Unit-2 Lasers and applications

PHY109 – ENGINEERING PHYSICS

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Brief introduction to the course

- **L: 3 T:1 P:0 Credits:4**
- **Unit 1: Electromagnetic theory [7 lectures]**
- **Unit 2: Lasers and applications [6 lectures]**
- **Unit 3: Fiber optics [5 lectures]**
- **Unit 4: Quantum mechanics [7 lectures]**
- **Unit 5: Waves [5 lectures]**
- **Unit 6: Solid state physics [6 lectures]**

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Unit-2 Lasers and applications

Contents:

- Fundamentals of laser
- Energy levels in atoms
- Radiation matter interaction
- Absorption of light
- Spontaneous emission of light
- Stimulated emission of light
- Metastable state
- Population inversion
- Lasing action

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Unit-2 Lasers and applications

Contents:

- Properties of laser
- Population of energy levels
- Einstein A and B coefficients,
- Resonant cavity
- Excitation mechanisms
- Nd - YAG, He-Ne Laser, Semiconductor Laser,
- Applications of laser in engineering, holography.

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LASER

- Light Amplification by Stimulated Emission of Radiation

Energy levels in atoms

- An atom can be excited by supplying energy with an amount equal to the difference of its any two energy levels.
- Then after a very short duration of time the atom shall radiate energy when it comes down to its lower energy state
- An electron undergoes a transition between two energy states E_1 and E_2 if the atom emits/absorbs a photon of appropriate energy,

$$\boxed{E_2 - E_1 = h\nu}$$

- Where, h =Planck's constant & ν = frequency of radiation

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Radiation matter interaction

<u>UV-visible interaction with matter</u>

- The absorption of a photon occurs only when the energy of the photon precisely matches the energy gap between the initial and final states.
- In such interaction of radiation with matter, if there is no pair of energy state that the photon energy can elevate the system from the lower to upper state, then the matter is said to be transparent to that radiation.

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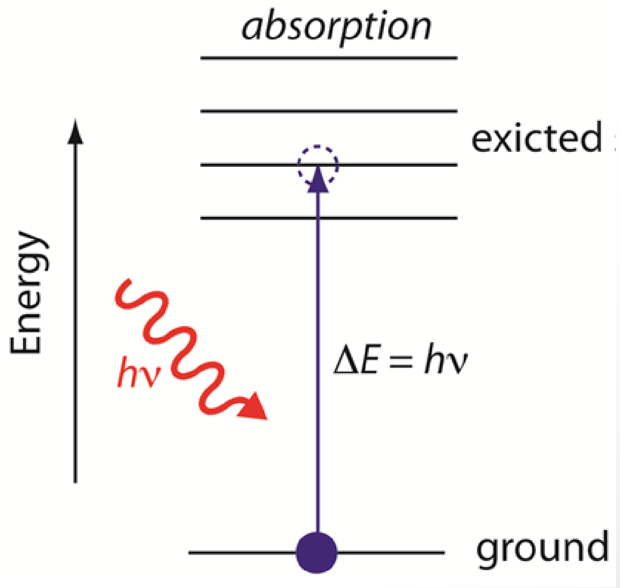
Absorption of light

- At low temperatures, most of the atoms stay in lower energy states.
- If an atom is initially in the *lower energy state* E1, it can be raised to the *higher energy state* E2 by the absorption of a photon of energy $h\nu$,



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Absorption of light

- The *probability of occurrence* of this absorption from state 1 to state 2 is proportional to the *energy density* $u(\nu)$ of the radiation,

$$\boxed{P12 = B12\ u(\nu)}$$

B12 = Einstein's coefficient of absorption of radiation

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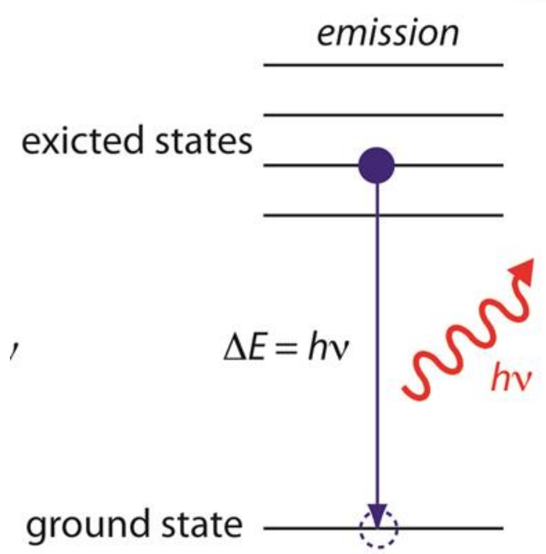
Spontaneous emission

- If an atom is initially in the upper state E2, it can come down to lower state E1 by emitting a photon of energy $E=h\nu$ …*spontaneous emission.*

- It is a natural radiation decay process that is inherent in all excited states of all materials.

- However, such emission is not always the dominant decay process !



Spontaneous emission

- The probability of occurrence of this spontaneous emission transition from state 2 to state 1 depends only on the properties of states, which is given as,

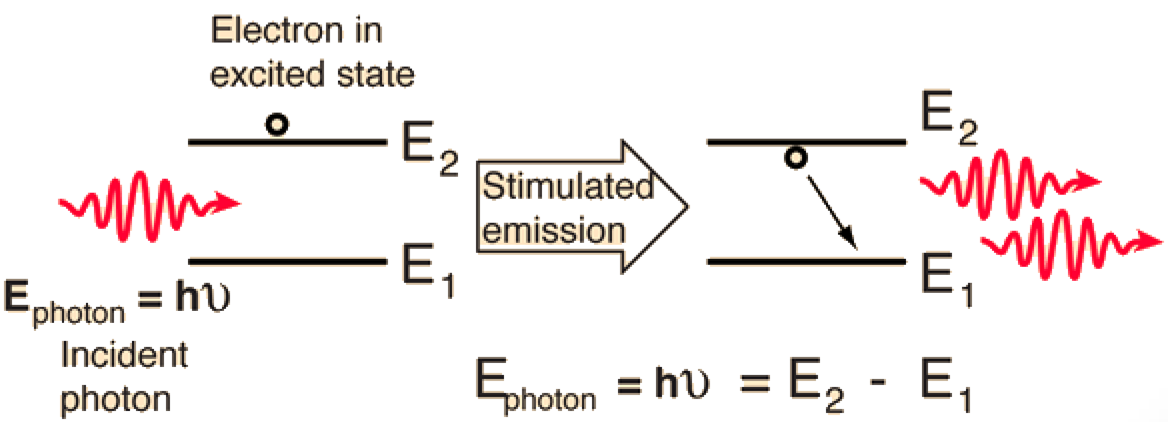
$$\boxed{P21' = A21}$$

A21 = Einstein's coefficient of spontaneous emission of radiation

Stimulated emission

- Induced emission…
- Founded by Einstein
- Incident photon of energy $h\nu$ causes a transition from upper state E2 to lower state E1,

$$\boxed{h\nu = \Delta E = E2 - E1}$$



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Population

- For a system of atoms in a thermal equilibrium, the number of atoms in a ground state is generally much greater than in a higher state *(normal population).*

- A state in which the number of atoms in higher energy state is greater than that of the lower energy state is known as *population inversion.*

- This population inversion sets the stage for stimulated emission of multiple photons, which is a precondition for the light amplification in a laser.

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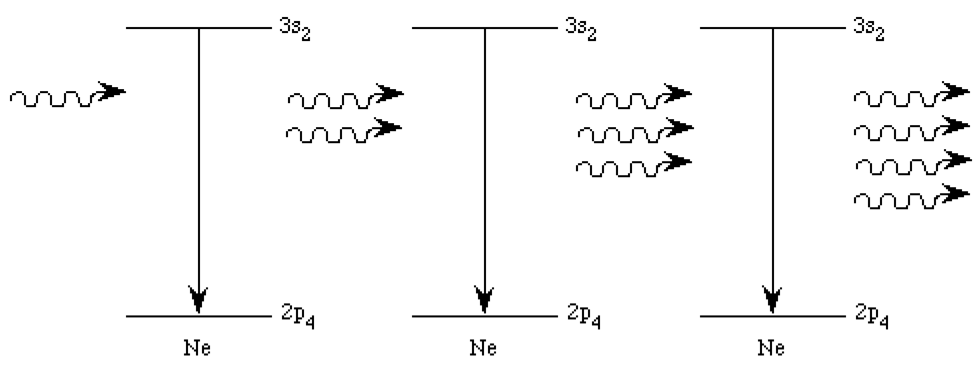
Stimulated emission

- Since the emitted photons have a definite time and phase relation to each other, the light has a degree of coherence.
- If these emitted photons are passed through an assembly of atoms, which fulfil the condition of population inversion, these are amplified.



(a)

Stimulated emission

- The probability of occurrence of stimulated emission transition from the upper level 2 to lower level 1 is proportional to the energy density u(ν) of the radiation and is expressed as,

$$\boxed{P21'' = B21\ u(\nu)}$$

B21 = Einstein's coefficient of stimulated emission of radiation

- Thus the total probability of emission transition form the upper level 2 to lower level 1,

$$\boxed{P21 = P21' + P21'' = A21 + B21\ u(\nu)}$$

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Relation between Einstein's coefficients A & B

$$\frac{A_{21}}{B_{21}} = \frac{8\pi h v^3}{c^3}$$

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Characteristics of laser light

- Highly intense and directional

<u>Main characteristics:</u>

(1) Coherent

Highly ordered (spatial and temporal)

(2) Monochromatic

Pure in color/wavelength

(3) Collimated

Means it does not spread out much

Achieved by parallel mirrors (to and fro)

Concave mirrors improve the coherence

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Main components of laser

Pumping

- The method of raising the molecules (gas laser) or atoms (solid state laser) from their lower energy state (E1) to higher energy state (E2) is known as pumping.

- Require to achieve population inversion (N2>N1)

- Rate of absorption will exceed the rate of emission

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Main components of laser

Active system

- A system in which population inversion is to be achieved is called an active system/gain medium

- Gain medium may be gas, liquid or solid

- The energy levels in gain medium those participate in the radiation, determines the wavelength of laser radiation

- Popular transitions in gases: 632.8 nm (Neon) & 10.6 μm IR from CO_2 molecule

Main components of laser

Resonant cavity

- The active system/gain medium enclosed in an optical cavity (resonant cavity)usually made up of two parallel surfaces, one of which is perfectly reflecting (100%) and the other is partially reflecting (~99%)

- In the resonant cavity, the intensity of photons is raised tremendously through stimulated emission process

Schemes: Population of energy levels

(1) 2 level system: Inappropriate

(2) 3 level system: Appropriate

(3) 4 level system (most efficient)

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Population inversion

Why 2 energy level system is not appropriate?

- Energies of states: E1 and E2
- Einstein's coefficient for upward/downward transitions: B12 = B21
- Even with strong pumping we can achieve (at the max) an equal population distribution
- Inversion of population cannot be achieved by 2 level system

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Metastable state

- Need of third intermediate state, metastable state, where electrons can stay for longer duration (m.sec)

- Frequency (time interval) of excitation of electrons from ground→highest energy level will *differ* from that of laser emission (metastable state to ground state)

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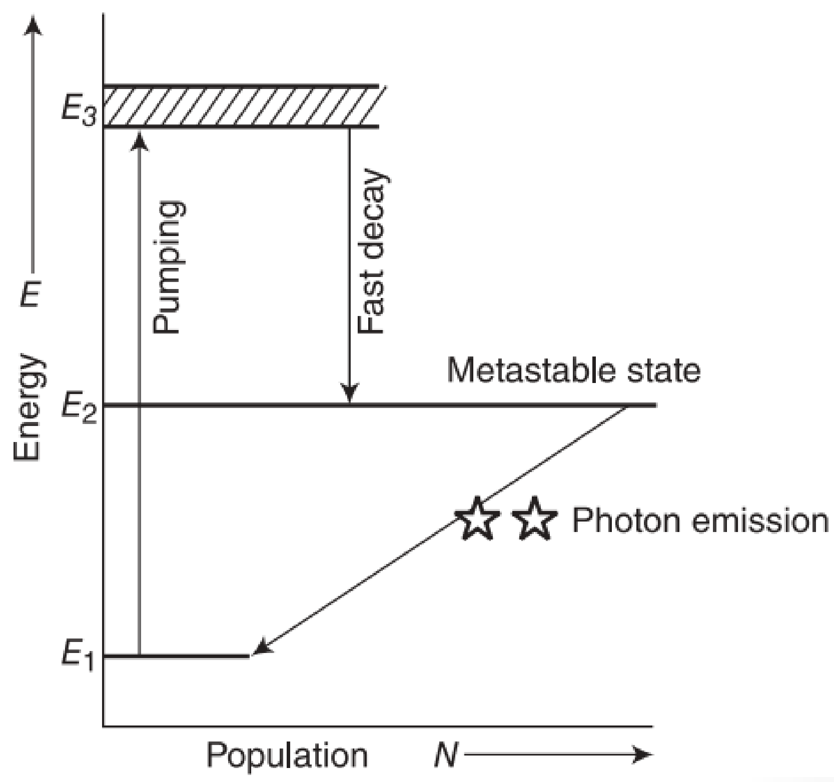
3 level system

- Electrical pulse/optical illumination
- Fast decay:radiation less/to lattice
- Ruby laser (eg)
- Needs high pumping power

(a ground state is involved)

- Low efficiency



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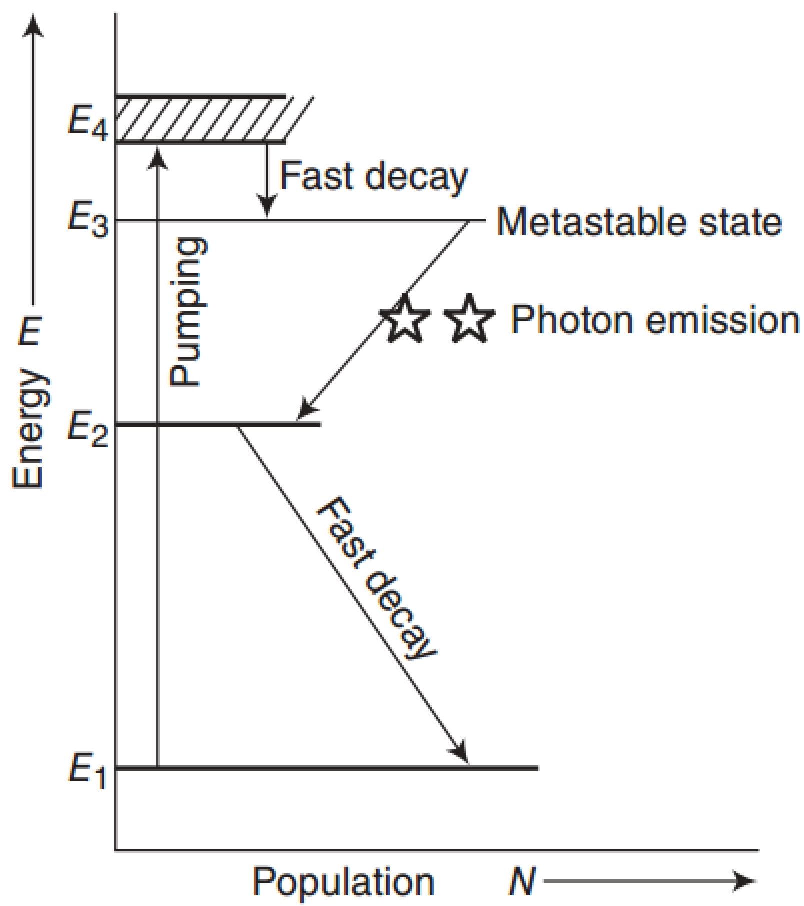
4 level system

- E2 to E1 fast decay helps maintaining PI
- Small number of atoms need to be pumped to E4 to maintain (E3-E2: PI)
- High efficiency
- Most popular 4 level solid state gain medium Nd-YAG (Neodymium-doped Yttrium Aluminum Garnet)



Population inversion

- System with 3 energy states
- E1<E2<E3
- N1>N2>N3
- System shall absorb photons (rather than emitting)
- When, N3>N2>N1 achieved, its called population inversion (non-equilibrium state).
- Prerequisite for stimulated emission…!
- Spontaneous emitted photons→stimulated emission→more stimulated emissions

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Population inversion

- Multilevel scheme
- Atoms are pumped to highest energy level
- Spontaneous decay to mid energy level (metastable state)
- Laser emission from this metastable state to lower/ground state

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Pumping mechanisms

- Different methods by which we can supply the suitable value of energy to raise the atoms from the lower energy level to higher energy level for achieving population inversion.

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Excitation/pumping mechanism

1. Optical pumping
2. Electrical discharge
3. Inelastic collisions between atoms
4. Direct conversion
5. Chemical reaction

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1. Optical pumping

- Suitable photon light source is used to supply luminous energy
- Most often this energy is given in the form of short flashes of light
- Firstly, used by Maiman in the Ruby laser and is also widely used in solid state laser
- In this method, the laser material is kept inside a helical xenon flash lamp similar to that which is used in photography

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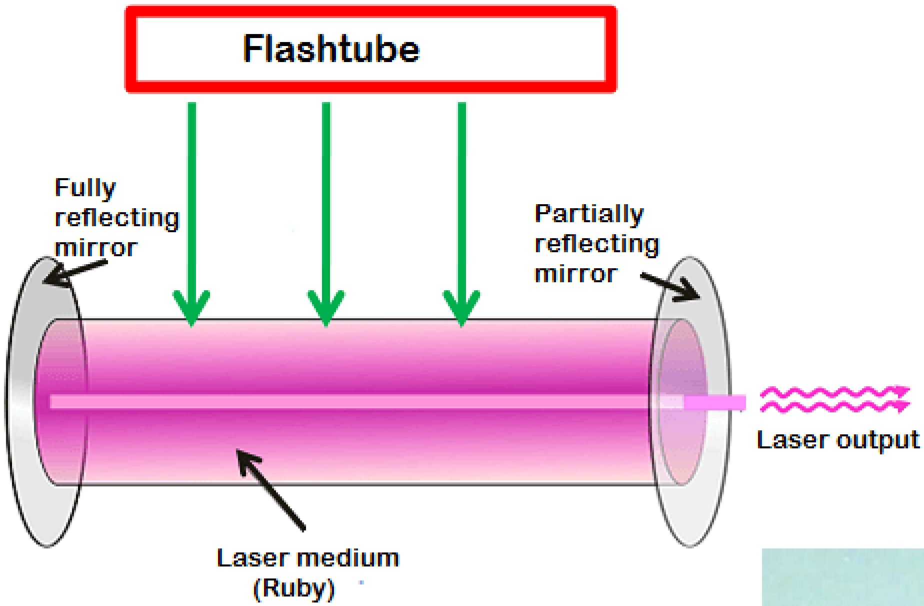

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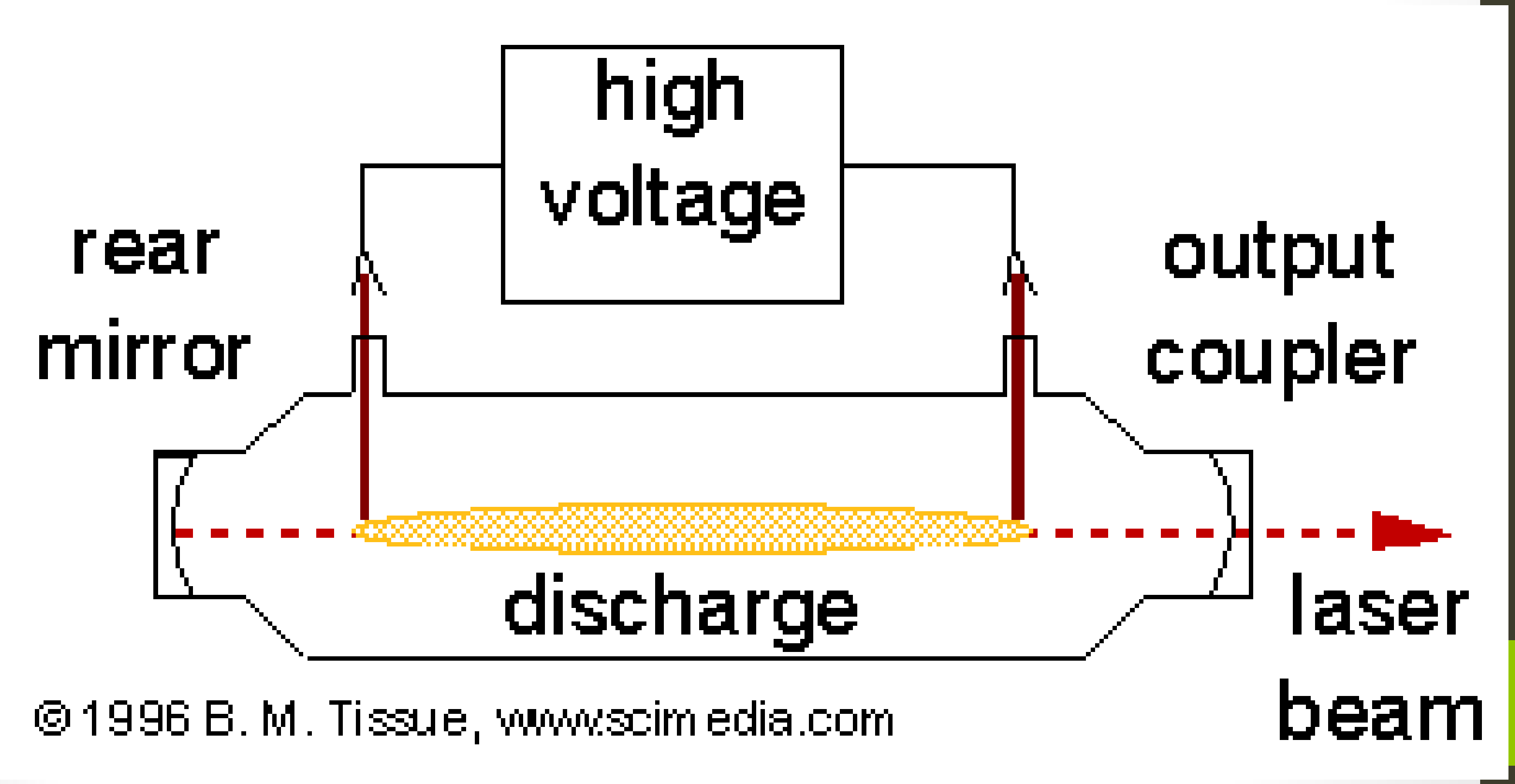
2. Electric discharge

- In this method, direct electron excitation occurs through an electric discharge
- Preferred pumping mechanism for gaseous ion lasers (eg. Argon ion laser)
- In the gas laser, a high voltage pulse initially ionizes the gas so that it conducts electricity
- An electric current flowing through the gas excites the atoms to the excited level from where they drop to the metastable upper laser level leading to population inversion



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3. Inelastic collisions between atoms

- In an important class of lasers, pumping by electrical discharge provides the initial excitation which raises one type of atoms to their excited states
- These atoms collide inelastically with another atoms and provide them enough energy to excite them to the higher energy level and thus help in PI.
- This type of pumping occur in He-Ne laser

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4. Direct conversion

- In light emitting diodes and semiconductors, the electrons recombine with holes producing laser light

- Thus the direct conversion of electrical energy into radiation takes place.

5. Chemical reaction

- In chemical laser, radiations come out of a chemical reaction, without any need of other energy source.
- Eg. When hydrogen combines with fluorine, heat energy is generated as,

$H_2 + F_2 = 2\ HF + \text{Heat energy}$

- This heat energy is enough to pump a CO_2 laser.

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Ruby laser

- Solid state laser
- Produces pulses of visible light at a wavelength of 694.3 nm (red color)
- Pulses of the order of millisecond

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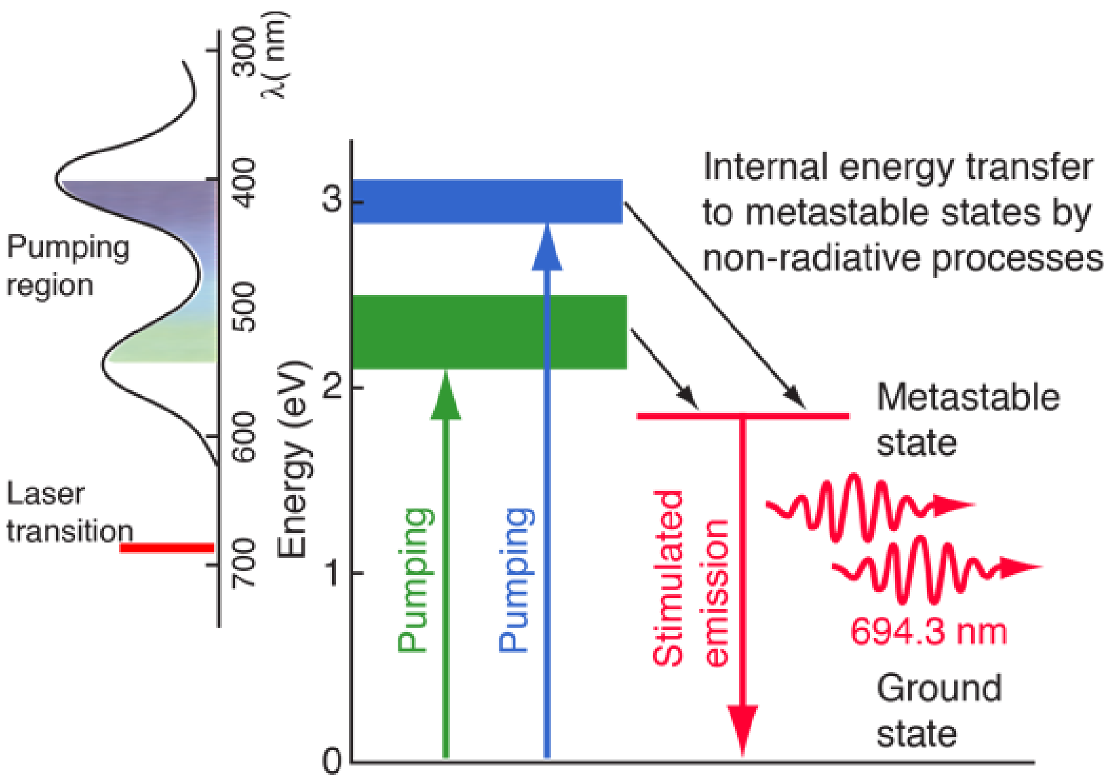
Principle

- Pumping: Xenon lamp as a light source (Optical)
- Gain medium: cylindrical crystal of ruby

- Ruby crystal: Chromium doped aluminium oxide Al_2O_3 (0.05% of the weight of a ruby crystal)
- Al^{3+} ions are replaced by Cr^{3+} ions

- Chromium atoms possess two energy level that correspond to a life time of 10^{-8} s
- Metastable state of life time 3×10^{-3} s

Energy level diagram



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Principle

- Cr^{3+} ions absorbs these photons to make a transition from the ground state to excited states E1 (~6600 A) and E2 (~ 4000 A)
- Non-radiative transition to metastable state (M) emitting extra energy (heat) to lattice
- Liquid nitrogen used as a cooling agent
- Population inversion achieved
- Cr^{3+} atoms go under stimulated emission thus providing light amplification

Principle

- Ruby has broad powerful absorption bands at 400-550 nm
- The lasing action is triggered by spontaneous emission of photons with a deep red color at a wavelength of 694.3 nm, with a very narrow line width of 0.53 nm
- As the flash lamp operation is pulsed the lasing output is also pulsed

He-Ne laser

1. Construction
2. Principle of operation
3. Pumping

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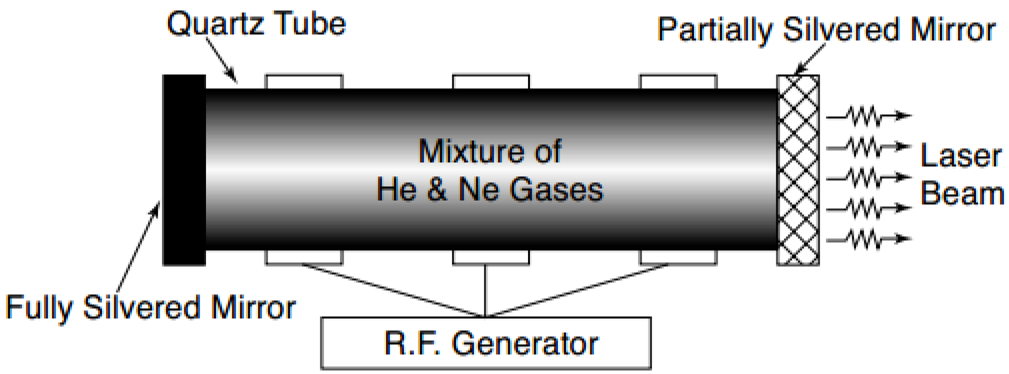
Construction of He-Ne laser

- It consist of a fused quartz tube that is filled with a mixture of He-Ne gases
- Quartz tube of 80 cm long and 1.5 cm in dia.
- Gas pressure: He (1 mmHg) & Ne (0.1 mmHg)



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He-Ne laser: Principle of operation

- First functional gas laser
- Active medium: mixture of He and Ne in the ratio of 10:1

- Firstly, He atoms need to be excited, which then collide with Ne atoms, thus raising them to higher energy levels

- Why He is required? (200% more efficient, energy matches well)

- Only Ne laser would have a very low pumping efficiency and hence there would be no lase

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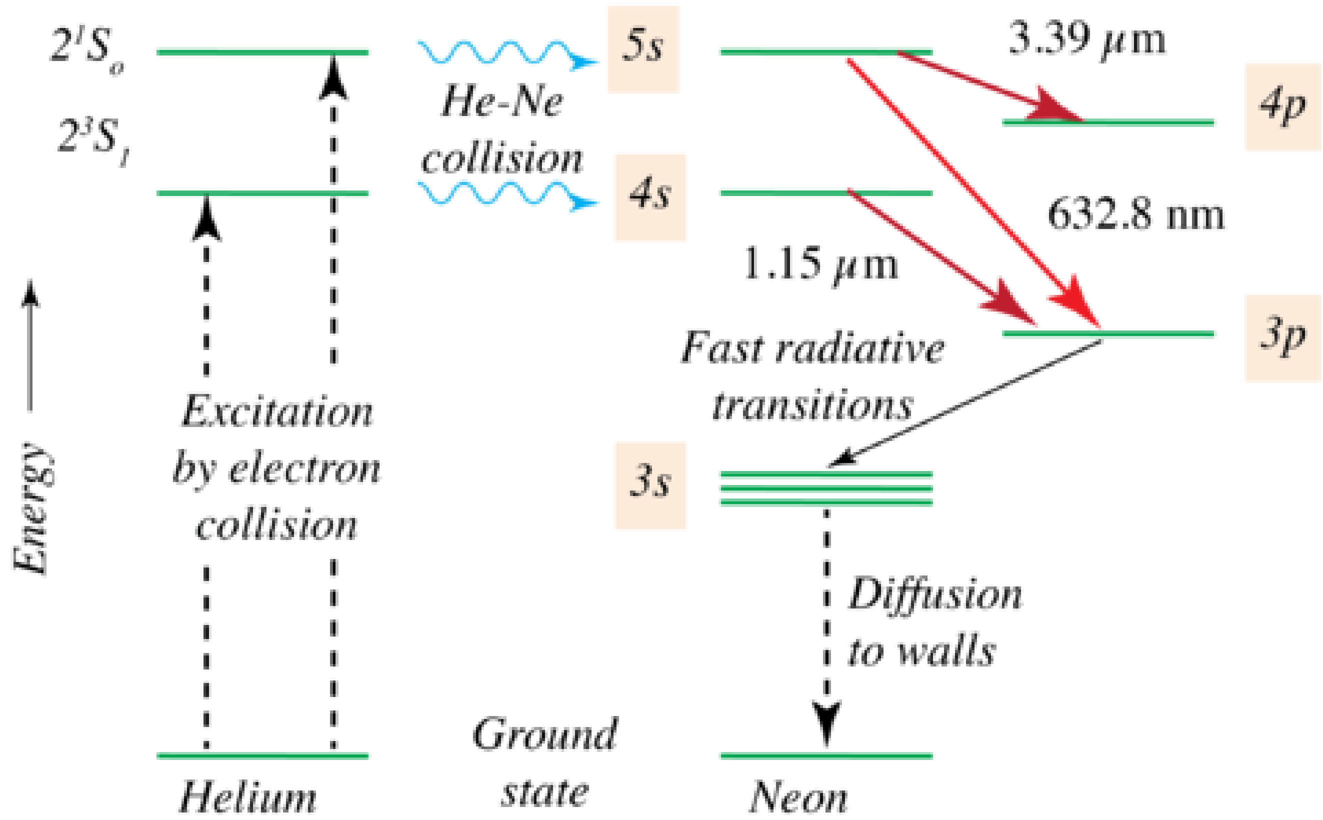
Energy level diagram



ΔE: energy difference between two excited states (~0.05 eV), which is supplied by the K.E.

Principle…

- A discharge passing through the gas mixture allows collisions of gas atoms
- Which raises He atoms to higher energy levels 2^3s_1 and 2^1s_0
- These are metastable states, thus does not allowing transitions from such states
- He atoms transfer their energy to the Ne atoms and return to the ground state-Ne atoms are promoted to higher metastable states 5s and 4s due to gained energy
- Since the metastable states 5s and 4s have higher lifetime than 4p and 3p states, population inversion occurs

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Pumping & optical resonator

- Energy for pumping is provided by high electrical voltage (1000-3000 V) discharge
- This discharge is passed through a gas mixture between the electrodes, that is anode and cathode, within a tube
- Optical resonator consist of two concave mirrors at each end, amplify the longitudinal mode radiation by reflection, gaining more power in each turn

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Lasing beam

- Excited Ne atoms relax from the metastable states 3s to states 3p (3.39 μm)and 2p (632.8 nm)
- Same way excited Ne atoms from metastable state 2s to state 2p (1.15 μm)
- These photons can in turn, be used to create a stimulated emission of photons of the same wavelength with the help of optical resonators
- Cascading effect ultimately produces an intense beam that exits through the partially reflecting mirror

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Nd-YAG laser

- Uses Neodymium (Nd) (rare earth element) and Yttrium Aluminium Garnet (YAG) for lasing action

- 4 energy level solid state laser

Nd-YAG laser

- Active material: Nd^{3+} doped in to YAG to replace Y^{3+}
- This active materials is shaped as a cylindrical rod to form the active element (laser rod)
- Krypton flash lamp is being used as a light source for pumping mechanism
- Capacitor controls the operation of flash lamp

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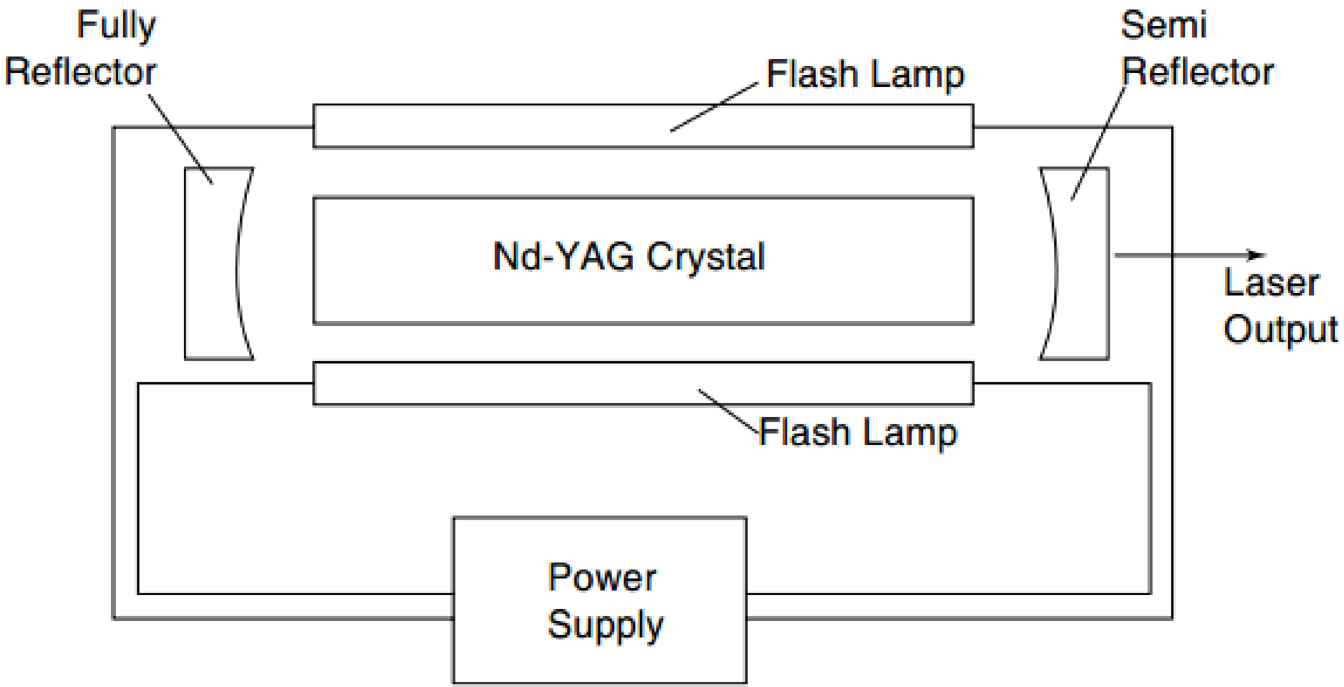
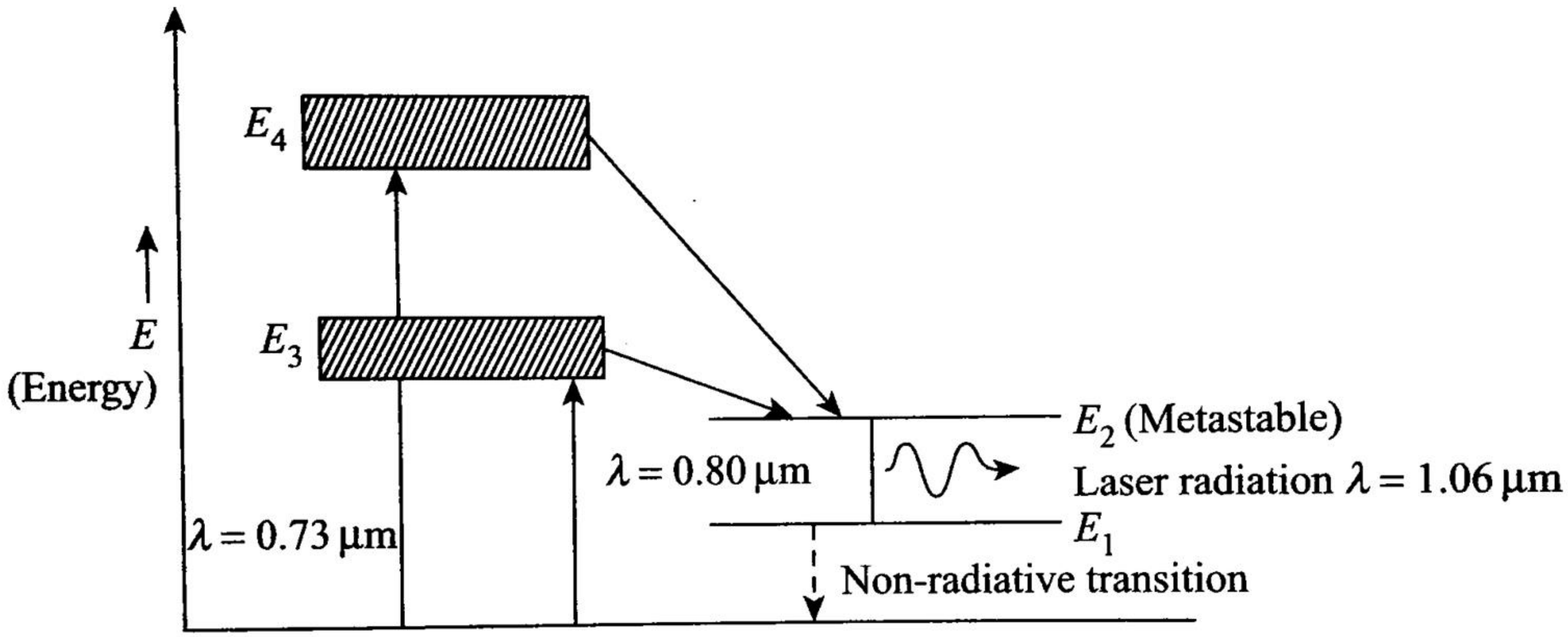
Construction



Energy level diagram



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Nd-YAG laser

- The laser rod and a flash lamp are kept inside an elliptical reflector cavity
- Nd atoms receives enough energy from photons of Krypton source and raises from GS to excited states E3 (0.80 μm) and E4 (0.73 μm)
- Nd* will undergo fast decay transitions from E3 and E4 to metastable state E2
- Creates PI between E2 and E1 (allowing spontaneous transitions from E2 to E1)

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Nd-YAG laser

- Which triggers stimulated emission of photons having same WL
- Resonant cavity multiplies the number of photons, hence light amplification
- Allows laser emission of WL 1.06 μm
- Transitions from E1 to GS is very rapid/non-radiative
- System can be cooled with the help of forced-air or water cooling mechanism

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Semiconductor laser

- Types: Homo and hetero
- p-n junction under forward bias
- Injection of carriers across junction
- Electrons and holes get recombined in the SCR
- Si, Ge (indirect band gap) releases energy in the form of heat
- Direct band gap semiconductors (GaAs) releases energy in the form of light

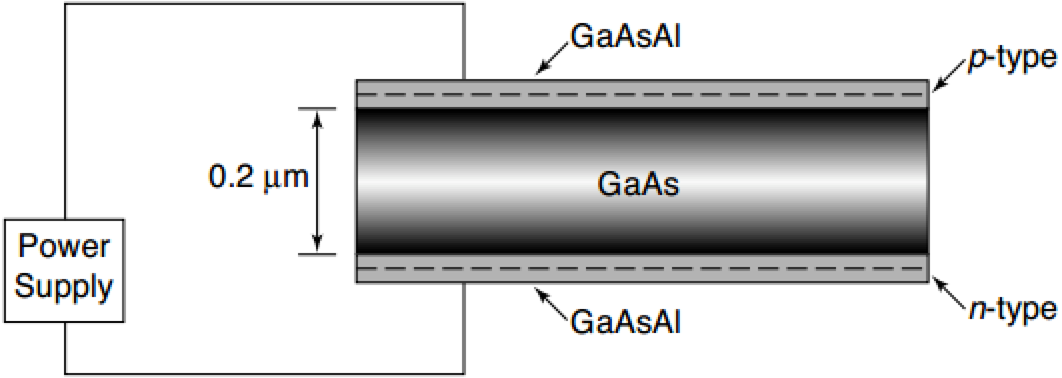

FIGURE 4.19

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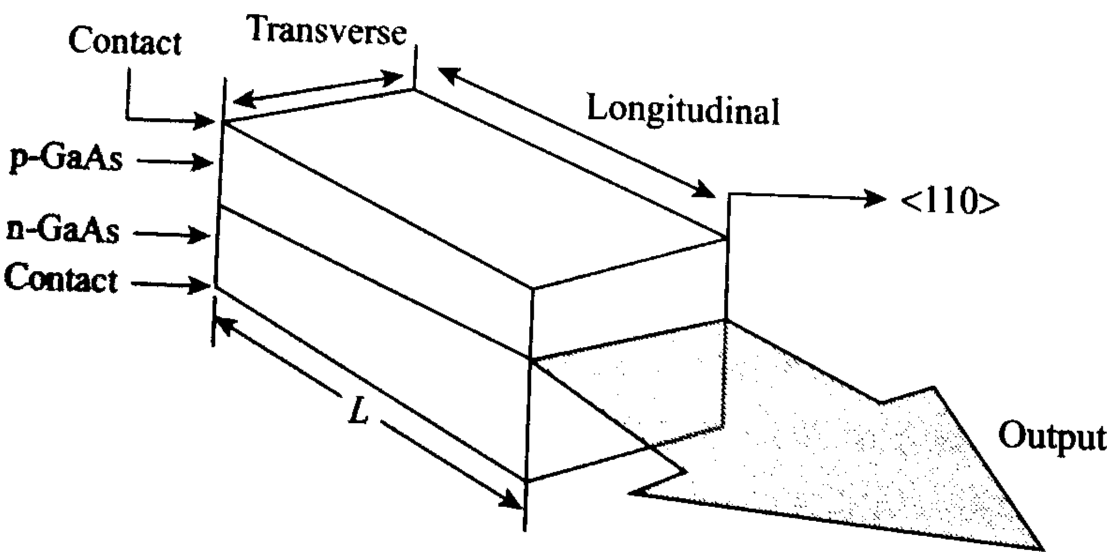
Homojunction laser



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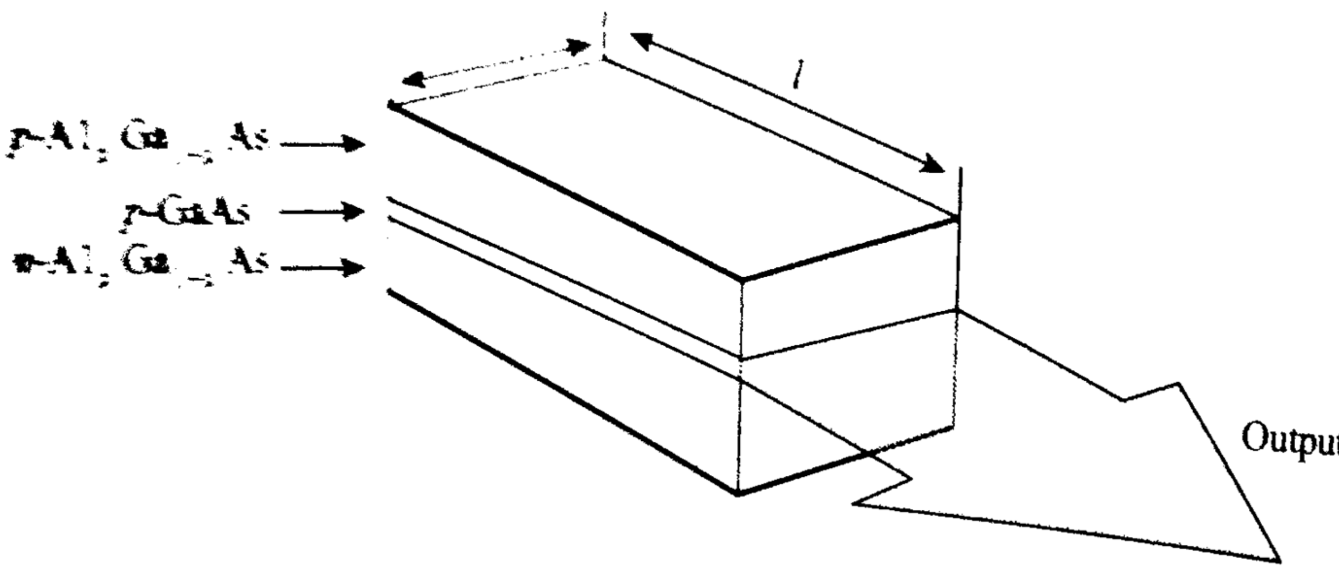
Heterojunction laser

- Different band gap semiconductors
- Lattice mismatch should be minimum



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Applications of lasers

Many applications in science, industry and medicine

1. To measure long distances, so they are very useful in surveying and ranging [fast laser pulse is sent to a target reflector at the point to be measured and the time of reflection is measured to get the distance]

2. Lasers are electromagnetic waves of very high intensity and can be used to study the laws of interaction of atoms and molecules

3. Lasers are suitable for communication and they have significant advantages because of high monochromaticity. So communication can be sent at a higher rates without overlap of the pulses

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Applications of lasers

4. Laser beams are highly intense and are used for welding, cutting of materials, machining and drilling holes, etc. Generally CO2 laser are used for such purposes, as it carries large power

5. Lasers are used in eye surgery, dental treatment and skin diseases

6. The laser beam is used in recording of intensity as well as in holography

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Applications of lasers

7. Laser is used in heat treatments of hardening

8. Lasers are used in barcode scanners in library and supermarkets

9. Laser is used in printers

10. Laser are used in photodiode detection

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Holography

- History
- Principle
- Recording
- Reconstruction

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Holography (Recording and reconstruction of hologram)

- Gabor in 1947 invented holography (no laser, mercury arc lamp was used for 1st experiemnt)
- Noble price: 1971
- Originated from Greek words "holos" and "grapho". The meaning of "holo" is "whole" and of "grapho" is "write"
- So holography means complete record of image
- First laser hologram: 1963 (Leith and Upatneiks)
- 3D laser photography

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Holography

- Light scattered from an object carries information about the object in the form of amplitude and phase
- In normal photography, only amplitude of the scattered light is recorded
- However, morphological information of the object which is contained in the phase is lost
- Thus ordinary photographs contains only 2D record of a 3D object

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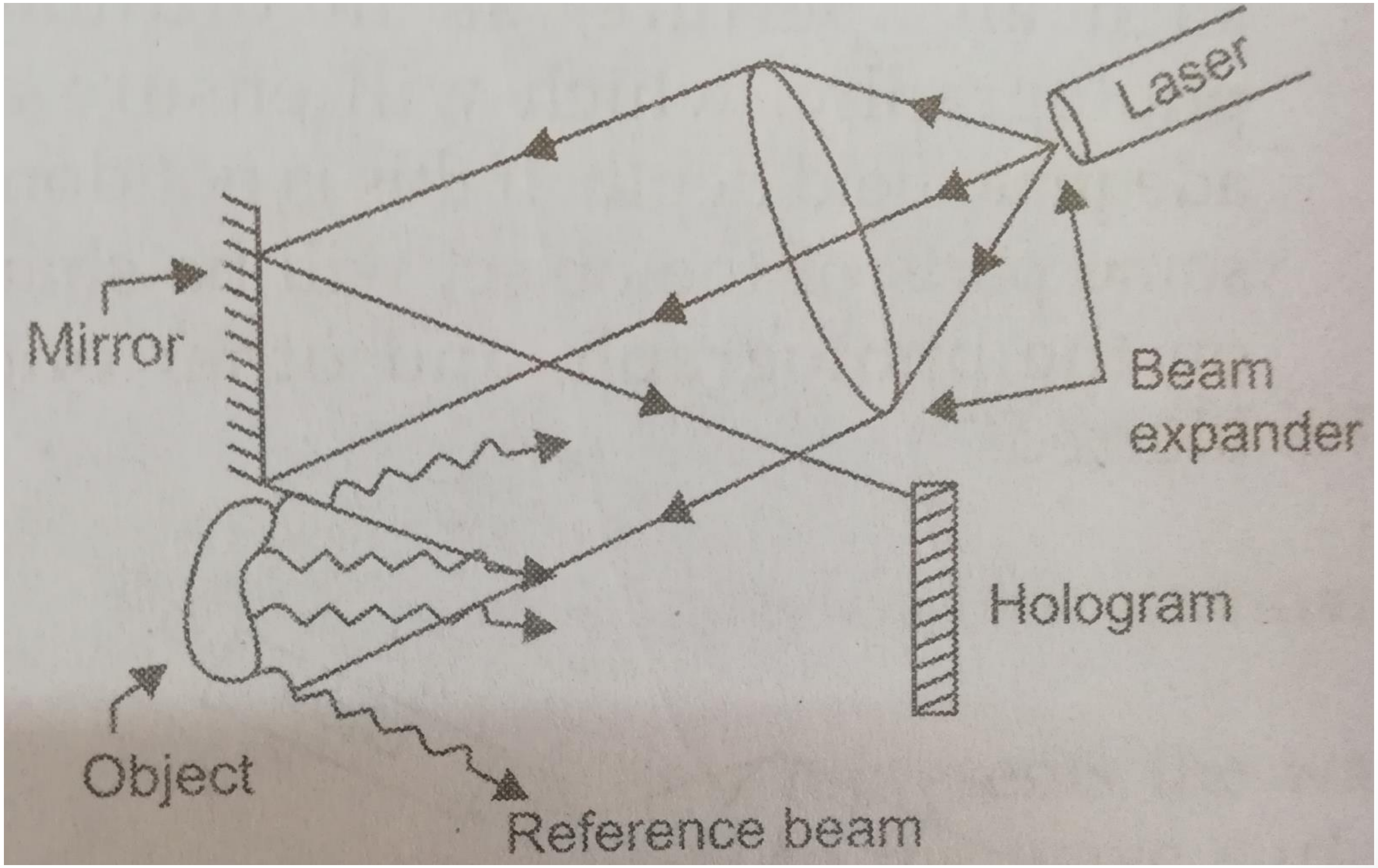
Principle of recording



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Recording of holograph

- A laser beam is split into two using a beam splitter.
- 1: illuminating beam (used to illuminate the object), illuminating beam scattered from an object is called <u>object beam or carrier beam</u>
- 2: reference beam (will be in coherence with illuminating beam)
- The holographic plate is exposed to the object beam and reference beam simultaneously, and it records the interference pattern form by them.

Reconstruction

- Then holographic plate is developed and again illuminated with the same interference beam (reference beam).
- Most of the light from such reference beam will pass through the holograph, however, some of it is diffracted due to the interference pattern recorded previously.
- The diffracted beam is identical with an object beam, and for an observer, the diffracted beam appears to come from the object itself

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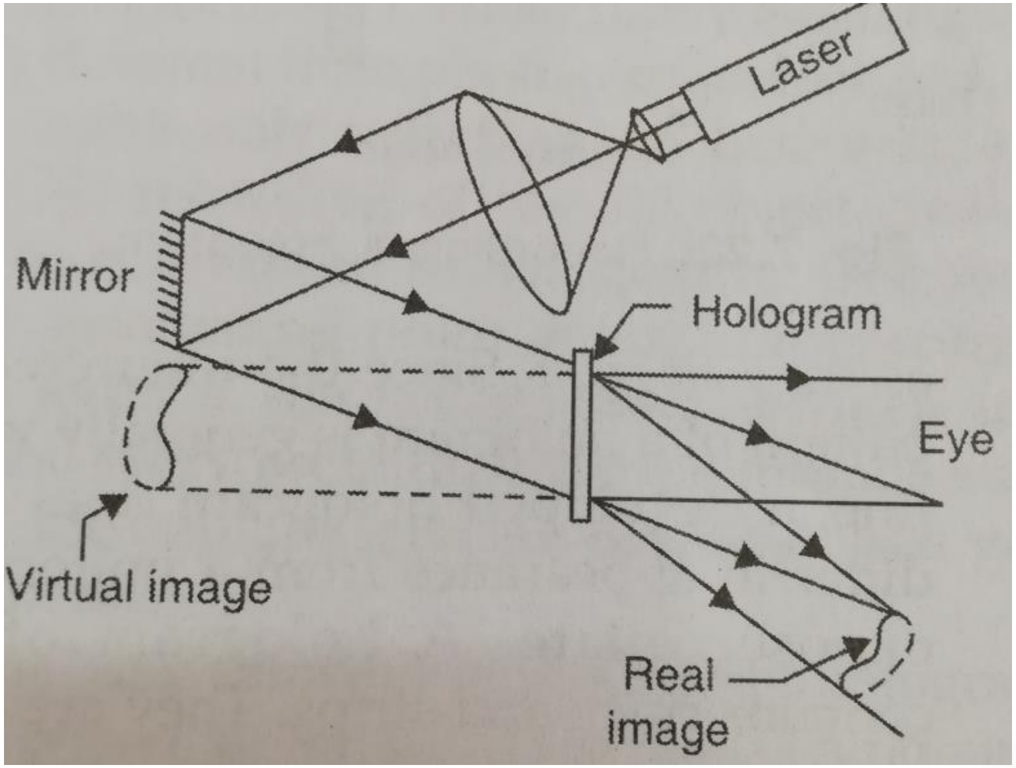
Principle of reconstruction

- A properly prepared and reilluminated holograph appears as a window, and an observer gets an experience of viewing a real object through the window with different angles and elevations.



Requirements

- (i) Since holography is an interference phenomenon, there should not be a path difference between the object wave and the reference wave more than the coherence length. This is necessary to achieve stable interference fringes.
- (ii) Spatial coherence is important so that the reference wave and the scattered object waves from different regions can interfere properly.
- (iii) Since reconstructed image coordinates depend on wavelength as well as position of the reconstructing source, it is necessary that the source emits a narrow band of wavelength and it is not broad in the interest of obtaining good resolution in the reconstructed image.

Requirements

- (iv) In order to obtain aberrations free reconstructed image, it is necessary that the reconstructing source is of the same wavelength and is situated at the same position with respect to the hologram as the reference source.
- (v) All recording arrangement like film, object, mirrors etc., must be motionless during the exposure.

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END OF UNIT-2

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