radiations are monochromatic
6	Example: Sun light, Mercury vapor lamp	He- Ne Laser, Co_2 laser

Problems

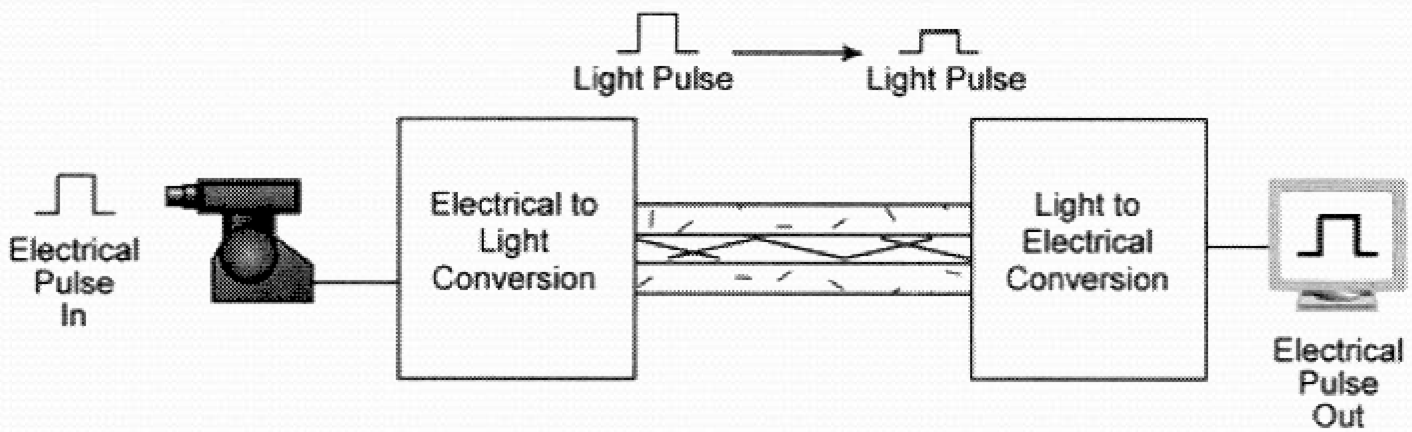
Question 1

Find the intensity of a laser beam of 10mW power having diameter 1.3nm. Assume intensity to be uniform across the beam.

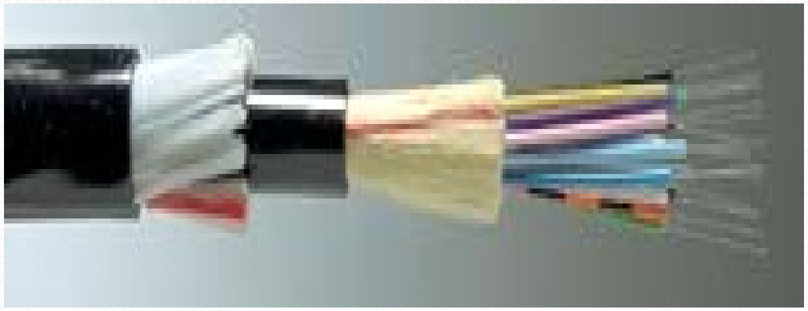
Question 2

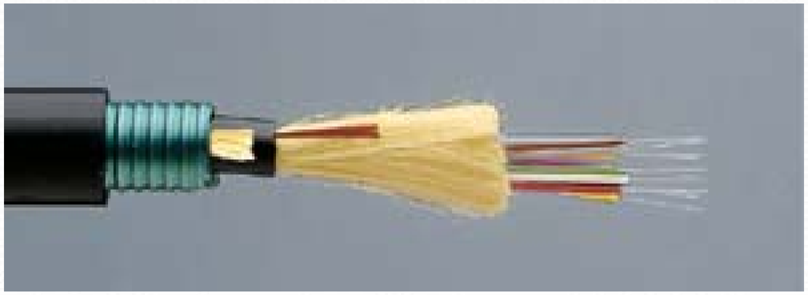
A laser beam can be focussed on an area equal to the square of its wavelength (λ^2). For a He-Ne laser, λ=6328A. If the laser radiates energy at the rate of 1 mW, find out the intensity of focussed beam.

Signal conversion

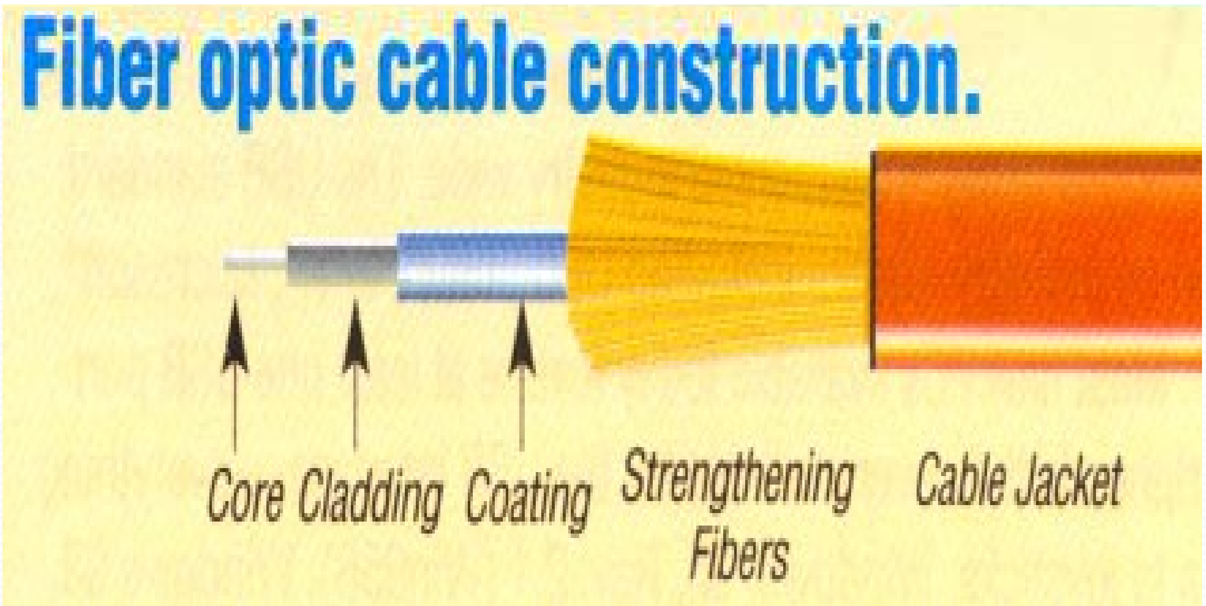


Optical fiber

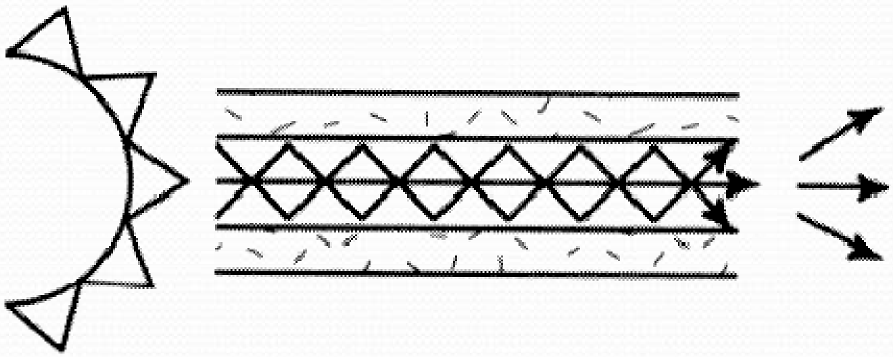


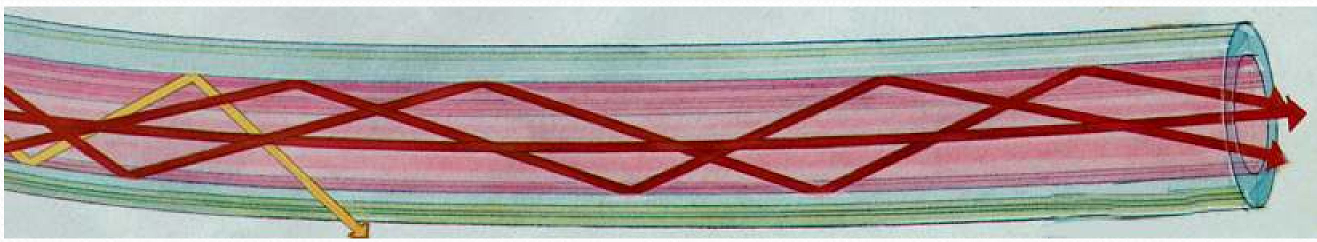


Fiber structure

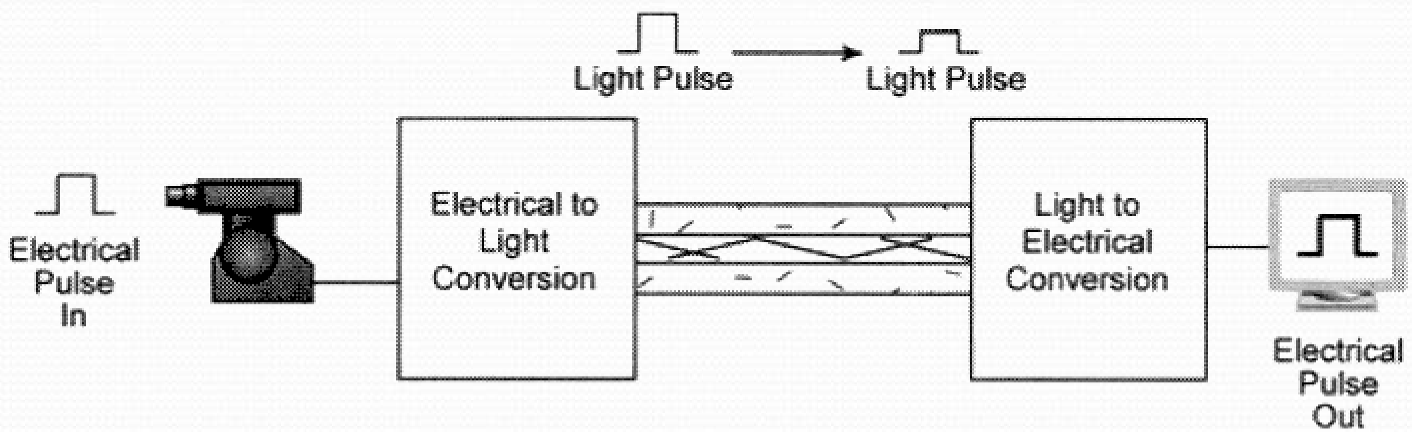


Wave propogation





Signal conversion



Unit 3

- **Laser Physics**

Introduction to Lasers, Laser and Ordinary Light, Laser beam Characterstics, Spontaneous and Stimulated emissions of radiations, Thermal equilibrium, Conditions for Light Amplification, Population inversion, Pumping (Three level and Four Level Pumping), Optical Resonator, Ruby Laser, He-Ne Laser, Semiconductor Laser, Nd-YAG Laser, Engineering Applications of Laser (Fiber Optics, Laser Material Interaction)