Laser Physics

Books

- Laser Fundamentals

  William Silfvast, Cambridge Publ.

- Optics

  Ajoy Ghatak

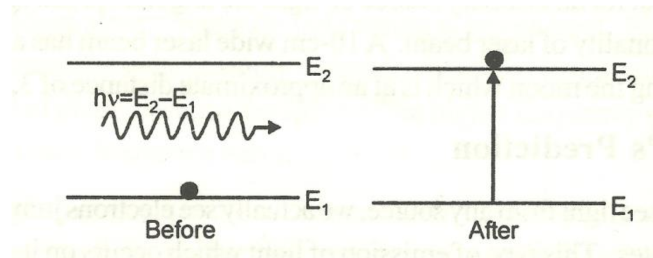
Background

- Light Amplification by Stimulated Emission of Radiation (LASER)
- Einstein – 1917 – Theory of Stimulated Emission, courtesy Population Inversion
- Charles H. Townes et. al., - 1951 – MASER
- Theodore Maiman – 1960 – Ruby LASER

Radiation interaction with atomic energy levels

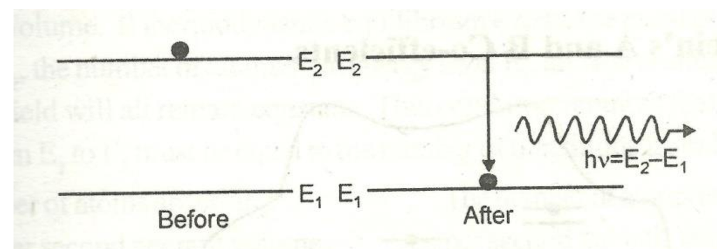
- Absorption

  (Depends on energy density of radiation & no. of atoms in lower level)



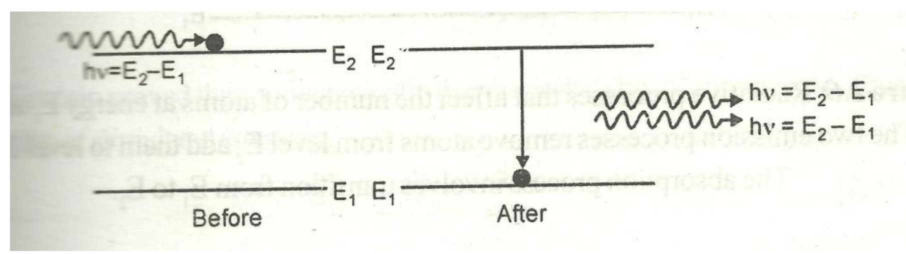
- Spontaneous Emission

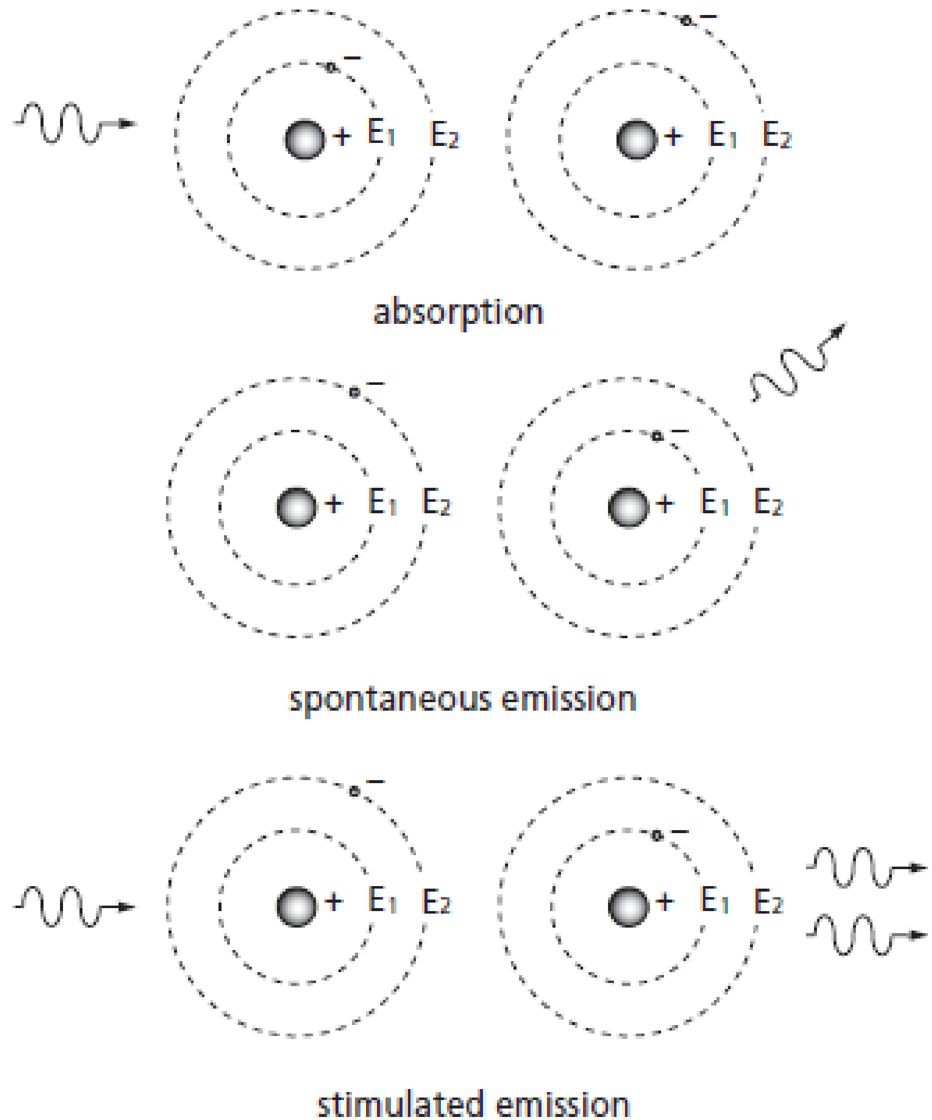
  (Depends on no. of atoms in excited level)



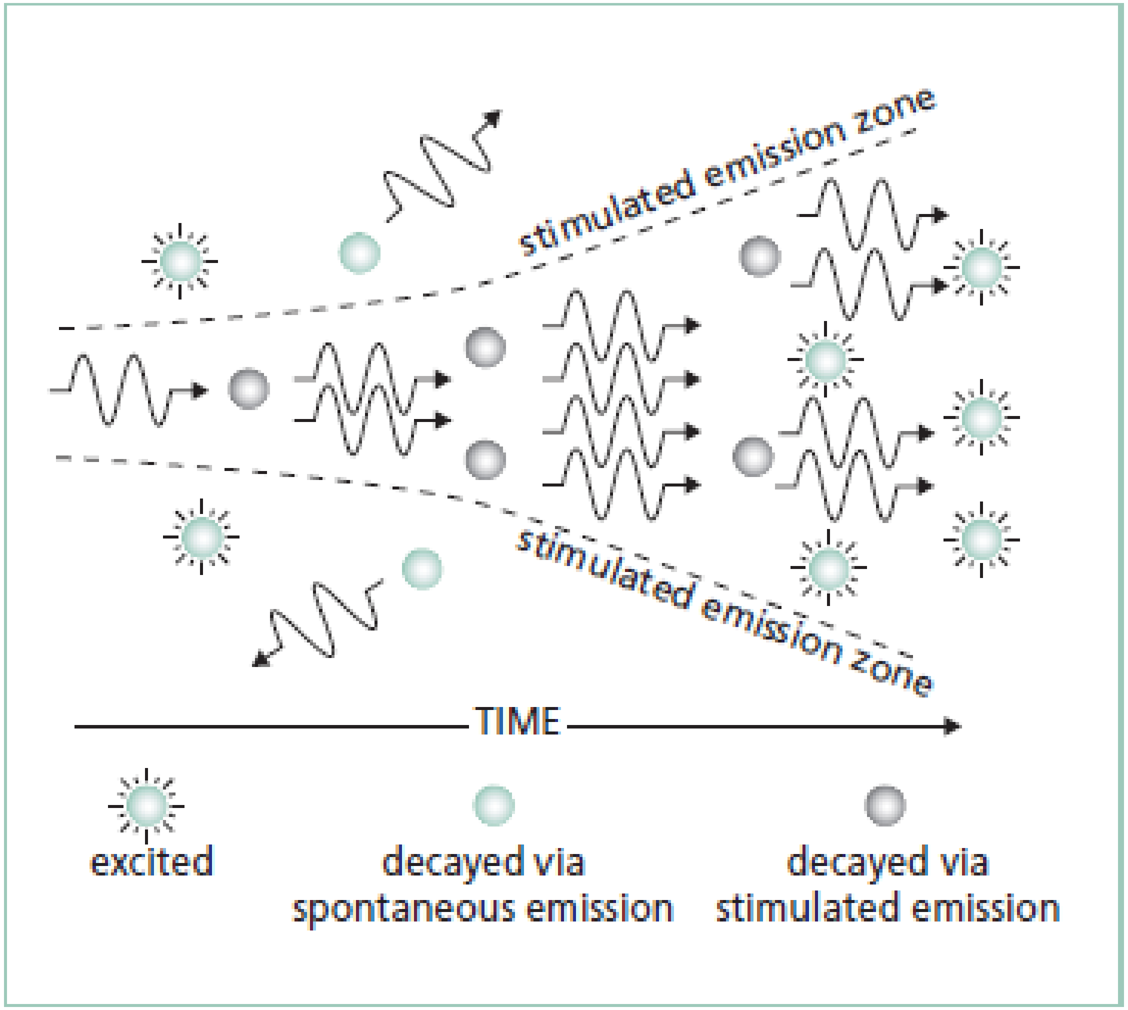
- Stimulated Emission

  (Depends on energy density of radiation & no. of atoms in excited state)




+ E1 E2
absorption
spontaneous emission
stimulated emission

Laser Principle



Properties of LASER

- Monochromatic
- Coherence
- High Intensity
- Directionality

Monochromaticity

- Light of single wavelength or frequency
- Practically, there exists a beam-width; very small compared to ordinary light
- Degree of non-monochromaticity,

$$\xi = \Delta\nu/\upsilon_o ,$$

$$\Delta\nu = \text{bandwidth}$$

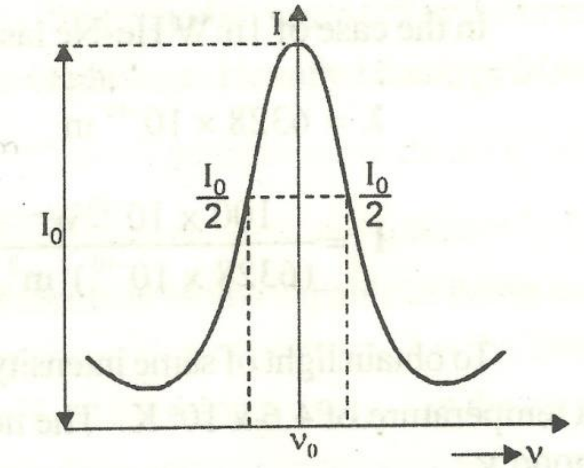


Figure 2.1: Line Width diagram

Reasons for Monochromaticity

- Transition between 2 well defined energy levels
- EM wave of frequency n = E_2-E_1 can only be amplified, n the line width
- Laser cavity forms a resonant system – laser oscillations sustained only at resonant frequencies – Narrowing of laser line width

Reasons for Broadening

- Doppler broadening

  (due to thermal motion of gas atoms – Gaussian distribution)

- Natural broadening

  (due to spontaneous emission – Lorentzian distribution)

- Collisional broadening

  (due to atomic collisions)

Coherence

- Waves need to be in phase with each other

- Conditions:

  Waves starts with same phase at same position

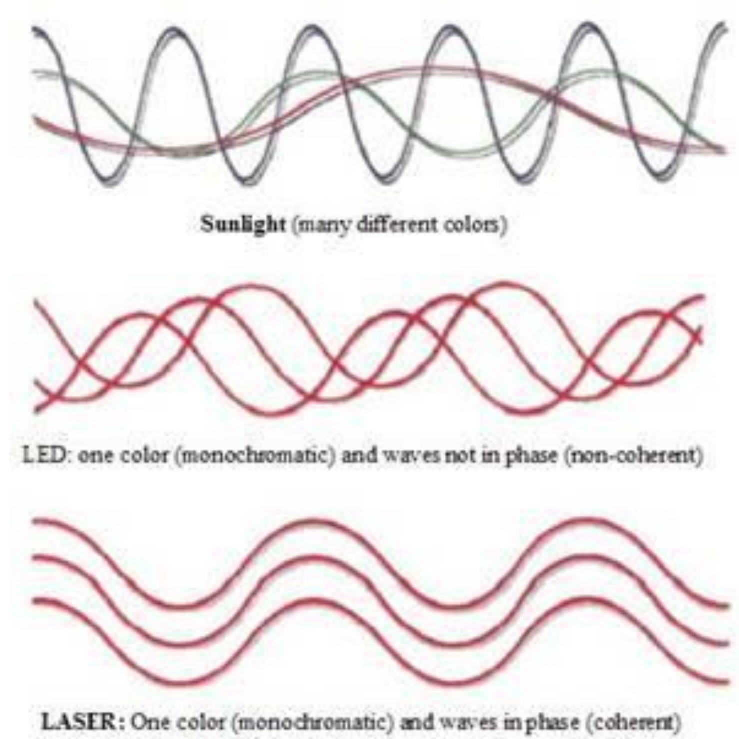
  Wavelengths must be the same

- Spatial –

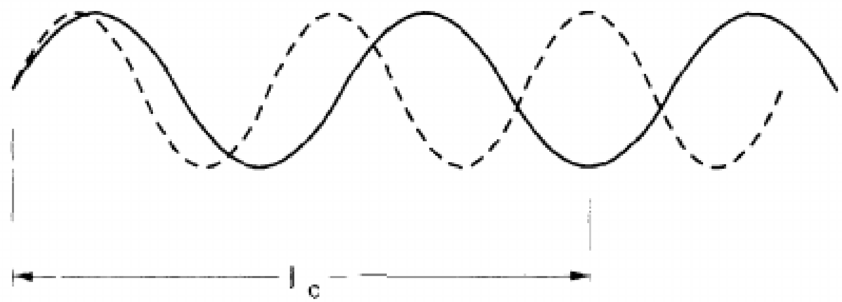
  Correlation between waves at different places – constant phase difference over any time ‘t’

- Temporal –

  Correlation between waves at one place at different times - constant phase difference over a given time interval



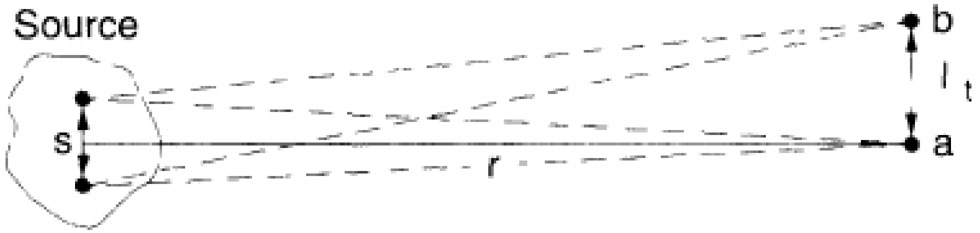
- Temporal Coherence



$$l_c = \lambda\left(\frac{\lambda}{\Delta\lambda}\right) = \frac{\lambda^2}{\Delta\lambda},$$

where $\lambda = (\lambda_1 + \lambda_2)/2$ & $\Delta\lambda = \lambda_1 - \lambda_2$

- Spatial Coherence



$$l_t = \frac{r\lambda}{s} = \frac{\lambda}{\theta_s}$$

Intensity

- Energy concentrated in a beam of very small cross section

- Intensity $I = P * (10/\lambda)^2$,

  P – power radiated by laser

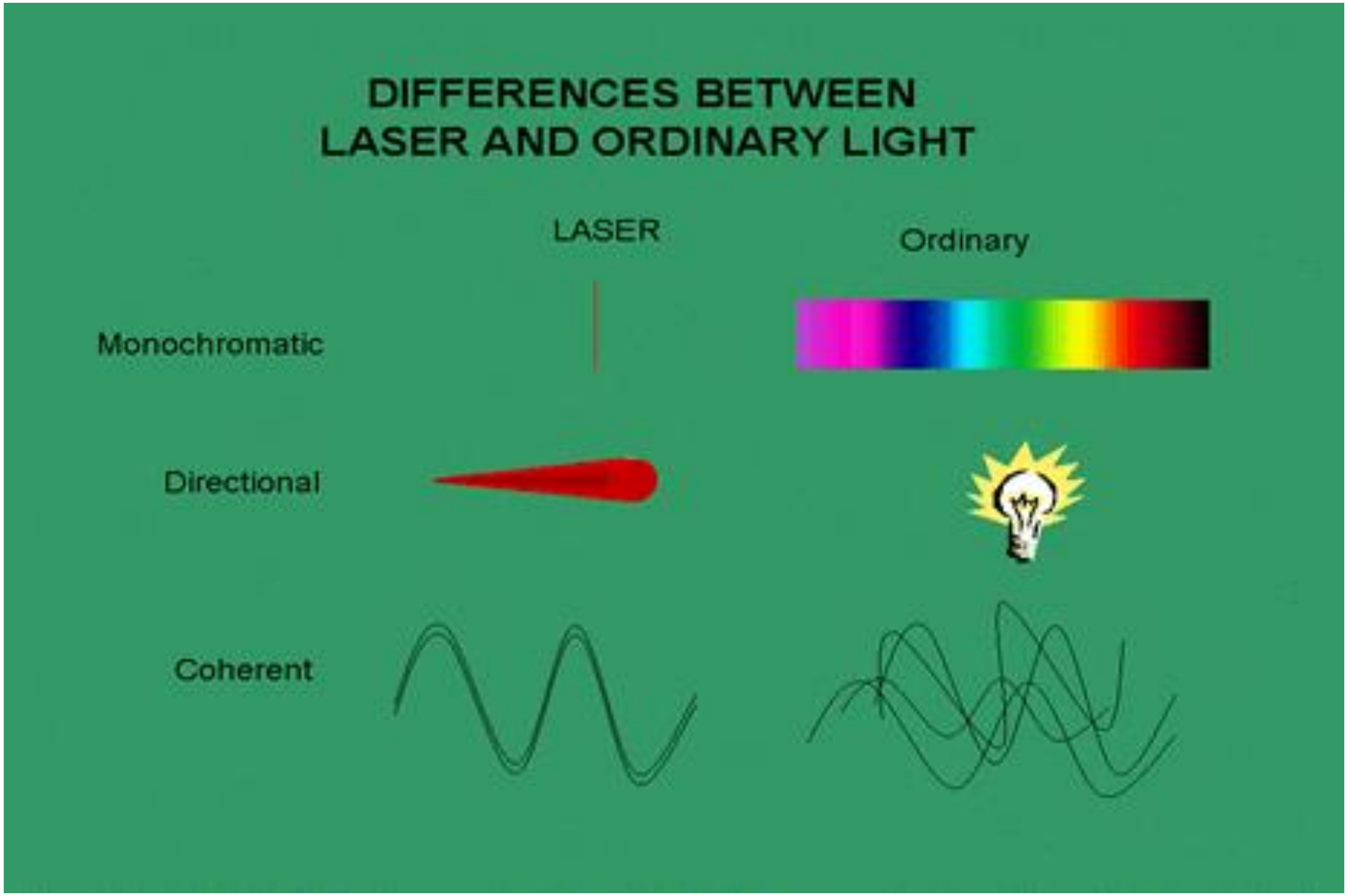
Directionality

- Highly Directional

- d^2/λ, d – diameter of aperture thru which light is passing

- Ordinary beam – angular spread **1m per 1m**
- Laser beam – angular spread **1mm per 1m**

Properties


DIFFERENCES BETWEEN
LASER AND ORDINARY LIGHT
LASER
Ordinary
Monochromatic
Directional
Coherent

Einstein Coefficients

- Concept of absorption and stimulated emission
- Let N_u be number of atoms in upper level 'u'

  and N_l be number of atoms in lower level 'l'
- At thermal equilibrium, number of atoms are related by Boltzmann distribution function….

i.e., $N_u = \exp(-E_u/kT)$ and $N_l = \exp(-E_l/kT)$

Hence, $\dfrac{N_u}{N_l}$

$$= \exp\left[-\frac{(E_u - E_l)}{kT}\right] = \exp\left[-\frac{(\Delta E_{ul})}{kT}\right] = \exp\left[-\frac{(h\nu_{ul})}{kT}\right]$$

- Let A_{ul} $(= 1/\tau_u)$ be spontaneous transition probability between levels u and l
- Number of spontaneous transitions from u to l/unit time/volume

$$= N_u A_{ul}$$

- Number of stimulated upward transitions from l to u/unit time/volume

$$= N_l B_{lu} u(\nu)$$

- Number of stimulated transitions from u to l/unit time/volume

$$= N_u B_{ul} u(\nu)$$

where A and B are Einstein coefficients

- Principle of detailed balance…

$$N_u A_{ul} + N_u B_{ul} u(\nu) = N_l B_{lu} u(\nu)$$

- $$u(\nu) = \frac{N_u A_{ul}}{(N_l B_{lu} - N_u B_{ul})}$$
$$= \frac{A_{ul}/B_{ul}}{(N_l B_{lu}/N_u B_{ul}) - 1}$$

- we know $\frac{N_u}{N_l} = \exp\left[- \frac{(h\nu_{ul})}{kT}\right]$
- Replacing here , we get

$$u(\nu) = \frac{A_{ul}/B_{ul}}{\{\exp\left[\frac{(h\nu_{ul})}{kT}\right]\left(\frac{B_{lu}}{B_{ul}}\right)\} - 1}$$

- Comparing with Planck's law of radiation,

$$u(\nu)d\nu = \frac{8\pi\, h\nu^3}{c^3\,[\exp\left(\frac{h\nu}{kT}\right)-1]}\,d\nu$$

$$u(\nu) = \frac{A_{ul}/B_{ul}}{(\exp[\frac{(h\ \nu_{ul})}{kT}])(B_{lu}/B_{ul}) - 1}$$

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

$$B_{lu} = B_{ul}$$

Conditions for Lasing

- Population Inversion (PI)

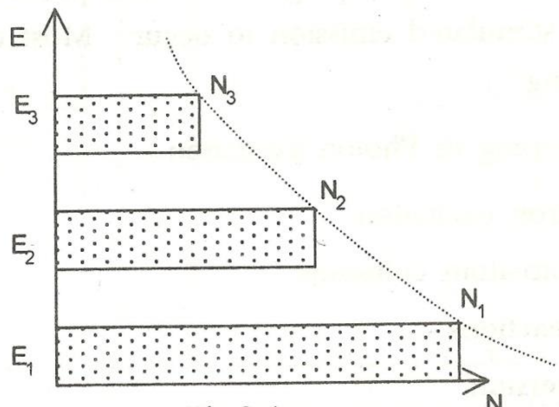


Fig 2.4.

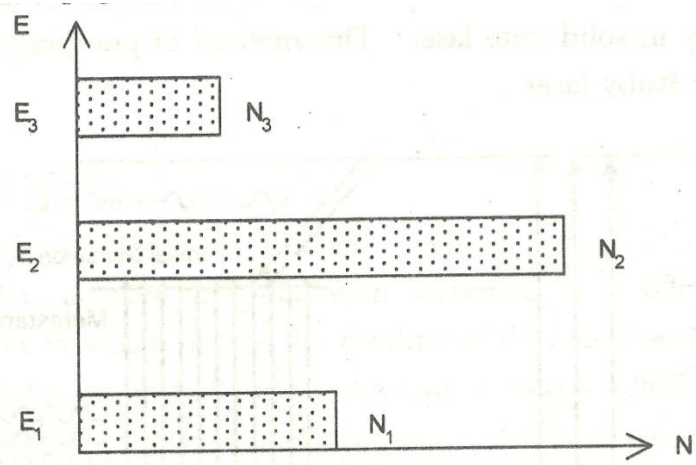
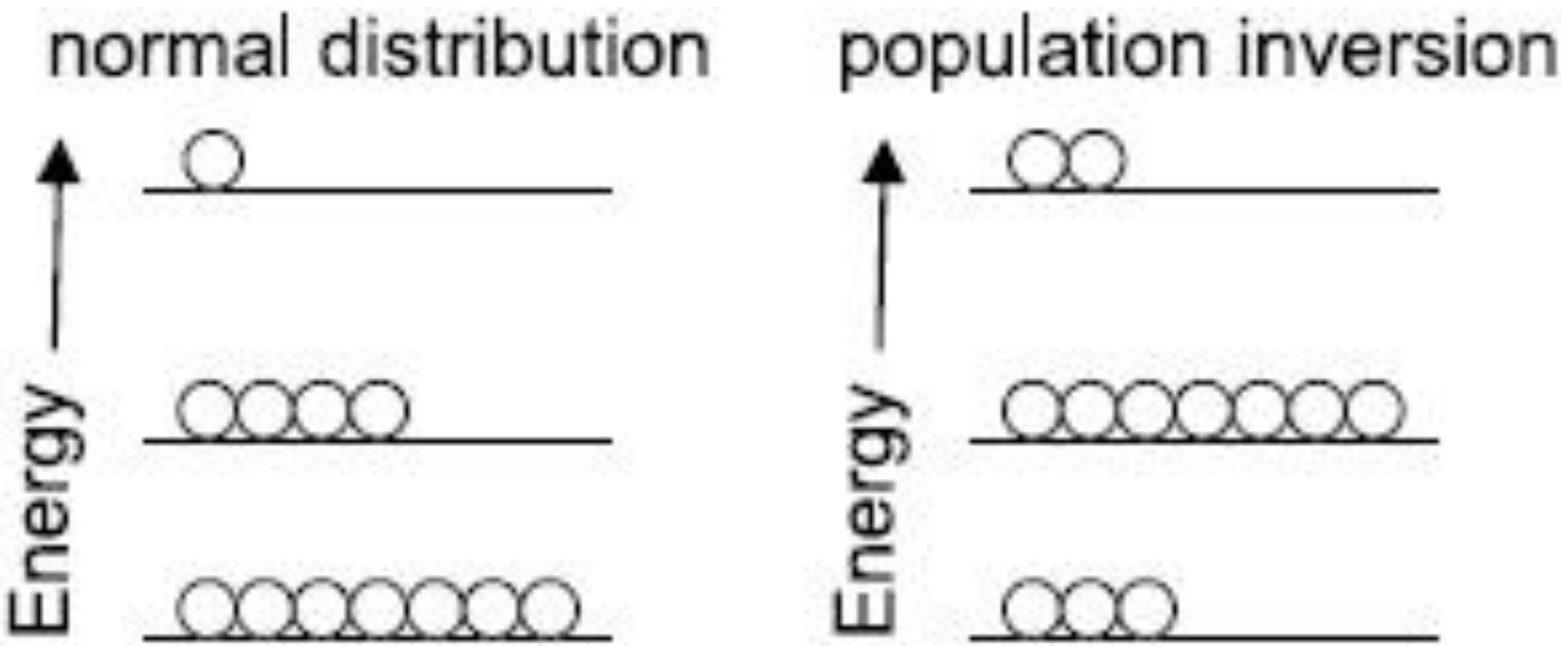


Fig 2.5.

Dotted curve – Boltzmann distribution

Population Inversion



Attenuation **Amplification**

Methods of achieving Population Inversion

- Active Medium

  Medium in which PI is achieved

  Solid, Liquid or Gas

- Pumping

  Process by which atoms are raised from lower level to upper level

Methods of Pumping

- Optical Pumping
- Electrical Discharge or Direct Electron Excitation
- Inelastic atom-atom collisions
- Direct Conversion

Optical Pumping

- For Solid State laser, ex., Ruby laser
- Light sources like Xe flash lamp

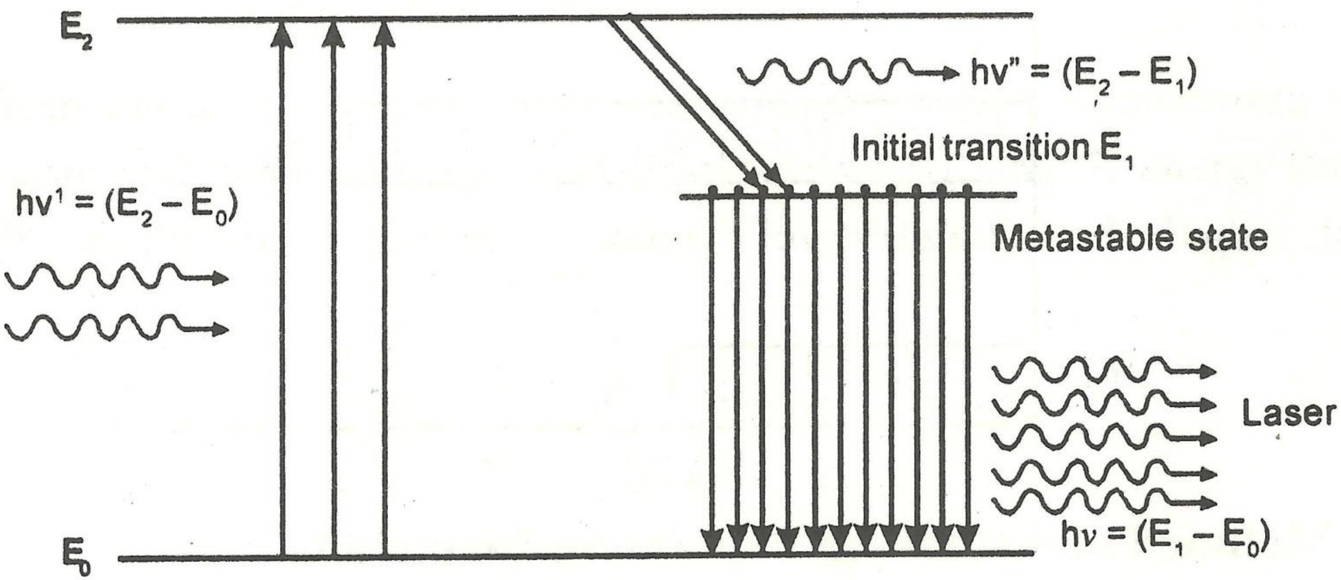


Fig 2.6. Optical Pumping

Electrical Discharge or Direct Electron Excitation

- For Gaseous lasers, eg., Argon ion laser
- Electric discharge thru gas – e$^-$ collide with atoms in medium, ionize and raise to higher level - PI

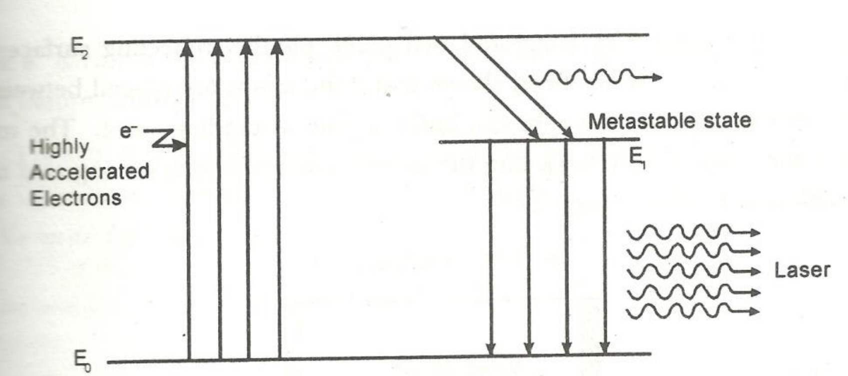


Fig 2.7. Direct Electron Excitation

Inelastic atom-atom collision

- Ex. He-Ne laser
- Initial excitation of A atoms - Electrical discharge – A*
- A* + atom B --- B* (PI)

Direct Conversion

- For Semiconductor lasers
- Current carriers are excited (not atoms)
- PI in junction region
- e^- - hole recombination leads to light

Pumping Scheme

- Two level
- Three level
- Four level

Two level pumping scheme

- Drawbacks
- Difficult to maintain collection of atoms in excited states until they are stimulated to emit photon
- Ground state atoms undergo absorption and thus will remove photons from the beam

Three level pumping scheme

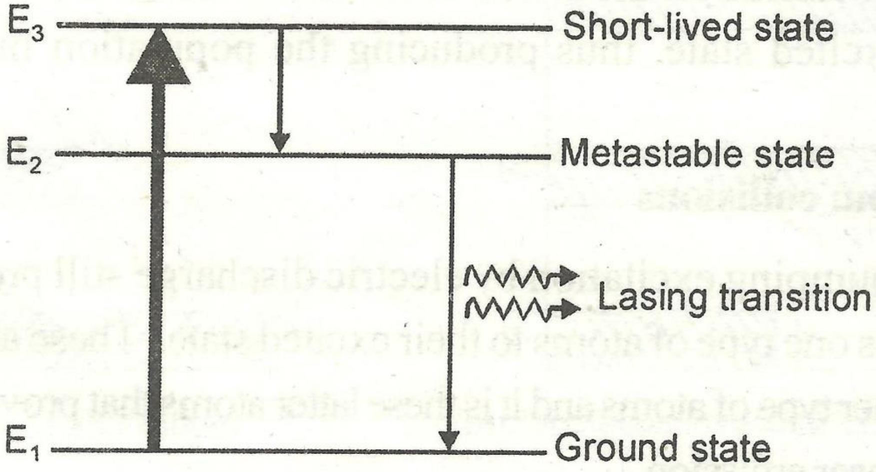


Figure 2.8(a): A three-level laser

Spontaneous emission to Metastable state

- Lifetime in metastable state - 10^{-6} to 10^{-3} s, More than excited state
- PI occurs in metastable state
- Presence of this metastable state Solves the problem of placing the atoms in excited states (drawback 1) , but not removal of photons from the beam (drawback 2)
- 3 level system requires high pump powers
- Pulsed light only

Four level pumping scheme

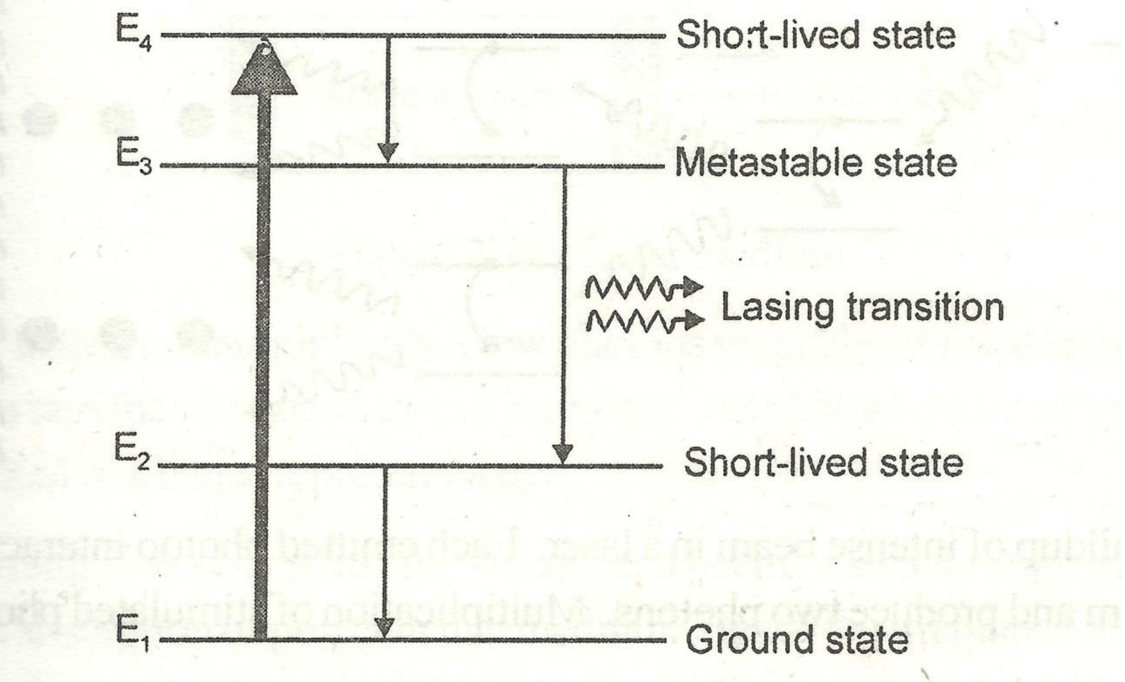


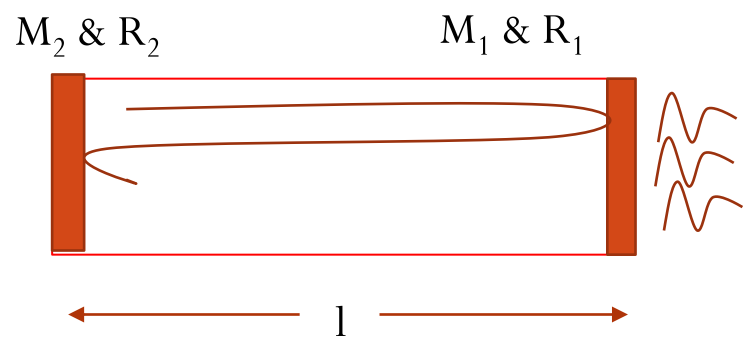
Figure 2.8(b): Four-level laser

- Solves the problem of photon loss
- Transition to metastable state (E3) on similar lines of 3 level laser
- Lasing from E3 to E2 state and E2 to E1 – Rapid decay
- Ground state atom cannot absorb at energy of lasing transition
- Require less pumping energy & continuous mode operation

Threshold Condition

- Consider a cavity made of 2 mirrors of length ‘l’
- Let I_0 be the initial intensity of radiation.
- Intensity after travelling a distance ‘l’ through the medium will be

$$I = I_0 \exp(-\alpha L)$$



- α – absorption coefficient
- This is attenuation

- For amplification, the eqn can be written as

$$I = I_0 \exp(kL)$$

where $k = -\alpha$ is defined as small signal gain coefficient

- Lets consider all possible losses
- Transmission at the mirror $\rightarrow$ useful loss
- Absorption and scattering by the medium
- Absorption and scattering by the mirrors
- Diffraction by the mirrors

- Let all losses except the useful loss be notated by γ

- Absorption eqn changes to

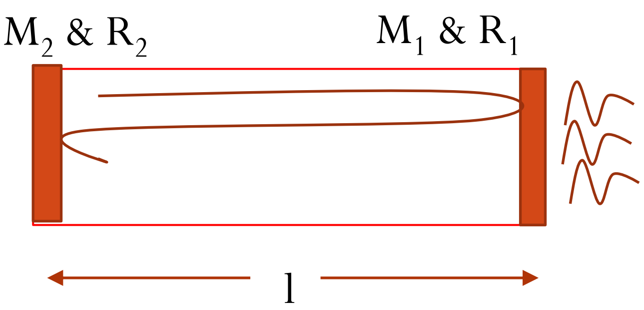
$$I = I_0 \exp (k- \gamma)L$$

- Intensity of beam after travelling a distance l and reflected from mirror M1 will be

$$I = I_0 R_1 \exp[(k-\gamma)L]$$

- Intensity of beam after coming towards M2 from M1 will be

$$I = I_0 R_1 \exp[2(k-\gamma)L]$$



- Intensity of beam after completing 1 cycle will be

$$I = I_0 R_1 R_2 \exp[2(k-\gamma)L]$$

- One round trip….

- Round trip gain G = Output intensity /Input intensity

- $$G = I / I_0 = 1 \text{ (for threshold condition)}$$

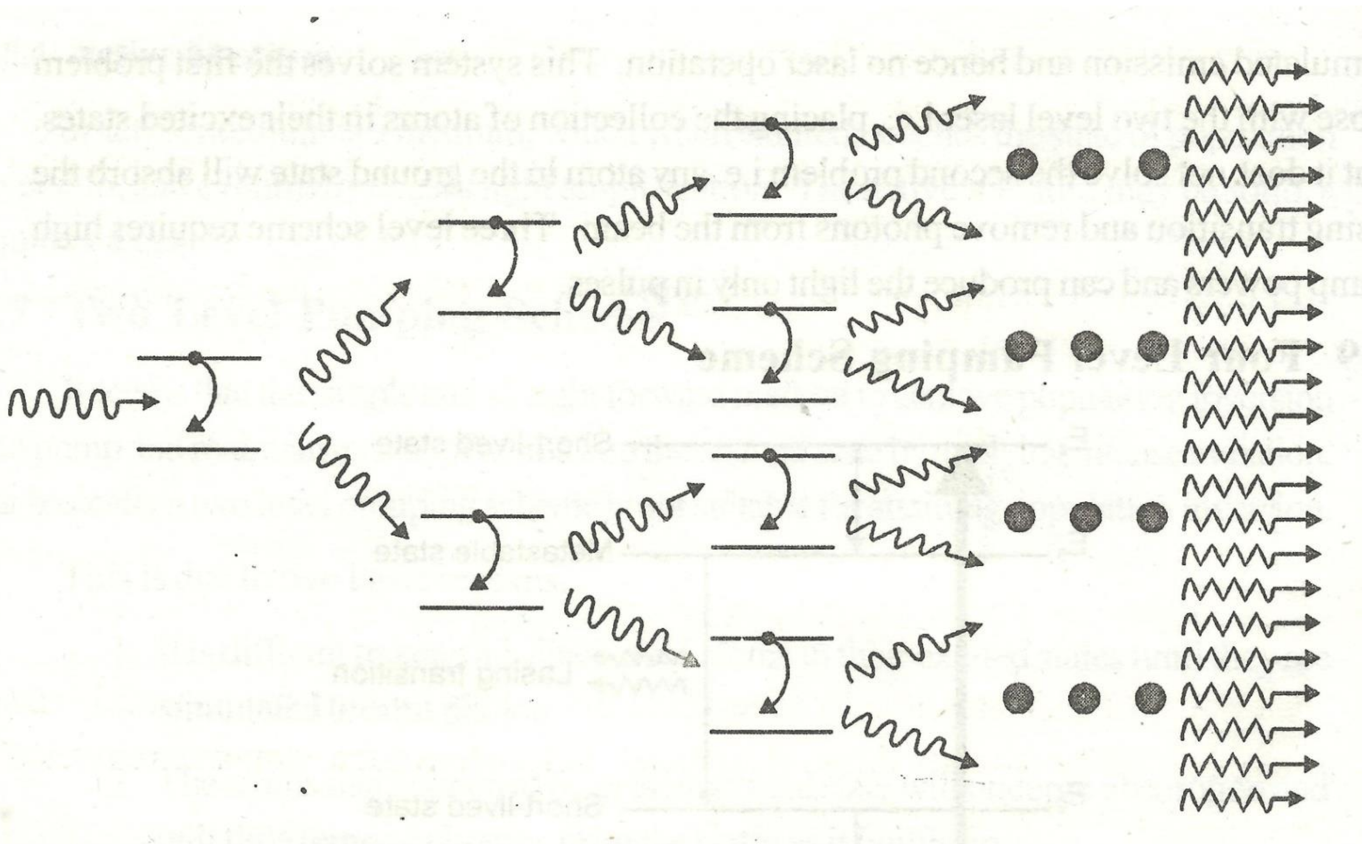
$$I_0 R_1 R_2 \exp [2(k-\gamma)L] / I_0 = 1$$

$$R_1 R_2 \exp [2(k-\gamma)L] = 1$$

$$\exp [2(k-\gamma)L] = 1/R_1 R_2$$

$$k_{th} = \gamma + (1/2L) \ln(1/R_1 R_2)$$

Principle of LASER



Multiplication of Photons

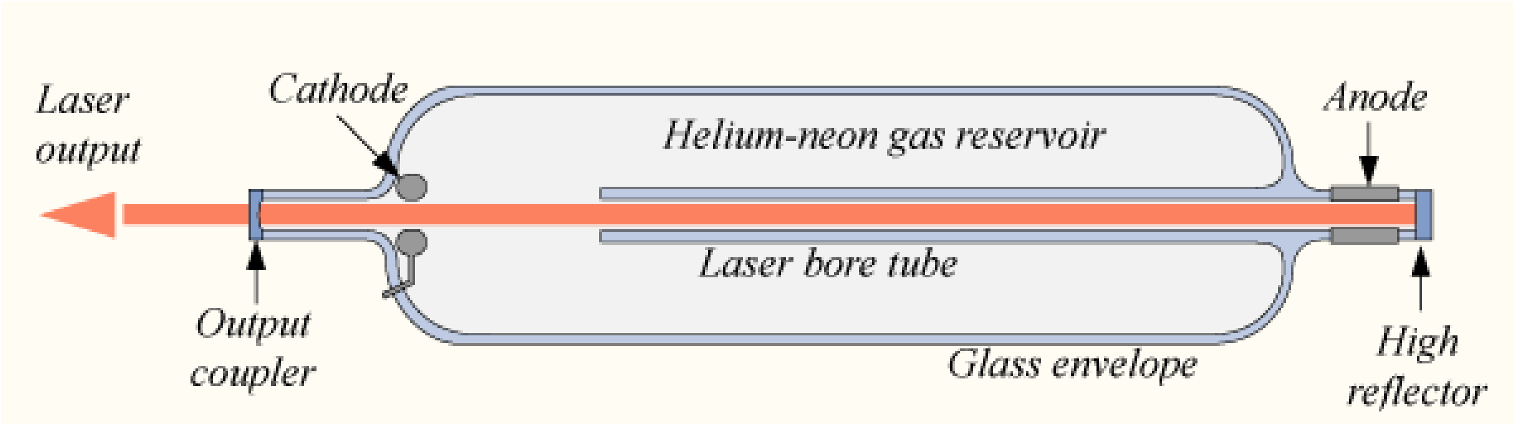
Lasers - Types

- Solid State laser - Ruby, Nd:YAG
- Gas laser – He-Ne, CO_2, Argon-ion
- Liquid laser – $SeOCl_2$
- Dye laser – Rhodamine 6G
- Semiconductor laser – GaAs, InP

He – Ne laser

- 1961
- Four level
- Active medium - He : Ne = 10 : 1 (approx.) (5:1 to 20:1); Low pressure
- Various λ – 633 nm, 1150 nm, 3390 nm
- Continuous Mode

He-Ne laser setup



1 kV - Electrical discharge – 5 to 100 mA current

Cavity length – 15 to 50 cm; O/P Power – 0.5 – 100 mW

He-Ne laser setup

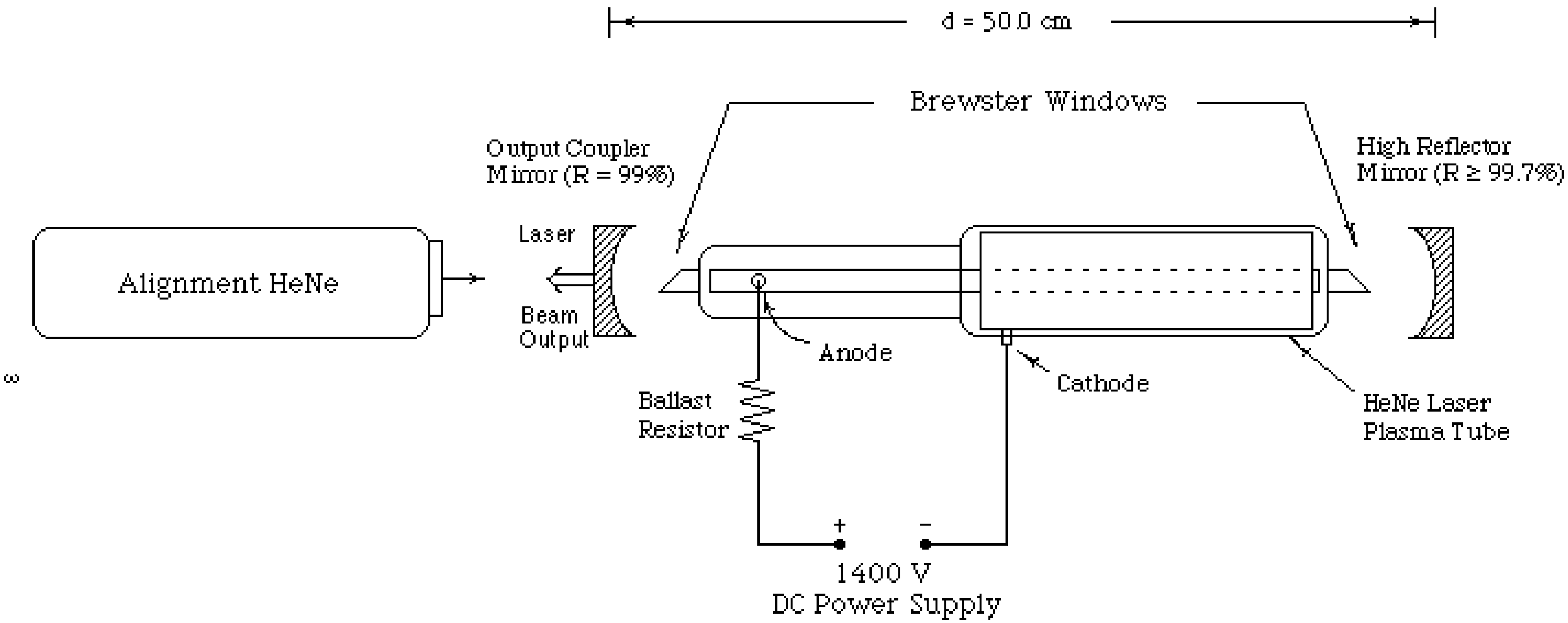
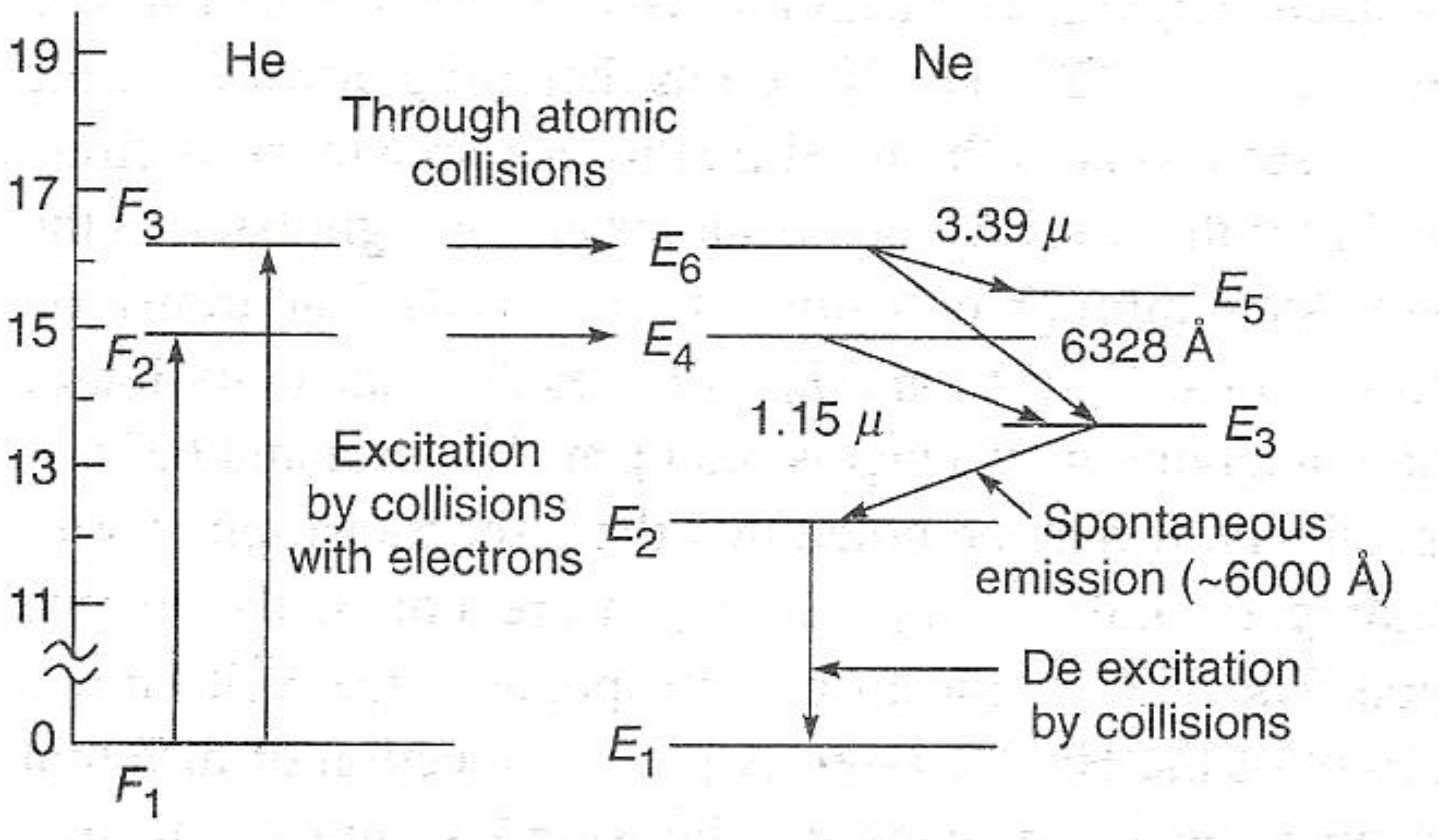


FIG. 2. Diagram of optical and electrical components used in the HeNe laser experiment

Energy Level Diagram



Working Process

- $e^- + He\ (GS)$ ----> $He^*(2^1S_0)(F_3)$

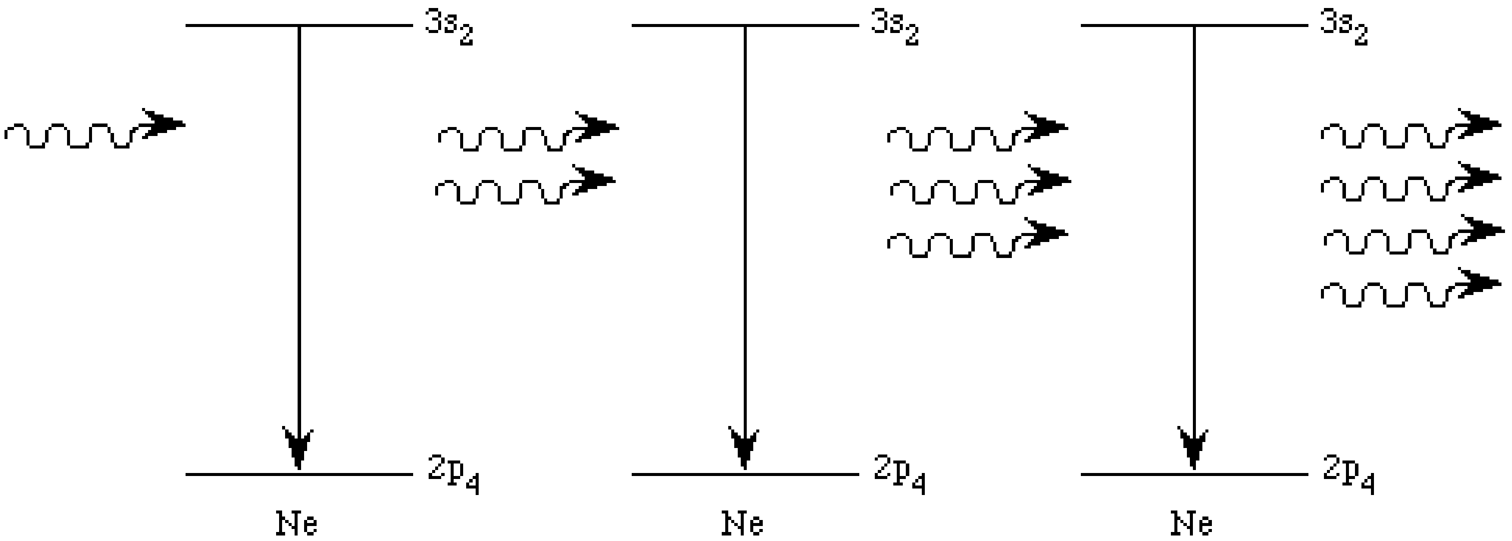
- $He^* + Ne\ (GS)$ -----> $Ne^*(3S_2)(E_6) + He(GS)$
  (Equiv. E levels – Resonant energy transfer occurs)

- $Ne^*(3S_2)(E_6)$ (Metastable–PI) --> $Ne^*(2P_4)(E_3)$ + 632 nm

- $Ne^*(2P_4)(E_3)$ -----> Ne (GS) (De-excitation)

- 632nm photon stimulates other excited $Ne^*(2P_4)(E_3)$ atoms leading to lasing

Stimulated Emission



(a)

Important Criteria

- Choose pressure of two gases such that PI is not quenched
- Selection of suitable end mirrors will lead to required wavelength of light
- E_2 is metastable - Atoms may get excited to E_3 leading to decrease in PI – Reduce the diameter of wall so that atoms get de-excited by collisions with the walls

Uses

- Reading Barcodes
- Holography – 3D images
- Industrial and Scientific

Solid State Lasers

- Active Medium – Solid Material (Glass or Crystal)
- Impurity atoms replace portion of solid material – act as lasing centers
- Solid material decides Physical properties (Thermal conductivity, Thermal expansion, etc.,) & Impurity atoms decides Optical properties
- Pulsed and Continuous mode

- Pulsed Lasers – Xe (or Kr) flash lamps
- Continuous Lasers – Halogen lamps, Mercury lamps

Nd Laser

- Neodymium (Nd^{3+}) impurity atoms (Active centers) – Rare Earth element

- Solid Host

  – Glass

  -Yttrium Aluminum Garnet (YAG)

  Crystal $Y_3Al_5O_{12}$

  - $LiYF_4$ (YLF) Crystal

Choice of Host

- Glass – Pulsed laser (High pulse power & slow pulse repetition rate) – 60% doping – Problem of low thermal conductivity

- YAG Crystal – High repetition rate pulses – 1% doping- Higher thermal conductivity helps removing large amount of heat from laser

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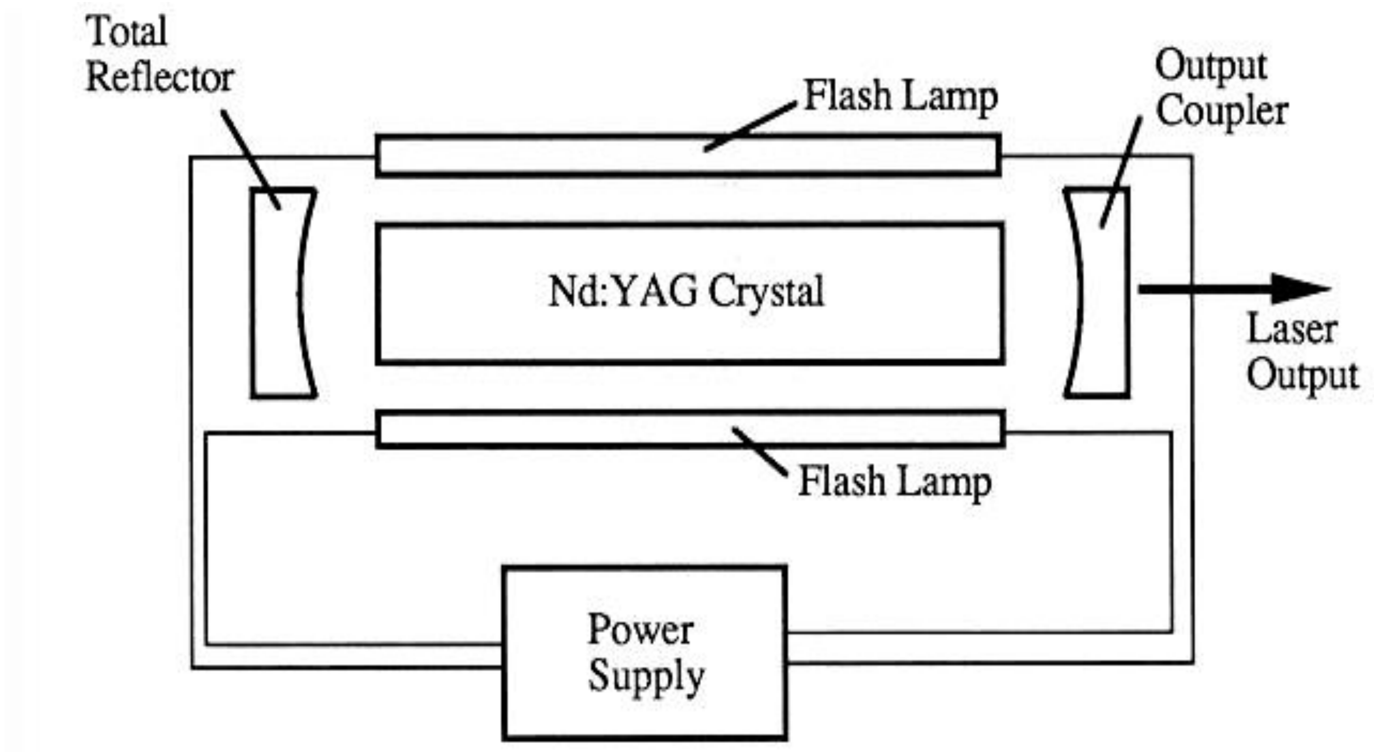
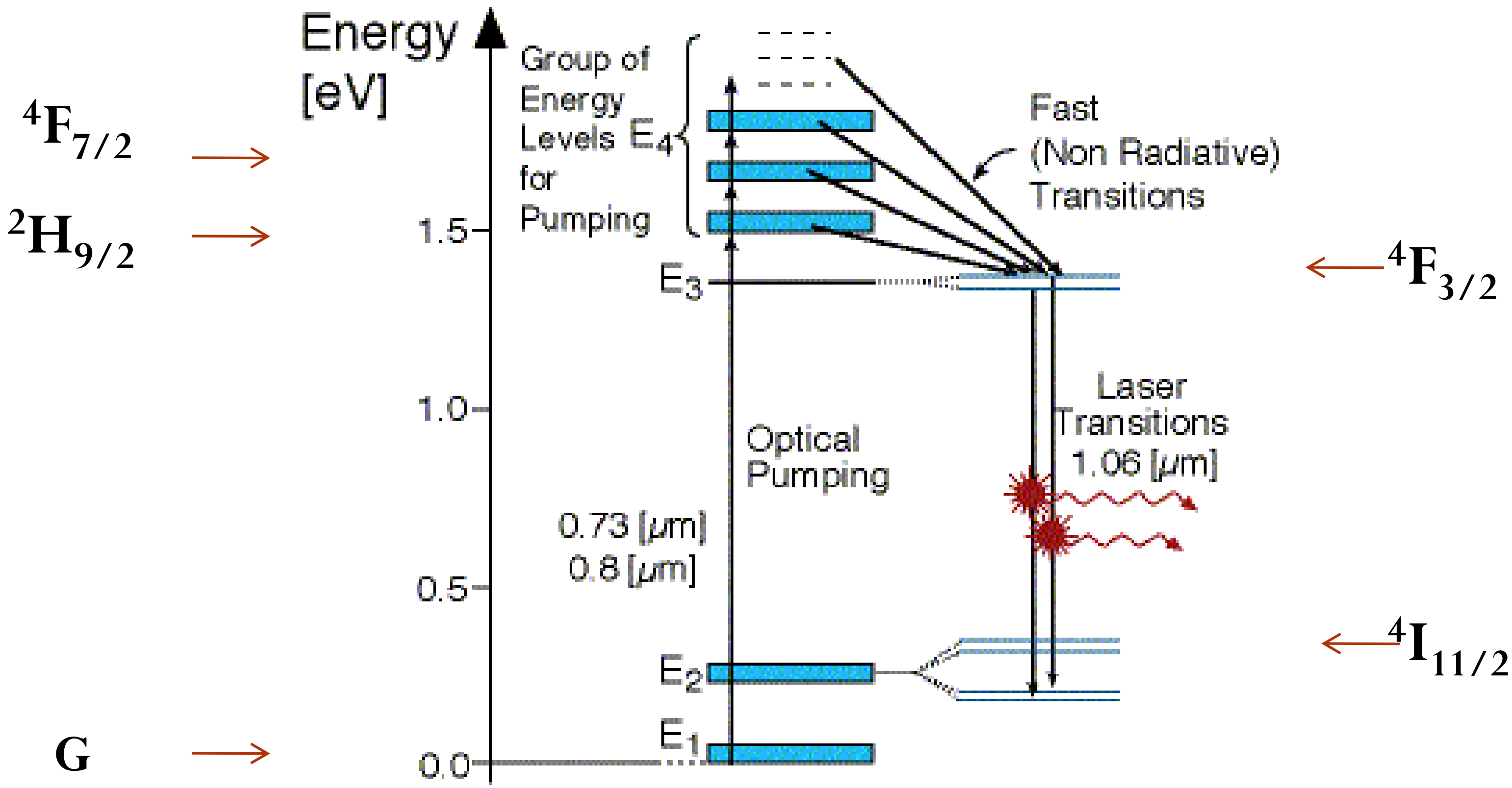
- Nd:YAG crystals – Absorption and Scattering losses are negligible

Schematic of Nd:YAG Laser

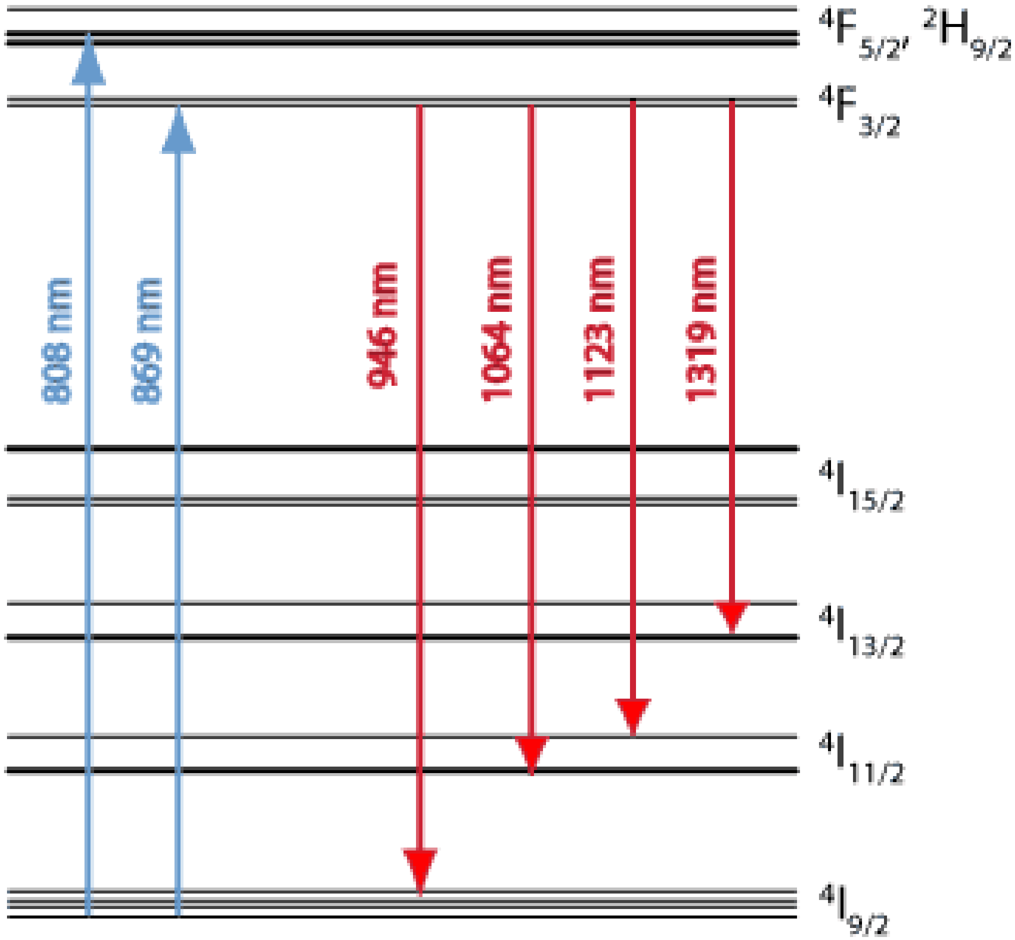


Optical Pumping

Energy Level Diagram



Various Possible Energy Levels Transitions



Operating precautions

- Efficiency 3%, But produces 30 times heat
- Cooling by flowing water over the outside of optical cavity

Applications

- Material processing like Drilling, Welding, Cutting etc.

- Medical Applications – Tissue evaporation

- Military Applications – Range finders, Target designators

- Scientific applications

- Pump sources for Dye lasers, Ti: sapphire lasers

Gas Lasers - Advantages

- Absence of effects like crystal imperfections, thermal distortion, scattering -> More directional and Monochromatic

- Operate continuously without need for cooling

Molecular Gas Laser

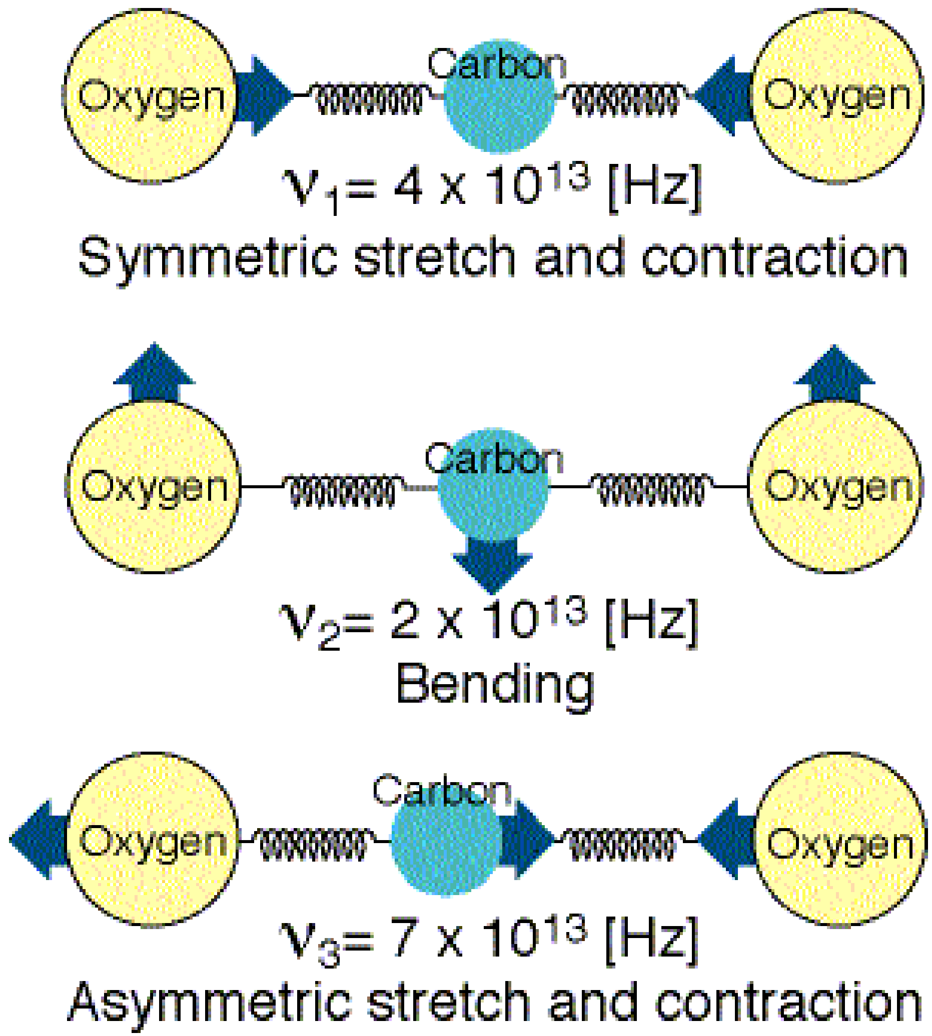
- Lasing in CO_2 molecule – C. Patel (1964)
- High power molecular gas laser
- Generate wide range of IR frequencies
- Suitable for Communication and Radar since scattering is very less

- Electric discharge pulse thru CO_2 gas – small laser o/p
- CO_2 - Active Medium – Lasing b/n Vibrational states
- CO_2 : N_2 : He ---- 1 : 1 : 8 **OR** 1 : 4 : 5 at various pressures

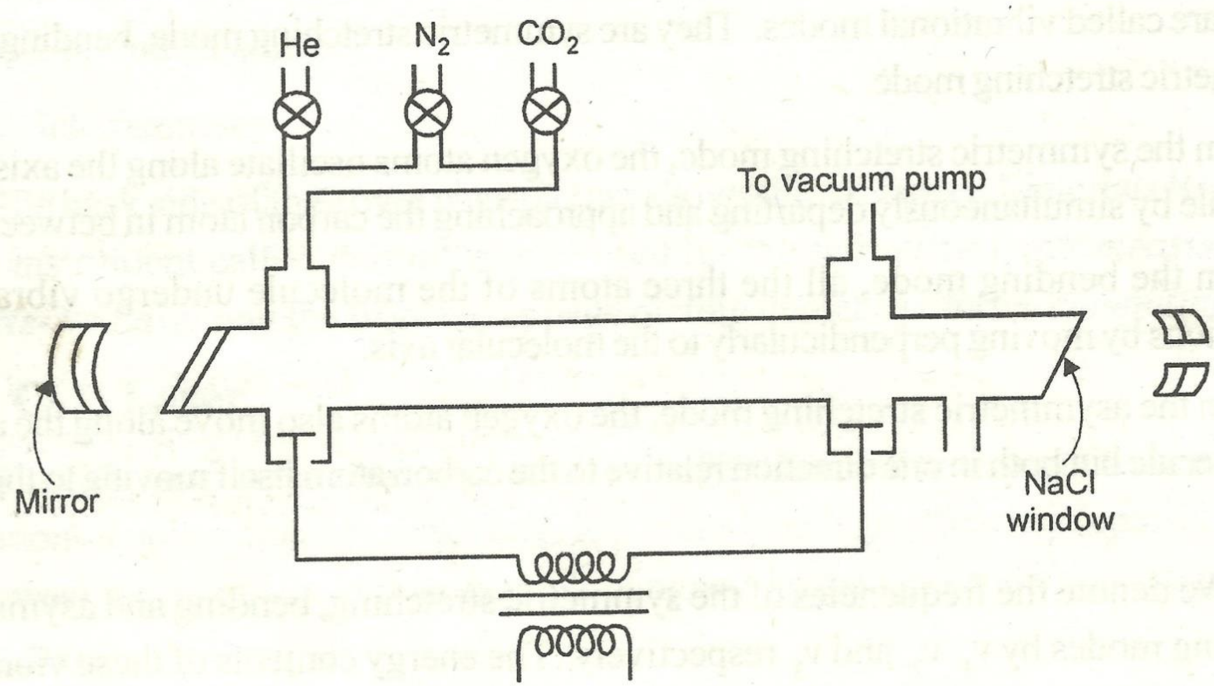
Laser comparison

Laser Type	Linear Power Density W/m	Maximum Power W	Power Efficiency percent
He – Ne	0.1	1	0.1
Argon	1 – 10	50	0.1
CO2	60 – 80	1200	15 - 20

Vibrational Modes of CO_2



Experimental Setup – CO_2 Laser



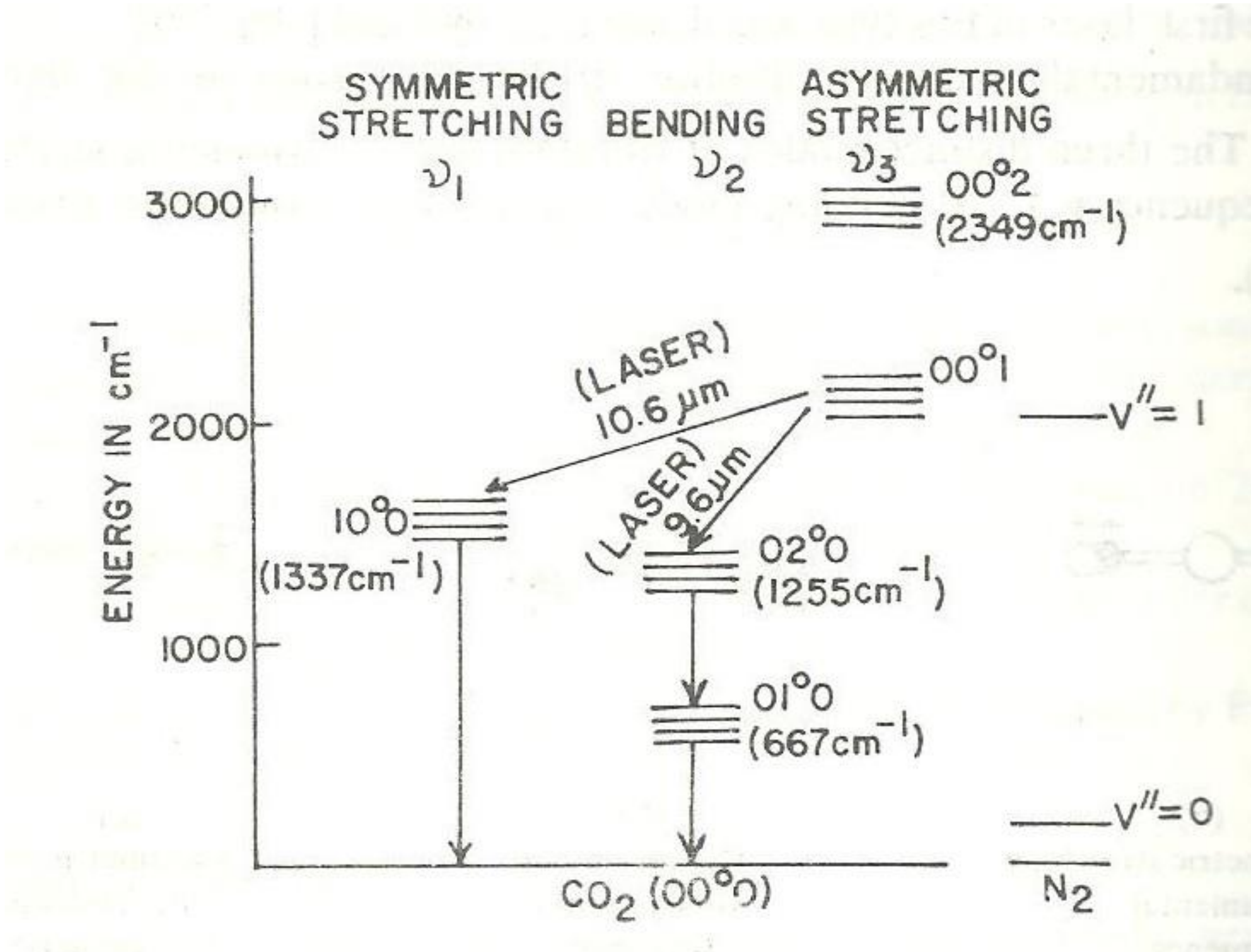
Gold Mirrors; Zinc Selenide Windows

Operating Mechanism

- High dc voltage cause electrical discharge
- CO_2 --------> $CO + O_2$
- Water Vapour added to regenerate CO_2

- N_2 excited by electron collision
- N_2 + e1 ------------> N_2^* + e2
- N_2^* + CO_2 ----------> CO_2^* + N_2
- Energy transfer thru resonant collisions
- He atoms act as a coolant and for relaxing to ground state

Energy Level Diagram



Merits and Demerits

- High Output power
- O/P power increase with increase in length of gas tube
- O/P power depends on operating temperature
- Required excitation energy is very less compared to He-Ne laser – Higher efficiency
- CO and O_2 contamination will affect laser action

Applications - Material Processing

- Laser Welding
- Laser Cutting
- Laser Drilling

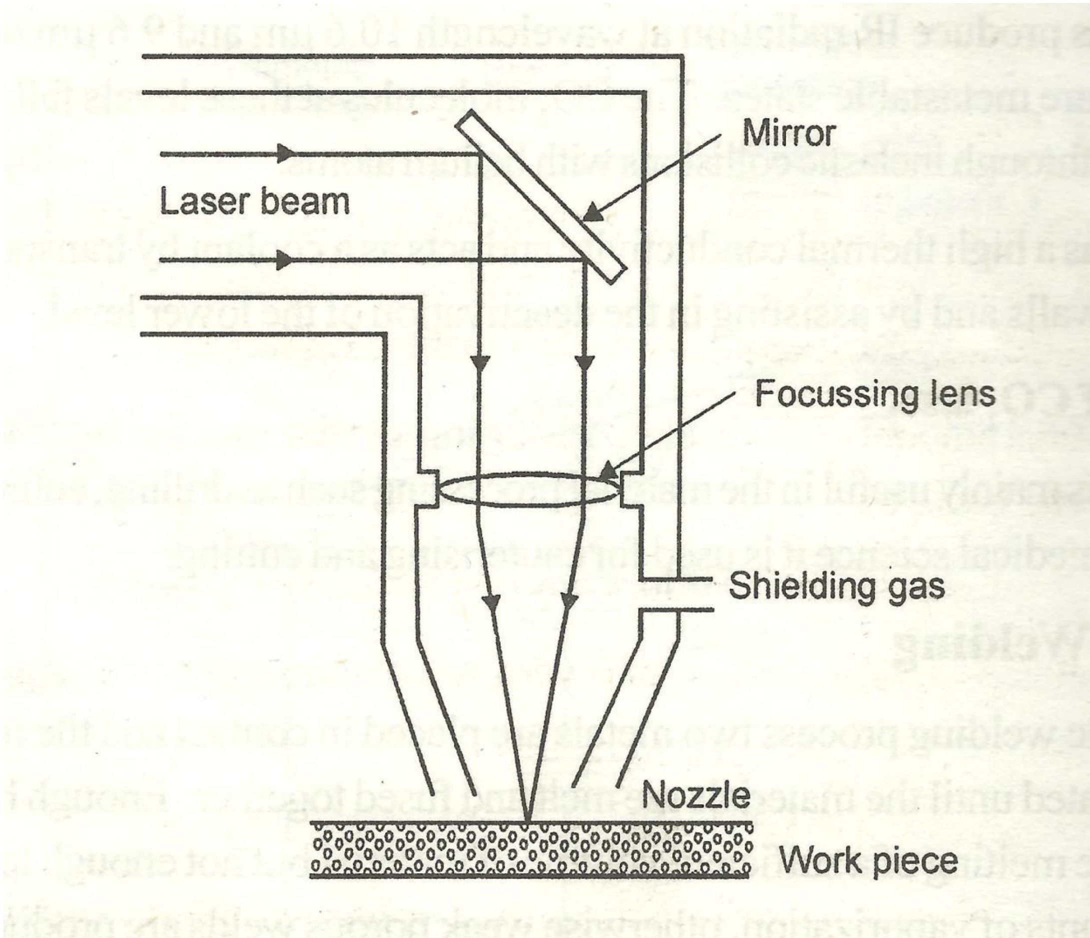
Laser Welding

- Joining multiple pieces of metal
- High power density (1 MW/cm^2)
- Laser spot size – 0.2 to 13 mm
- Both continuous and pulsed beams
- Continuous – Deep welds
- Pulsed – Thin materials like razor blades

Working

- Focal spot is targeted on the work-piece surface
- Large concentration of light energy converted to thermal energy
- Surface starts melting and progress thru surface conductance
- Beam energy is maintained below vaporization temperature
- Shielding gas (Inert gas) – Eliminate oxidation

Welding



Mirror
Laser beam
Focussing lens
Shielding gas
Nozzle
Work piece

Types

- Spot Welding and Seam Welding

- Spot Welding - Use Low and Moderate powers

  - For thermally sensitive environment

  Ex: Connection of Nickel lead to a Nickel alloy tap in transistor base, for microelectronic components

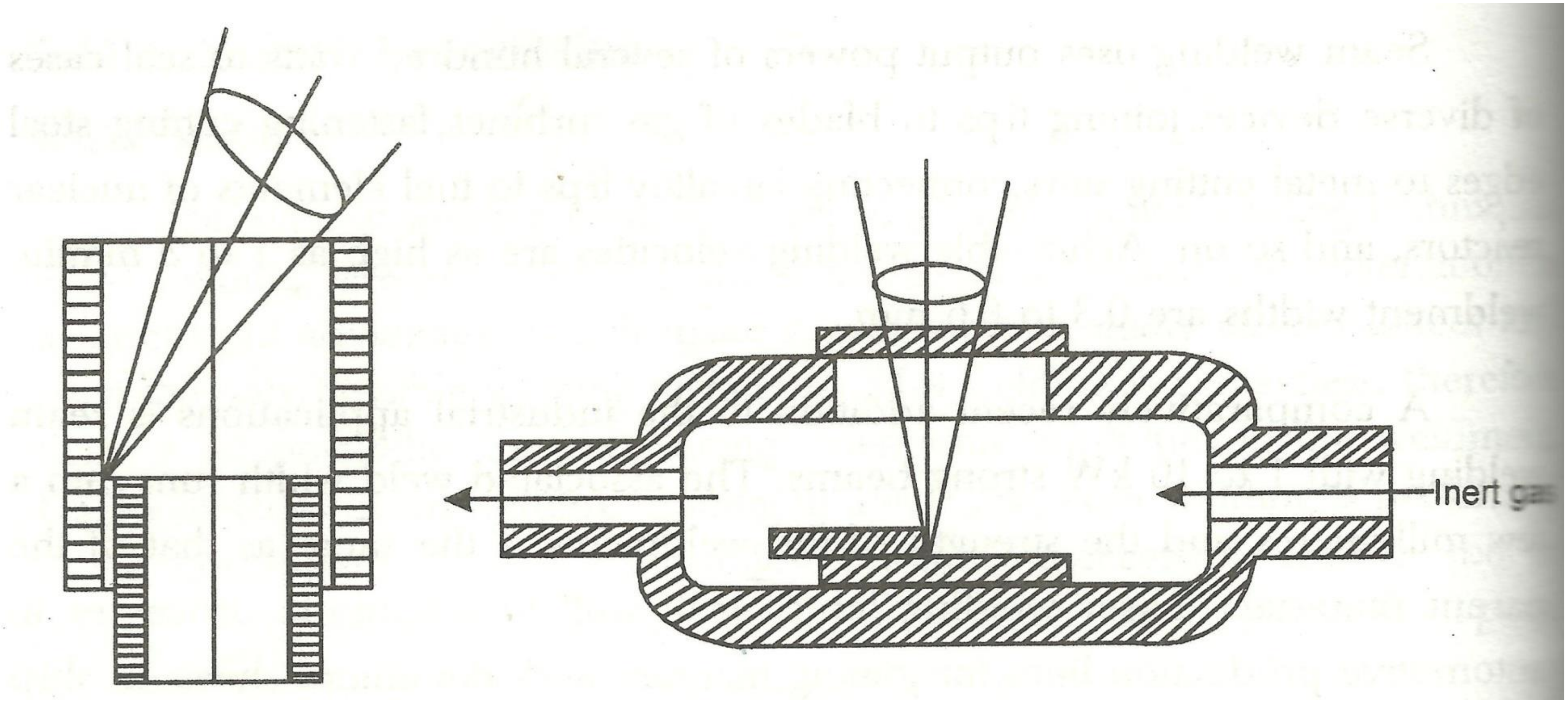
- Seam Welding – Use High powers (100's W); 2cm depth in one pass of beam

  Ex: Joining tips of blades in gas turbines, connecting circalloy tips to fuel elements of nuclear reactors

Advantages

- Deep and Narrow welds can be done
- Absence of distortions in welds created
- Minimal heat affected zones
- Excellent metallurgical quality
- Non-Contact and Increased travel speeds
- Welds Inaccessible regions

Welding Inaccessible Regions



Laser Cutting

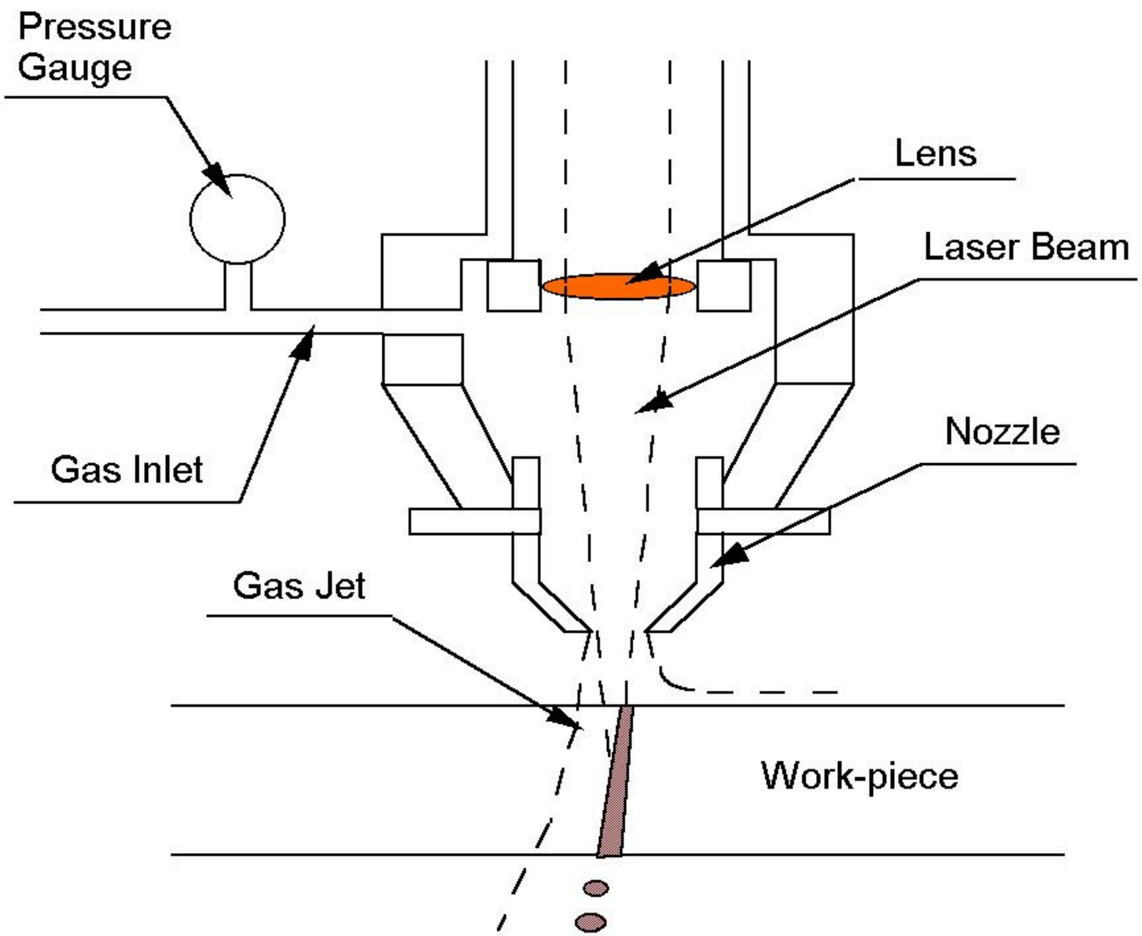
- Directing the O/P of the laser on the material

- Material vaporizes, melts or burns away leaving an edge with high quality surface finish

- Laser power depends on the material being cut

  Ex: 50mm thick boards – 200 W CO_2 laser – 0.7mm width ; 10mm thick glass – 20 kW power

Laser Cutting



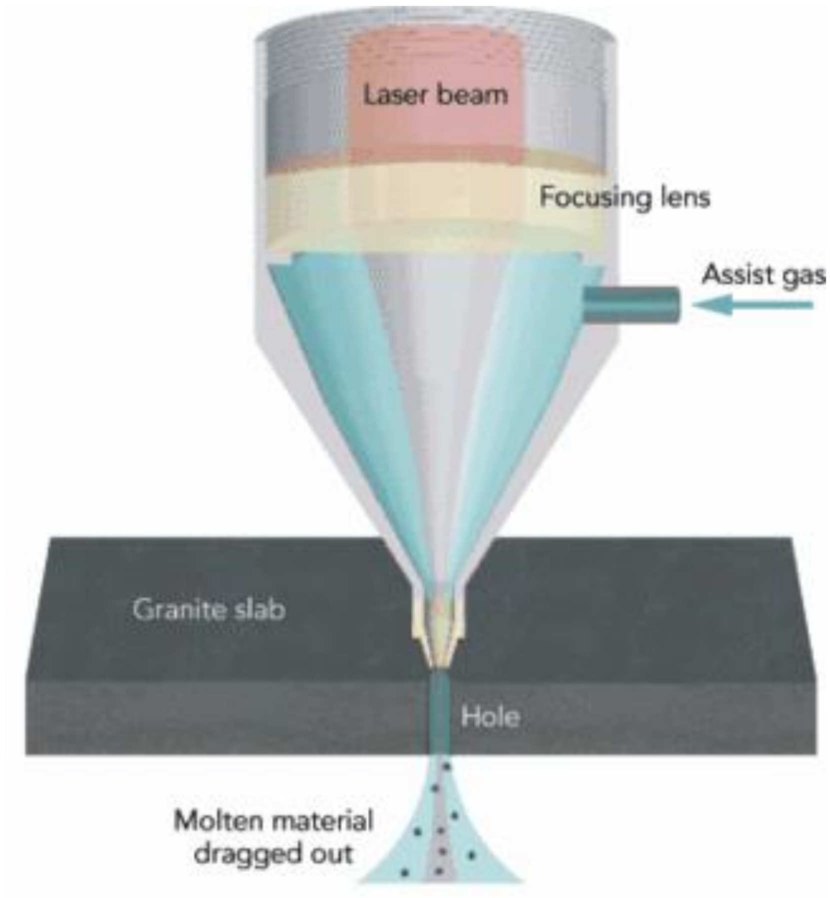
Advantages

- Wide range of processed materials (paper, cloth, glass, plywood, ceramics, sheet metal etc.)
- Fine and Precise cuts
- Chemical purity – No contamination
- 2D and 3D cuts
- Minimal mechanical distortion

Laser Drilling

- Intense evaporation of material heated by powerful pulses of light – Thermal removal process
- 10^{-4} to 10^{-3} s duration – power densities 10^6 to 10^7 W/cm^2
- Use of short pulses minimizes lateral diffusion of energy and controls size and shape of hole
- CO_2 laser – Both Metallic and Non-metallic materials
- Nd:YAG – Metallic only (absorbed by metals)

Laser Drilling



Advantages

- High precision and desired direction
- Large aspect ratios (l/d) possible
- Hard materials drilling possible
- Non-contact process

Numerical

- Consider a two level system at temperatures 400 K and 4000 K. What are the relative populations N_1 / N_0 corresponding to transitions that would occur at 470 nm?

- $N_1/N_0 = \exp[-h\nu / kT]$

  $= \exp[-hc / \lambda kT]$

- At T = 400 K,

- $N_1/N_0 = \exp[-hc / \lambda kT]$

  $= \exp[-(6.626 \times 10^{-34} \times 3 \times 10^{8}) / (470 \times 10^{-9} \times 1.38 \times 10^{-23} \times 400)]$

  $= 5.31 \times 10^{-34}$

At T = 4000 K,

$N_1/N_0 = 4.7 \times 10^{-4} = 0.00047$

- Determine what emission frequency width would be required to have a temporal coherence length of 20 m at a source wavelength of 532 nm.

$$l_c = \lambda^2/\Delta\lambda$$

$$\Delta\lambda = \lambda^2/ l_c$$

$$= (532 \times 10^{-9})^2 /20$$

$$= 1.41 \times 10^{-14}$$

- $c = \nu\lambda$
- $\nu = c/ \lambda$
- $d\nu = [(-c/ \lambda^2)] \times d\lambda$

$$= 15 \text{ MHz}$$

A laser light emits light at a source wavelength of 560 nm. What would be the maximum emission bandwidth allowed of the light source if the coherence length of the laser is at least 10m.

$$\Delta\lambda = \lambda^2/ l_c = 3.14 \times 10^{-14}$$