GAS & DYE LASERS

Gas Lasers

Most widely used lasers and most varied.

- Low power (He-Ne) to High power (CO_2) lasers
- Operates with rarified gases as active medium excited by electric discharge.
  - **Neutral atom lasers**
    - Helium- Neon Laser
  - **Ion Lasers**
    - Argon Laser
    - Krypton Ion Laser
    - Helium-Cadmium Laser
    - Copper-Vapour Laser
    - Gold-Vapour Laser

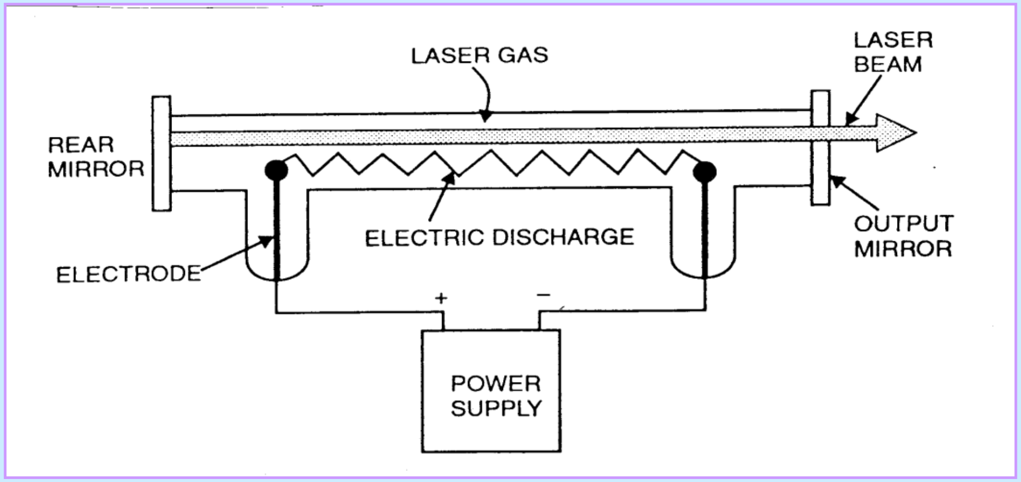
- **Molecular Lasers**
  - Carbon Dioxide Laser
- **Excimer Lasers**
  - Excited rare gas dimmers; Ar_2^*, Kr_2^*, Xe_2^*, . . .
  - Rare gas Oxides; ArO^*, KrO^*, XeO^*, . . .
  - Rare gas atom in combination with halide atom; ArF^*, KrF^*, $XeCl^*$. . .
- **Chemical Lasers**
  - HF Laser

Schematic of Gas Lasers

- **In gases**, energy levels of atoms involved in lasing action are well defined and narrow; ***broad pump bands do not exist***
- To excite gaseous atoms; pump sources with sharp wavelengths are required
  $\Rightarrow$ ***Optical pumping not suitable for gas lasers***.
- Finding an appropriate optical source for pumping – **A problem ?**

❖ **Most common method**; Passing electric discharge through the gas medium.

- Gas contained in a tube with cavity mirrors.
- A high DC voltage ionizes the gas for conduction.
- Electrons in the discharge transfer energy to atoms in the gas by collisions.



Schematic arrangement of a gas laser

- **For optimum operation, in practice, laser medium contains a mixture of two gases (A&B) at low pressure**
  - Atoms of kind A are initially excited by electron impact
  - Transfer their energy to atoms of kind B, which are actual active centres.

- **Cavity mirrors can be either inside the gas container or outside**
  - If inside, the output light is generally unpolarized
  - For outside case, mirrors placed at Brewster angle $\Rightarrow$ Polarized light

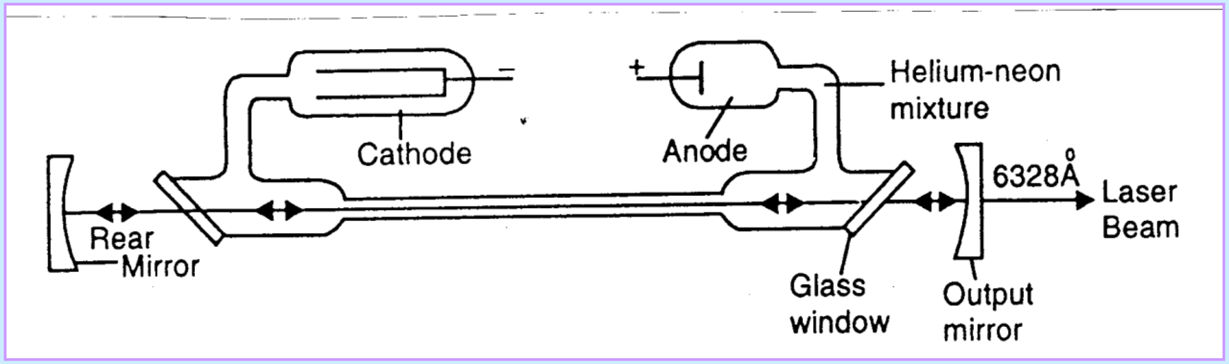
- **Gas lasers; vary widely in characteristics;**
  - Output wavelength from UV to Far IR region
  - Operates in pulsed mode and some in CW modes
  - Ouptut power, less than a mW to over 10 kW

☞ **First gas laser: He-Ne in 1961 at Bell Telephone Labs, USA**

He-Ne Laser

❖ ***First gas laser ever developed*** **;** Still one of the most widely used lasers.

- **He-Ne**: An atomic laser employs **Four-level pumping scheme**.
  - Active Medium; a mixture of 10 parts of He to 1 parts of Ne
  - **Ne-atoms; *active centres***- have energy levels suitable for laser transitions
  - **He-atoms help efficient excitation** of Ne-atoms

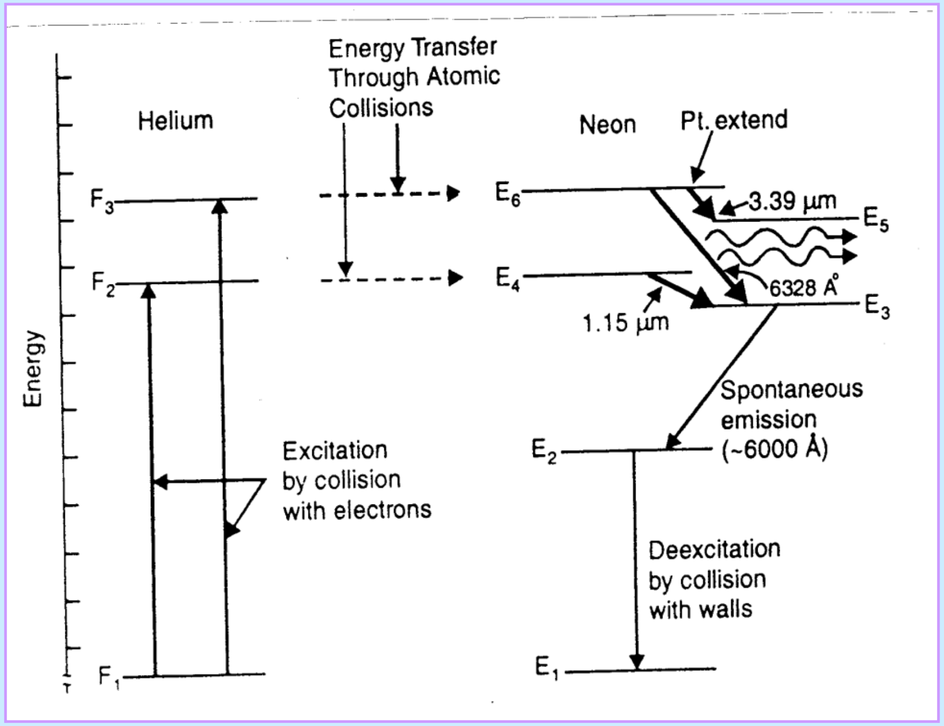


Schematic of a He-Ne laser with external mirrors

- Discharge tube of about 30cm long, 1.5 cm in diameter, filled with a mixture of He & Ne gases in 10:1 ratio.
- Electrodes connected to HV (~10kV) to produce discharge in gas.

- HV of 10kV applied across the gas- ***ionizes the gas***
- Electrons & ions accelerated towards anode and cathode
    - Electrons being smaller in mass acquire higher velocity

- Electrons transfer K.E. to He atoms through inelastic collisions.
- He atoms excited to levels F_2 & F_3 – ***metastable levels***
- Transfer energy to Ne-atom through collisions
    - ***Resonant transfer of energy***
- Possible in He-Ne atoms



Energy levels of He and Ne atoms and transitions between the levels.

- ❖ Ne-atoms being heavy, could not be pumped up efficiently without He-atoms.

- Role of He-atoms is to excite Ne-atoms and cause P.I.
  - Probability to transfer energy from He-Ne is more ; 10 He per 1 Ne atoms.
  - Reverse probability i.e. Ne-He is extremely small

- E_4 & E_6 levels in Ne ; **Metastable States** $\Rightarrow$ Accumulation of atoms
- Population inversion between
  - E_6 and E_5, E_3 levels
  - E_4 and E_3 levels
- Lasing takes place and light is produced corresponding to

$$\left.\begin{array}{l} \bullet\ E_6 \rightarrow E_5 \\ \bullet\ E_6 \rightarrow E_3 \end{array}\right\} \quad \text{and} \quad E_4 \rightarrow E_3$$

- ❖ $E_6 \rightarrow E_3$ transitions; laser beam of red colour at 632.8 nm (6328 A^o)
- ❖ $E_4 \rightarrow E_3$ transitions; laser beam at wavelength of 1150 nm (11500A^o)
- ❖ $E_6 \rightarrow E_5$ transitions; laser beam in IR region at 3390 nm (33900A^o)

☞ In reality, several laser transitions ≈**150 possible**, however, only three are dominant transitions.

- ***Ne-atoms in level E_3 decays rapidly to E_2 (a metastable state) $\rightarrow$ Accumulation may take place unless removed by some means***
  - $E_2 \rightarrow E_1$ transition induced by collisions with walls of discharge tube.
  - Discharge tube made as narrow as possible to enhance probability of atomic collisions with walls.

- **E_2 level is more likely to be populated by the electric discharge itself**
  - An increase in population at E_2 causes decrease in P.I. $\Rightarrow$ **Lasing ceases**.
  - Current in discharge tube maintained at low level

  $\Rightarrow$ Reason for not getting high power He-Ne lasers

- **Major applications as Red light at 632.8 nm**
  - Resonator mirrors coated with multi-layer dielectric coatings.
- **He-Ne laser**: Simple, less expansive, practical, high quality beam

Applications: Laboratories, Interferometry, Laser Printing, Bar Code Reader, Scanners, Surface Testing, Surveying, Alignment etc.

Ion Gas Lasers

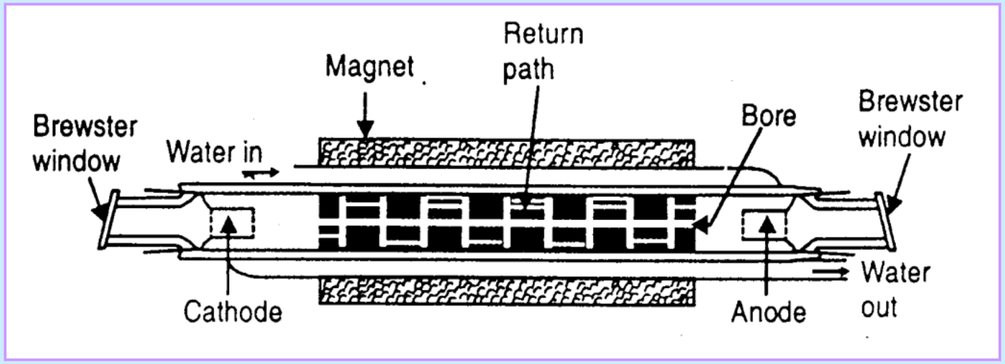
- **He, Ne, Ar, Xe and Kr** $\rightarrow$ Rare/noble gases have electronic state capable of laser transitions.
- Except for Ne, noble gases difficult to pump and hence not of practical interest
- However, if first ionized by electron collisions $\Rightarrow$ **Easy to pump**

- **Argon laser**
- **Krypton lasers**
- **He-Cd laser**
- **Copper vapour laser**
- **Gold vapour laser**

Argon Gas Laser

- **Four level laser;** Operates in Visible region over wavelength, **350 - 520 nm**
- **Most powerful CW laser** operating in visible region (powers ≈100W)
- Extensively used in laser light shows
- Provides approx **25 Visible and 10 UV** wavelengths

- Active medium; Ar gas
- Active centres; ionized Ar-atoms
- A narrow water cooled ceramic tube for arc discharge

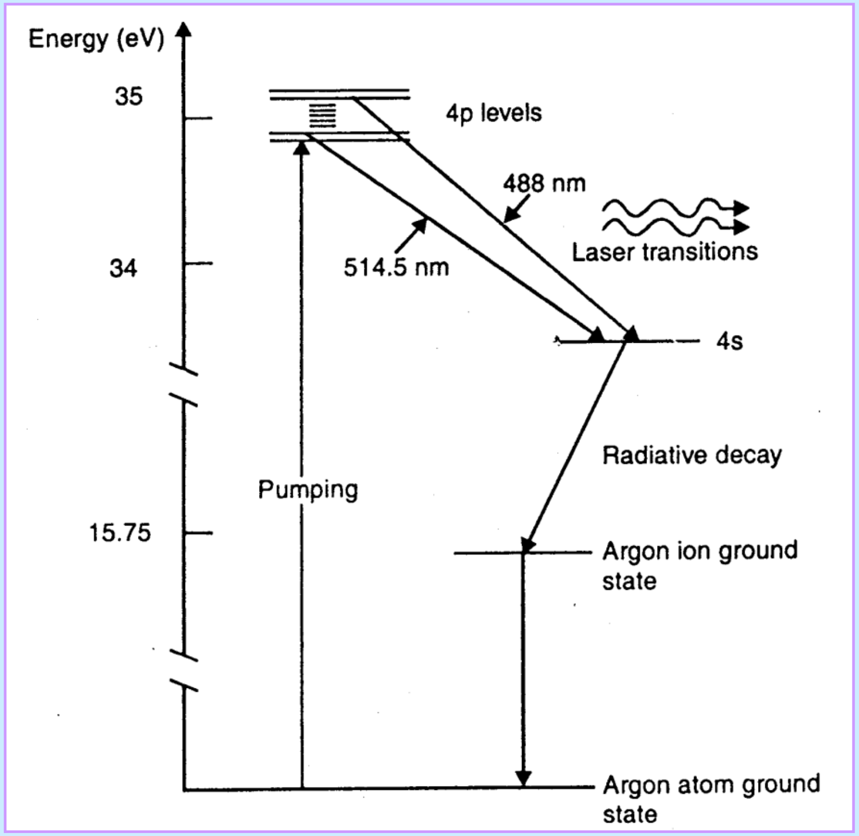


Schematic of a typical ion laser tube

- Anode and cathode space communicate through a return path which ensures free circulation of gas.
- A magnet surrounds the discharge tube to restrict the discharge area and increase the concentration of ions along the axis of tube.

- Initial HV ionizes the gas to conduct current
- Electrons transfer energy to Ar-atoms, ionize them and raises the ions to a group of high energy levels.

- Different process populate the metastable state (4p level)
- Three possible are:
  - ✓ Electron collision with Ar^+ ions in ground state
  - ✓ Collision with ions in metastable state
  - ✓ Radiative transitions from higher states.
- **Conditions for P.I. satisfied between 4p and 4s levels.**



Energy level scheme for an Argon atom

❖ **Transitions can occur between many pairs of upper and lower lasing levels**

⇒ Many laser wavelengths emitted

- Most important and more common are: **488 nm (Blue)** and **515 nm (Green)**
- Ar^+ ions quickly drop from lower laser level to ground state of the ion by emitting UV-light at 740A°.
  - ***Available for further action as UV light***
- Any desired wavelength can be selected through the cavity optics (using small prisms or gratings)

- During operation, positive ions collected at cathode; neutralized and slowly diffuse back into discharge ⇒ leads to pressure gradient
- A return path is provided between anode and cathode to equalize the pressure

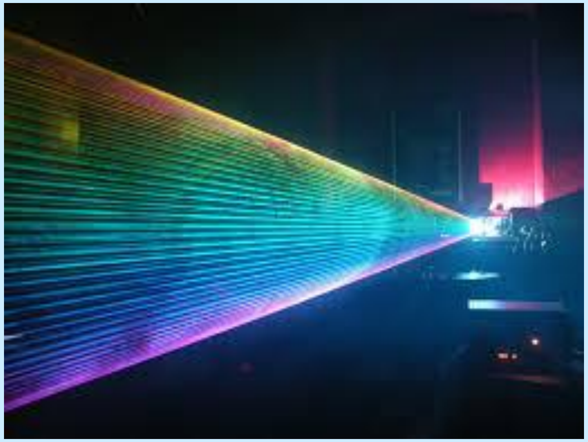
❖ **Laser needs active cooling**

❑ **Argon lasers used extensively in Eye Surgery;** For treatment of Diabetic retinopathy, Retinal detachment, Glaucoma and Macular degeneration

Krypton Ion Laser

- **Resembles the Ar-ion laser in energy levels and operation**
  - Provides different laser wavelengths
  - Dominant Outputs: 4067A^o, 4131A^o, 5309A^o, 5682A^o, 6471A^o, 6764A^o
    - A broader spectrum of wavelengths

- **Used in multi-colour displays**
  - Combination of Ar laser & Kr laser demonstrate beautiful multi coloured laser shows.



Helium-Cadmium Laser (Metal-Vapour Laser)

- **He-Cd : Most widely used metal-vapour laser**
  - Produces continuous output
    - UV region at 325nm & 354nm
    - Visible region 442 nm (Blue)

- Operation similar to He-Ne laser within discharge tube of 1-2 mm bore.
  - Cd metal heated to 250^{o}C and vaporized at anode to produce Cd-vapour needed for laser action.
  - Need discharge voltages ≈1500V and currents ≈ 60-100 mA.
  - Lifetimes 4000 to 5000 hrs.
  - He atoms transfer energy to Cd-ions through Resonant collision transfer.

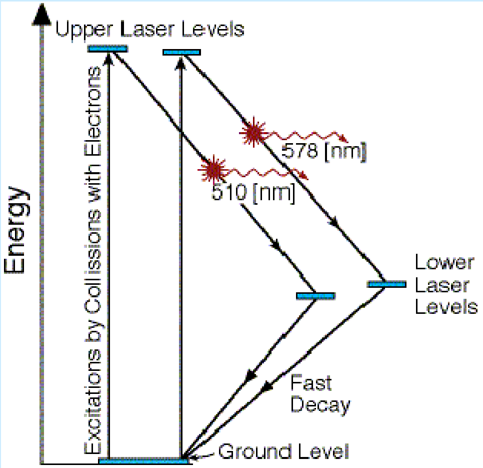
Major Applns; Photolithography, Inspection of PCBs, CD-ROM master, Fluorescence analysis etc.

Copper-Vapour Laser

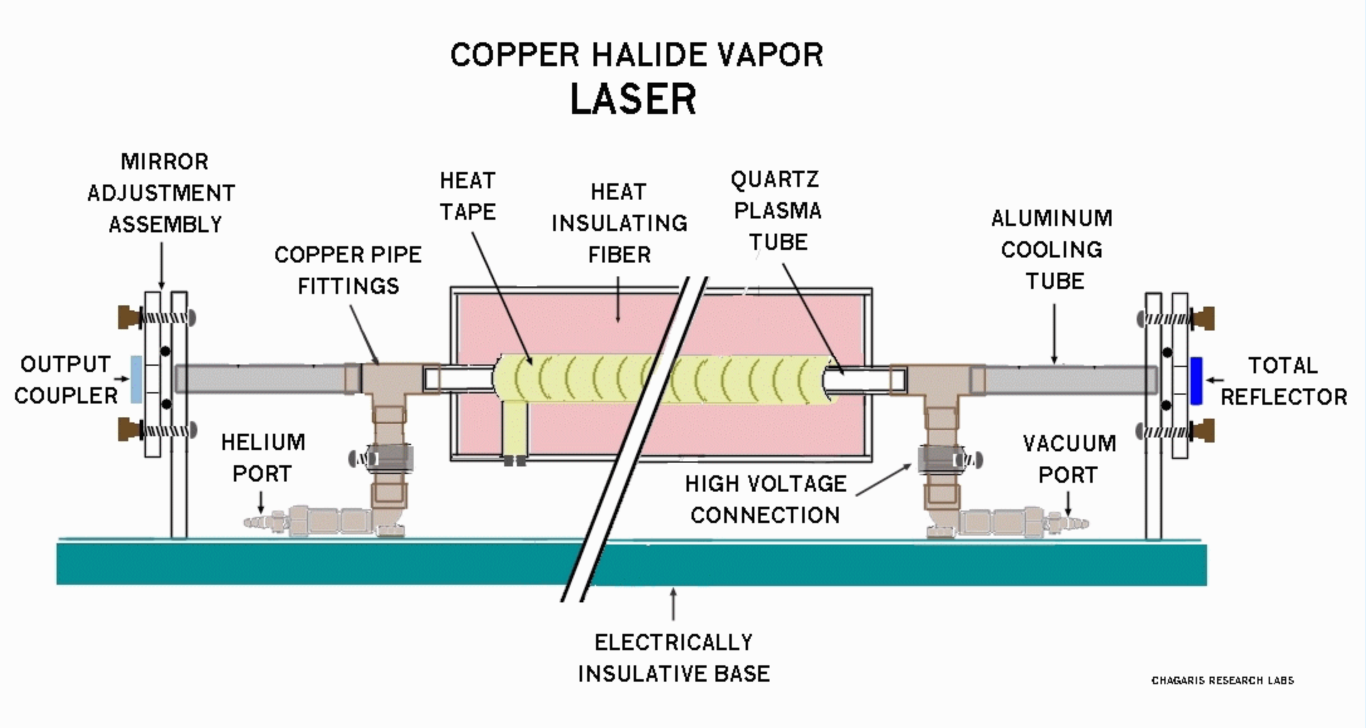
- **Metal vapour laser : Operates only in Pulsed mode**
  - Pulsed energy ≈ 1mJ and Average powers of 10-100 W
  - Output wavelengths: **5105 A^o (Green)**, **5782 A^o (Yellow)**

- Metal vapours contained in cylindrical discharge tube filled with He or Ne gas as a buffer gas
- Optimum pressure ≈ 1Torr of metal vapour for laser action- requires Cu to be heated upto 1500^{o}C.
- Typical lifetime ≈ 500-1000 hrs – Reloading of Cu required

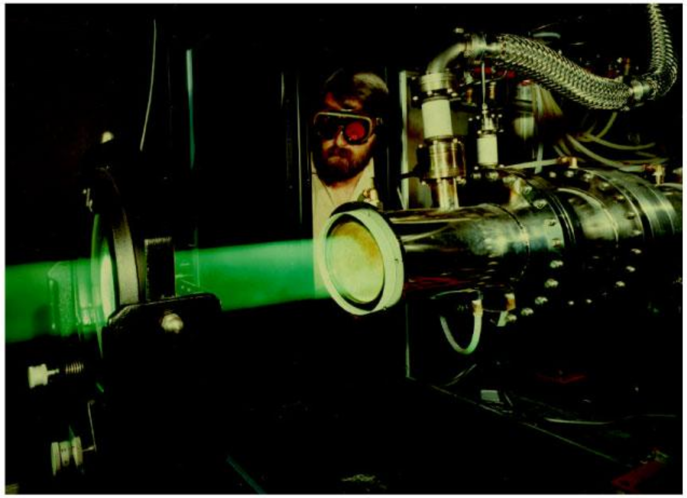
- With electric discharge Cu-vapours excited to upper laser level ⇒ **Onset of Stimulated Emission**
- Lower laser level - metastable level
  - Accumulation takes place, laser action ceases (100 ns)
  - Depopulation by collision with walls of tube



- **Copper laser: High gain – operate without resonant mirrors.**



COPPER VAPOR LASER



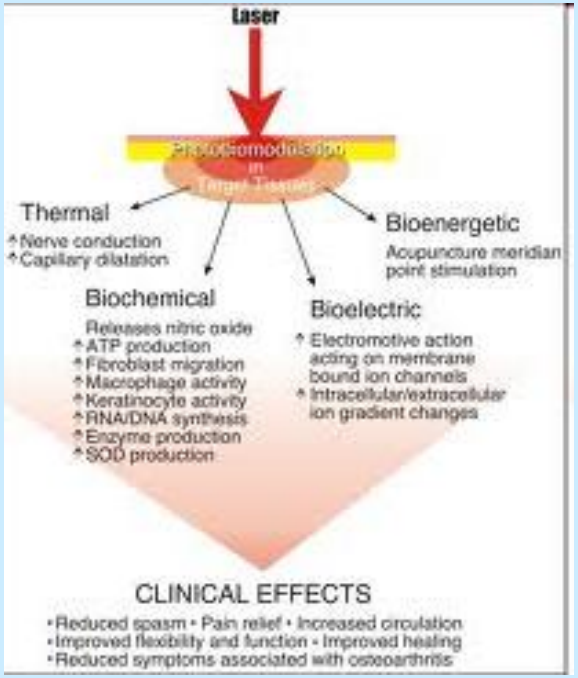
<u>Applications</u>:

- Pump for dye lasers
- Flash photography
- Material Processing

Gold-Vapour Laser

- **Operation similar to that of Copper vapour laser**
  - **Orange beam at wavelength of 6278 A^o**

- **Uses**: Photodynamic therapy for destroying cancerous tissues.



Carbon Dioxide Laser

- **CO_2 laser**: One of the most powerful & efficient lasers
  - **A four level molecular laser**
    - Operates on a set of vibrational-rotational transitions.
    - Output in mid IR-region at 10.6 μm and 9.4 μm
    - **Both CW and pulsed modes**; CW power output >100kW and pulsed energies as much as 10kJ

Energy levels of CO_2 molecules

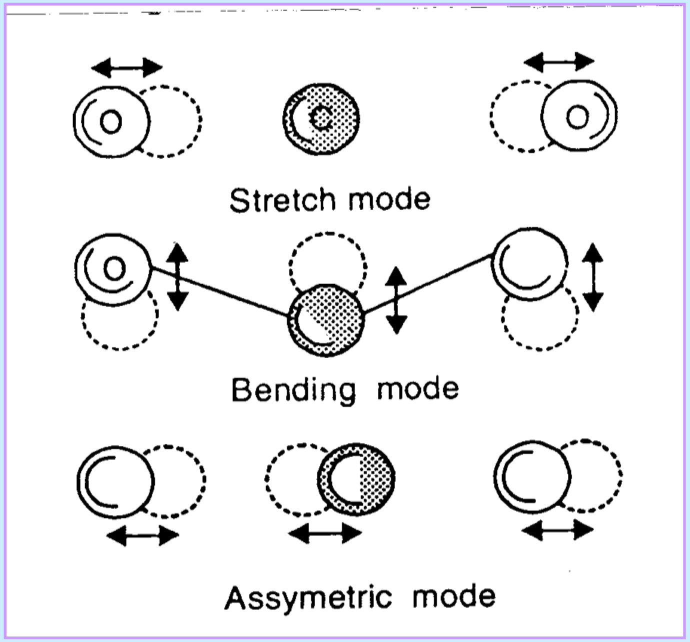
- Energy spectrum of molecules complex and includes many additional features.
- ***Each electron level associated with number of vibrational levels and each vibrational level in turn has a number of rotational levels.***
- CO_2 molecule; a linear molecule consisting of central carbon atom with two oxygen link one on either side.

- Can undergo Three independent vibrational oscillations – **Vibrational modes**.

  - Stretching mode
  - Bending mode
  - Asymmetric stretching mode

- **Each mode is quantized**; molecules can have 0,1,2 units of vibrational energy in each mode

- At any one time, CO_2 molecule can vibrate in any linear combination of three modes



Vibrational modes of CO_2 molecule

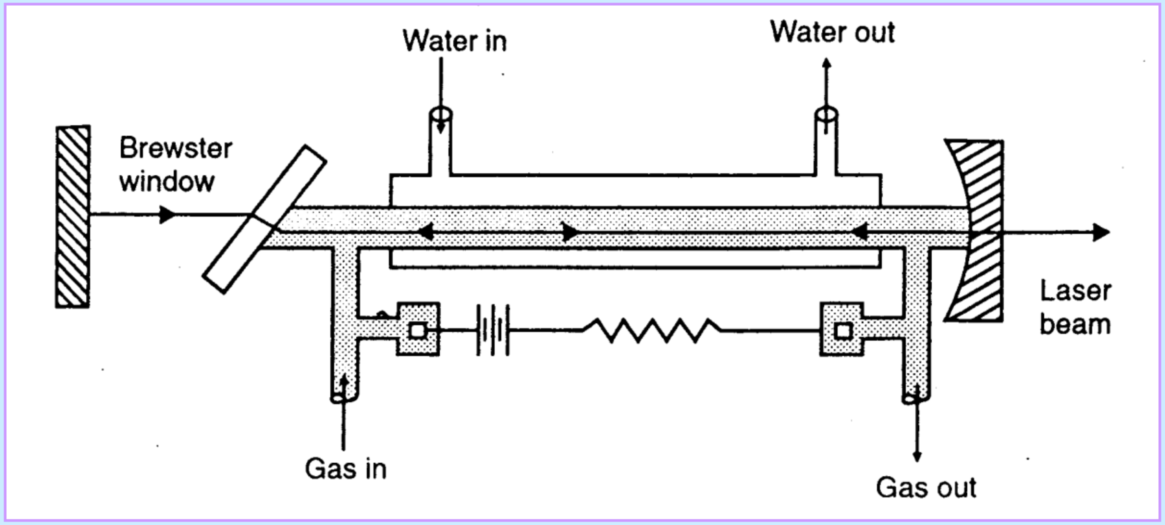
❖ Each energy state represented by three quantum numbers (m,n,q) $\Rightarrow$ represent the amount of energy associated with each mode.

❖ (0 2 0)$\rightarrow$ pure Bending Mode with two units of energy.

❖ Each vibrational state associated with rotational states corresponding to rotation of molecule about its centre of mass

❖ Much smaller energy separation between vibrational-rotational states.

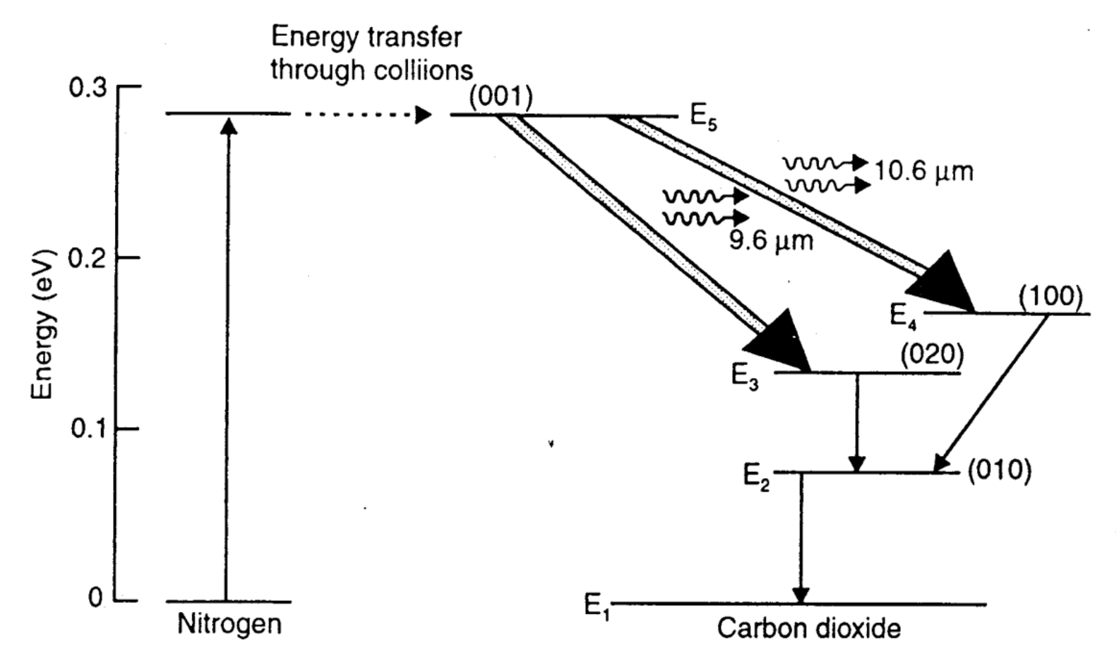
- A discharge tube having a bore of cross-section 1.5 cm^2 & length ≈ 25 cm
- Tube filled with a mixture of CO_2, N_2 & He gases in 1:4:5 proportions.



A schematic of a typical CO_2 laser

- A high DC voltage causes an electric discharge to pass through the tube
- Discharge breaks down CO_2 molecules to O & CO
- A small amount of water vapour added to gaseous mixture to regenerate CO_2 gas.

- In CO_2 laser, N_2 plays the same role as He in He-Ne laser
- Lowest vibrational levels of N_2 have nearly same energy as asymmetric mode of CO_2
- Readily transfer of energy by N_2 to CO_2 molecules in resonant collisions.
- CO_2 molecules excited to (0 0 1) E_5 level.



Energy levels of carbon dioxide and nitrogen molecules and transitions between the levels.

- **E_4 & E_3 ; *metastable states***
  - **P. I. established between E_5 and E_4 levels & E_5 and E_3 levels**

❖ **Lasing transitions**:

- $E_5 \rightarrow E_4$ transitions at 10600 nm
- $E_5 \rightarrow E_3$ transitions at 9600 nm

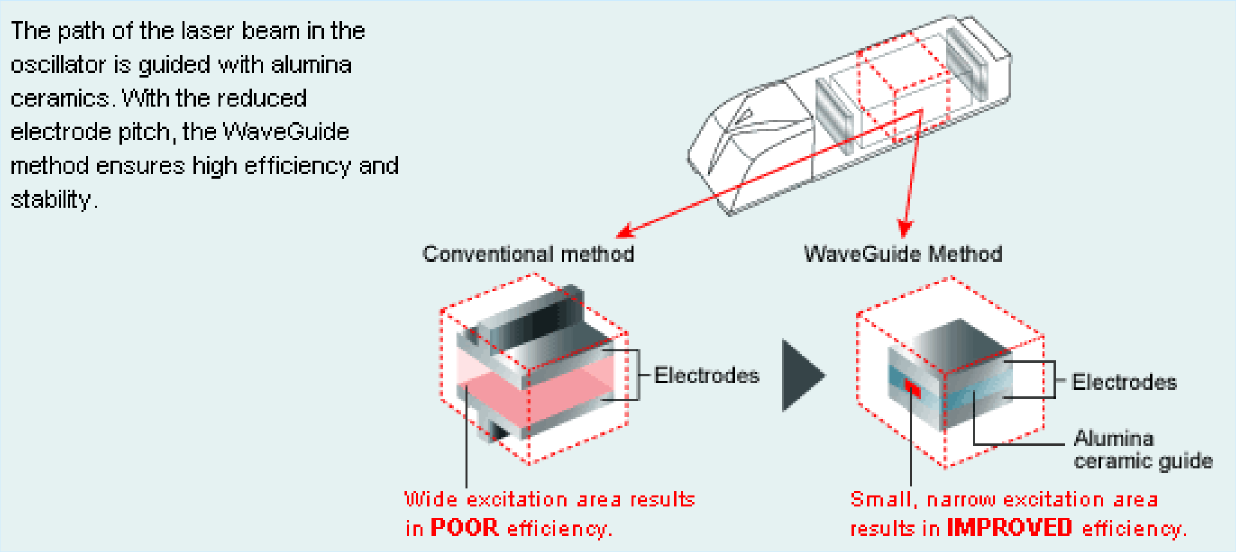
- **CO_2 molecules at E_4 & E_3 drops to E_2 through inelastic collision with He atoms**
  - Decay from E_2 level to ground state to be very fast – *accumulation leads to decrease in P.I.*
  - He-atoms help to depopulate level E_2 through collisions.

- ***E_2 level very close to ground state; tends to populate by thermal excitations***
  - Necessary to keep the temperature of CO_2 low
  - He has a high thermal conductivity and conduct heat away to walls and keeps CO_2 cool.

- **In CO_2 Lasers; N_2 helps to increase population of upper laser level whereas, He depopulates the lower laser level.**
- **Available in different configurations and varying output powers.**

Wave-guide CO_2 laser

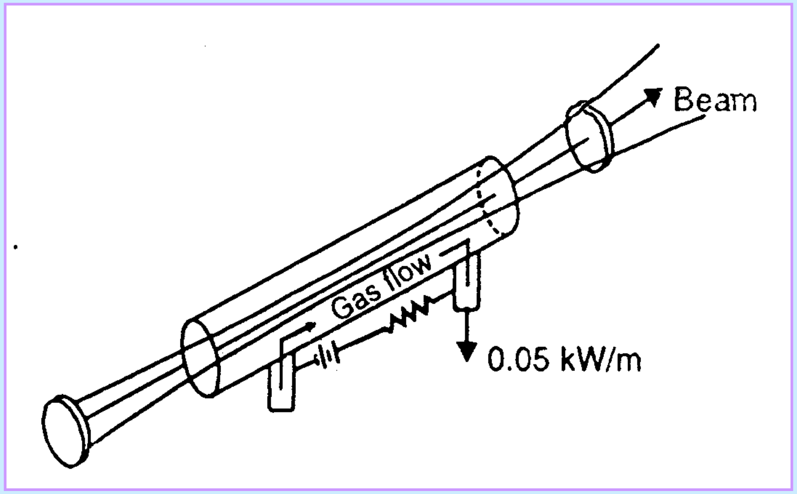
- Most efficient structure to produce a compact CO_2 lasers.
- Consist of two transverse RF electrodes separated by insulating sections that form bore region; *lateral dimensions of bore up to few mm.*
- Provide an RF field across electrodes within bore region
- Can produces CW power of about 100 W.



Gas-Dynamic CO_2 laser

- An Electric discharge; not only way to produce P.I. In CO_2 gas

❖ Rapidly flowing hot, high pressure CO_2 gas is ***allowed to expand supersonically*** through an expansion nozzle into a low pressure region.



Schematic of an axial flow CO_2 laser

- Expansion causes gas to super cool
- In the process, all the molecules do not drop to lower levels

$\Rightarrow$ P.I. Condition is attained

❖ **Design produces CW output > 100 kW**

TEA CO_2 lasers

- Laser operates at a gas pressure of ≈ 1 Atmosphere with pulsed electric discharge through gas.
- Works better if electric discharge is transverse to the laser axis.

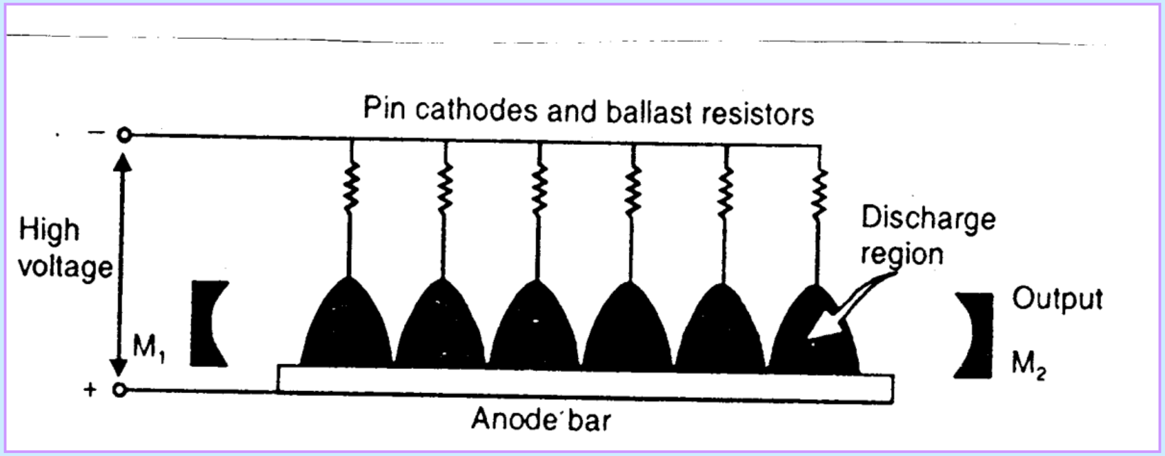


Illustration of a discharge in a TEA laser

❖ **Application of CO_2 lasers**

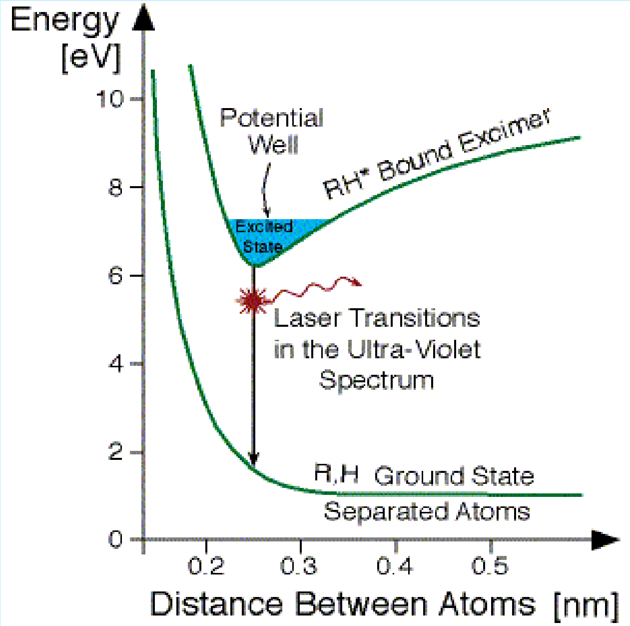
- **Material processing:** cutting, drilling, welding, etching, melting, annealing, hardening etc.
- Medical applications such as cutting, crushing etc.

Figure 2

Excimer Lasers

- ❖ **An Interesting & Important class of molecular lasers**
- ❖ First demonstrated in mid 1970s; **Most powerful UV laser**

- **Active Medium**; Diatomic molecules that can be bound into a single system when they are in excited state only.
- These diatomic molecules exist only as monomers in the ground state $\Rightarrow$ ***repel one another in atomic distances.***
- An excitation modify the state of atoms and there appears an attractive force with other atoms.



Internal energy of a rare gas halide molecule in excited and ground state

- ➢ Such molecules which exist only in excited state

  $\Rightarrow$ **Excited state dimers** or **Excimers**

- ➢ Atoms of inert gases can be bound to molecules by imparting energy to them.

- **Excimer State; *A metastsble state***
  - When atoms are bound together in the excited state $\Rightarrow$ *can occupy several vibrational levels in the potential well.*

- Excited by passing a short, intense electric discharge through a mixture of desired gases
- Electrons in discharge transfer energy to the lasing gas causing formation of excited molecules.
- Molecules remain excited for ≈ 10ns $\Rightarrow$ drop to ground state and dissociate.
  - ULL- electronic excited states
  - LLL- electronic ground state
- P.I. occur as soon as atoms bound to form molecules in excited state
  - Once molecule drop to lower laser level, it separates out into atoms

    $\Rightarrow$ lower laser level is always vacant.

- **Excimer Lasers**: High gain, No cavity mirrors required; one fully reflective mirror used in rear & unsilvered transparent window used as output mirror.

▪ Examples of active medium for Excimers

- An excited rare gas dimers; Ar_2^*, Kr_2^*, Xe_2^*,
- A rare gas oxides; ArO^*, KrO^*, XeO^*,
- A rare gas atoms in combination with a halide; ArF^*, KrF^*, $XeCl^*$,

Excimer Lasers

Type	Wavelength (A^o)
Ar_2^*	1260
$ArCl^*$	1750
ArF^*	1930
$KrCl^*$	2220
KrF^*	2490
$XeCl^*$	3080
XeF^*	3500

Major Applications:

- Mainly used in **refractive vision correction** of Eye (LASIK, PRK)
- Manufacturing of semiconductor devices, Photolithography
- Material processing,
- Pumping of dye lasers.

Chemical Lasers

- **Pumped by energy liberated in a chemical reaction**

  - **Most well known chemical lasers are;**

    - HF (Hydrogen Fluoride) $\Rightarrow$ Output wavelength range 2.6 to 3.3 μm
    - DF (Deuterium Fluoride) $\Rightarrow$ Output wavelength range 3.5 to 4.2 μm

- Operates on vibrational transitions $\Rightarrow$ output wavelengths always in IR region

  - Primarily developed for military and space applications where pumping power in form of electrical energy may not be available.
  - **Produces powers of several megawatts (MW)**

HF Lasers

- **Ingredients**: molecular Hydrogen and Fluorine gas; He added as buffer gas
- Molecular species react at normal temperatures under external excitation such as UV radiations.
- **Reaction**; ***Highly Exothermic*** $\rightarrow$ Produces a large amount of chemical energy.

- Excess energy is equivalent to pumping energy- enormous compared to other forms of pumping energies.

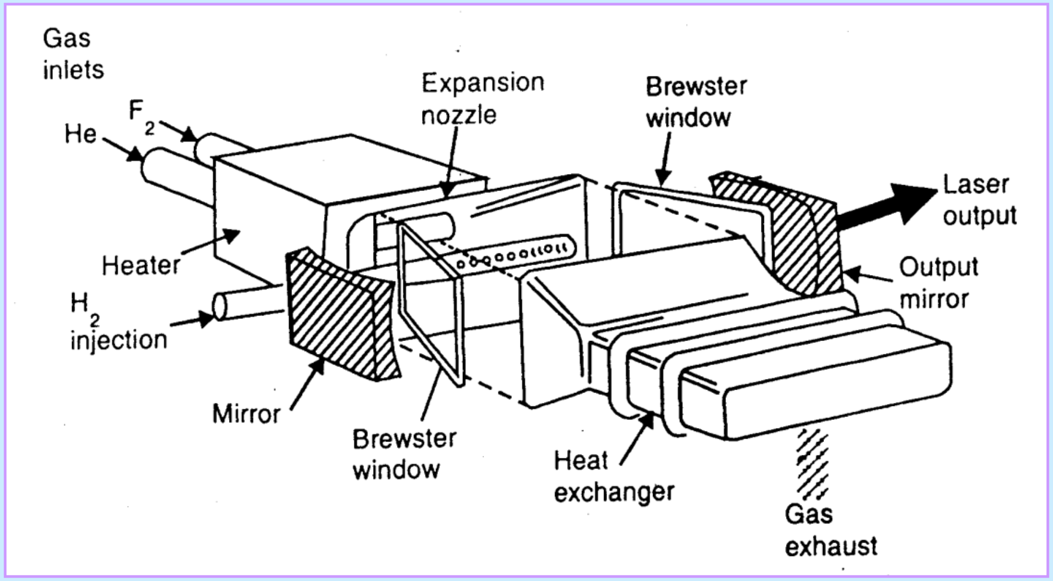
- Reaction between atomic and molecular H & F gases
  - $F + H_2 \rightarrow HF^* + H$; $\Delta H = -31.7$ kcal/mole
  - $H + F_2 \rightarrow HF^* + F$; $\Delta H = -97.9$ kcal/mole

- Reaction produces vibrationally excited HF^* molecules

  $\Rightarrow$ **Lasing action**

- End product contains atomic H and F

- Once reaction starts, it continue until all the molecular H_2 & F_2 are consumed.



Schematic of a chemical laser

❖ **Main Application**: High power weapons on battle field or in space.

Liquid Lasers

❑ Tunable Dye lasers

- ❖ **Active materials** : A dye dissolved in a host medium of a liquid solvent
- ❖ Situation similar to SSLs; where Cr^{3+}, Nd^{3+} or Ti^{3+} ions used in a solid host

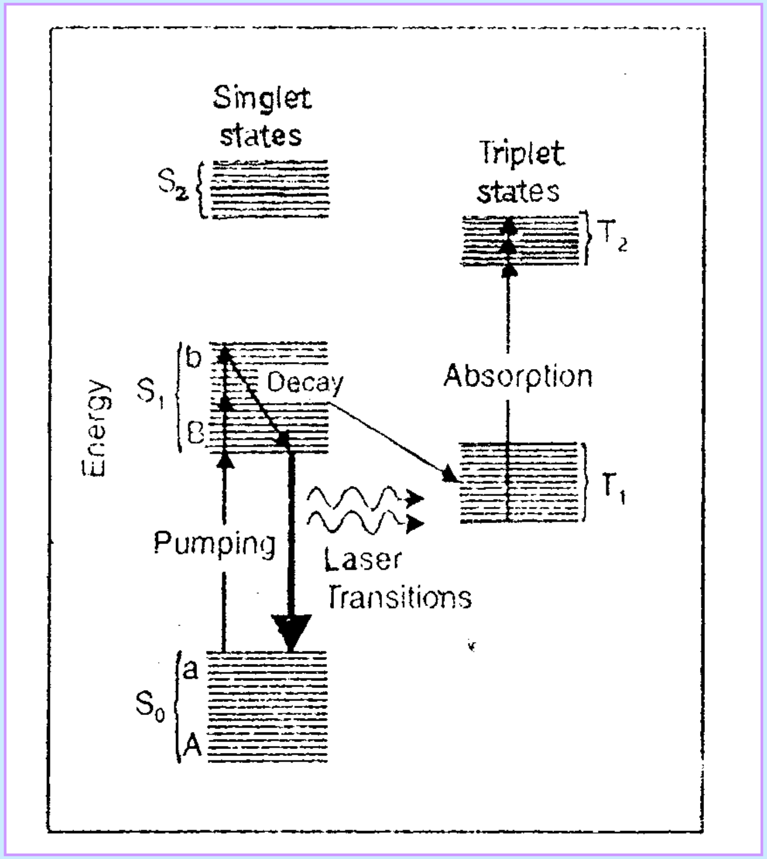
  ☞ ***Advantages of liquid host is that concentration of the active ions can be easily varied.***

  - **Typical dye concentrations**; 10^{-4} to 10^{-3} molar solution
    - ➢ 10^{24} to 10^{25} dye molecules per cubic meter.

- Over 200 dyes; Most important one being **Rhodamine 6G**
  - When used, produce tunable output over wavelength range 320 -1200 nm
- **Operates both in CW & Pulsed modes**
  - **Pulsed dye laser**; pumped by a flash lamp or other laser $\Rightarrow$ 400J in 10 μs pulses
  - **CW dye laser**; pumped by other CW laser (Ar– ion) $\Rightarrow$ Output Power $\approx$ 2W

❖ **Gain of dye medium is very high** ; a small volume of dye solution is sufficient to sustain lasing action.

- Organic dye molecules have two sets of excited states
  - Singlet sates; S_0, S_1, S_2
  - Triplet states; T_1 & T_2
- Transitions from singlet states to triplet states $\Rightarrow$ **forbidden**



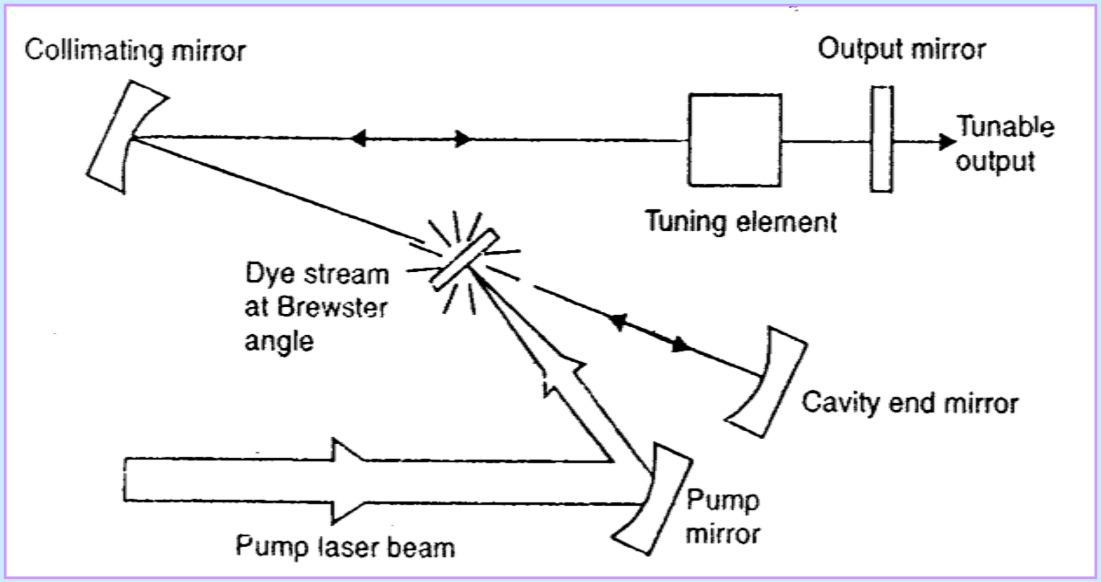
Schematic representation of the energy levels of an organic dye molecule.

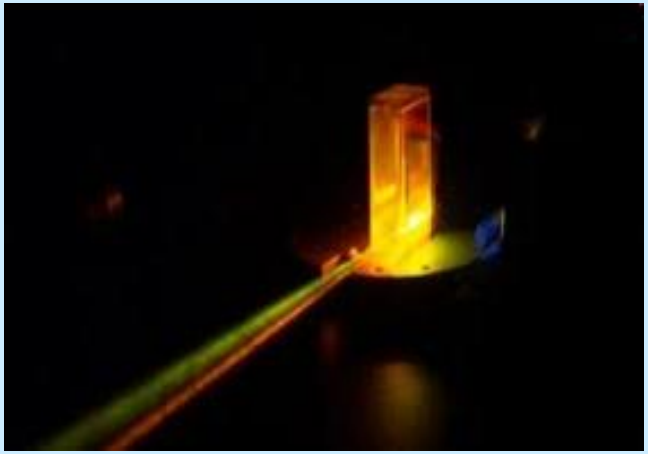
- Optical pumping excites dye molecules from lowest vibronic level of ground state S_0 to one of upper vibronic level of excited state S_1
- Undergo non-radiative transition to the lower vibronic level of S_1 – acts as ULL

❖ Role of LLL played by one of the upper vibronic levels of S_0 – closely spaced levels $\Rightarrow$ form a continuum

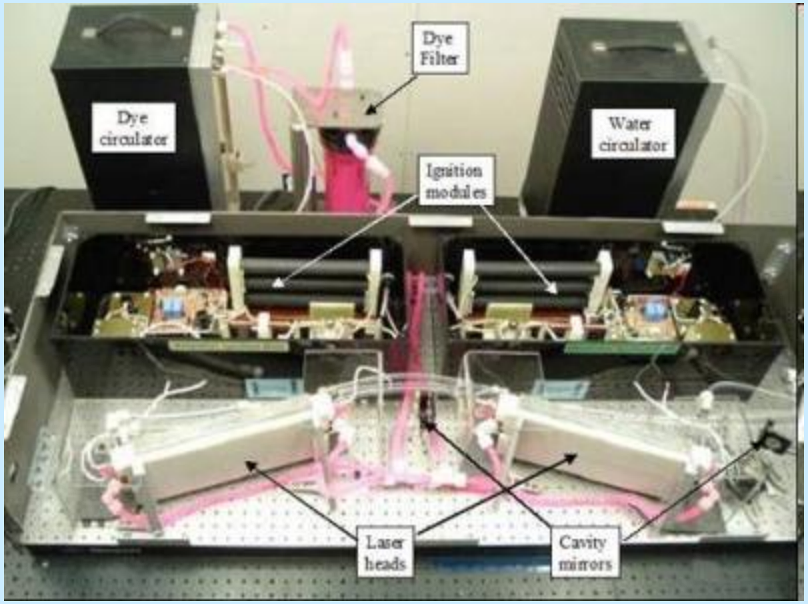
- Laser transitions can be to various levels within a range defined by vibrationally excited sublevels on the ground state

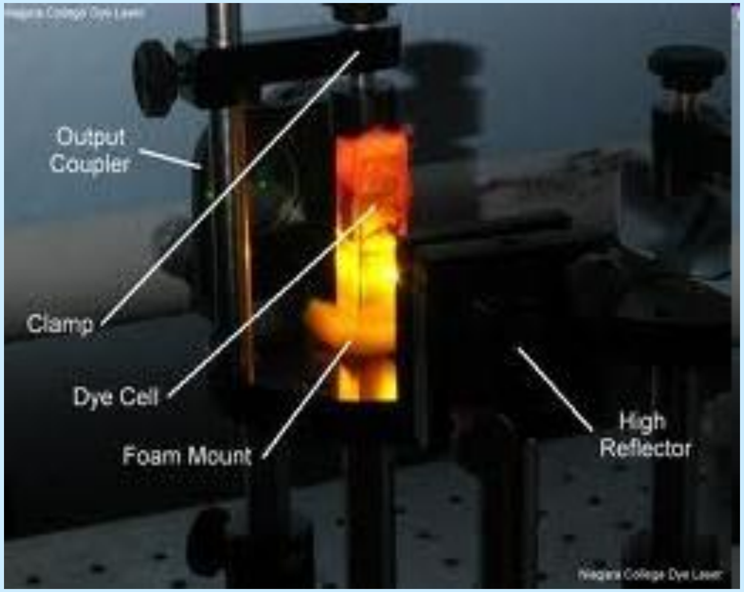
⇒ Laser operates over a wide/broad range of wavelengths.

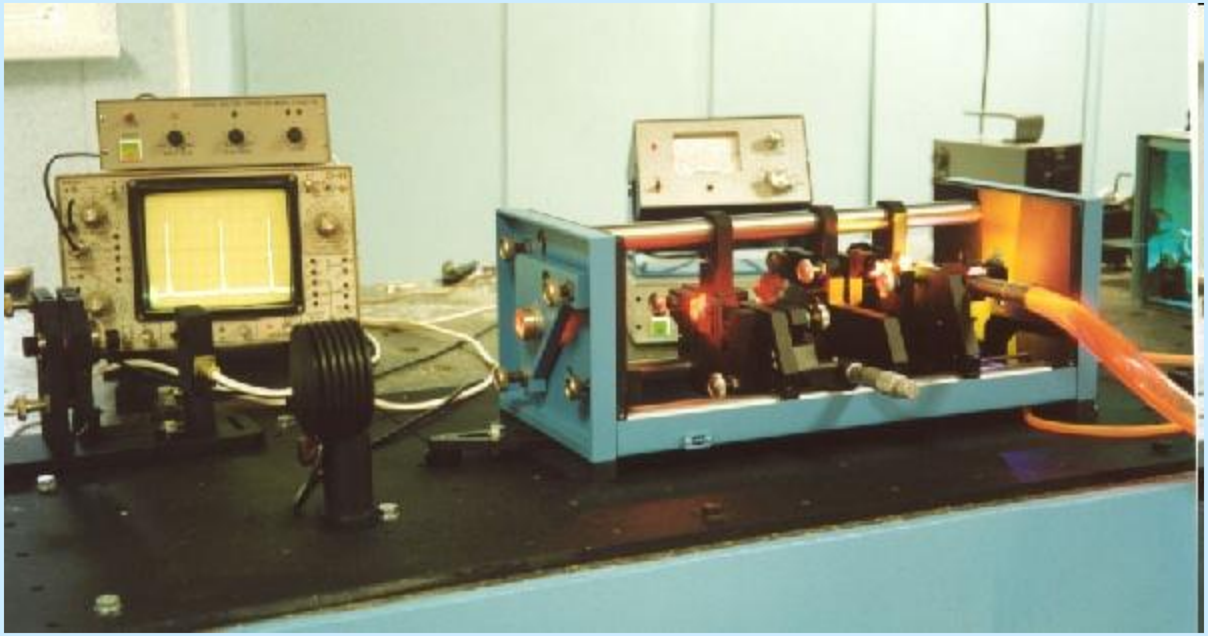




Schematic diagram of a laminar-flow dye laser


Dye Filter
Dye circulator
Water circulator
Ignition modules
Laser heads
Cavity mirrors


Output Coupler
Clamp
Dye Cell
Foam Mount
High Reflector
Niagara College Dye Laser



Characteristics of Selected Laser Dyes

Dye	Peak wavelength (nm)	Tuning range (nm)	Pump Source	Solvent
p-Terphenyl	340	323-346	KrF (249 nm)	Cyclohexane
	340	333-348	Nd-YAG (266 nm)	Cyclohexane
	341	334-347	XeCl (308 nm)	Cyclohexane
	341	335-355	Flashlamp	Dimethylformamide
	341	335-349	XeCl (308 nm)	p-Dioxane
Stilbene 420	424	410-454	XeCl (308 nm)	Ethanol/H_2O, 9:1
	424	411-436	Nd-YAG (355 nm)	Methanol
	425	400-460	N_2 (337 nm)	Ethanol/H_2O, 1:4
	425	405-467	XeCl (308 nm)	Ethanol
	425	408-453	N_2 (337 nm)	Methanol
	432	406-448	Ar (uv)	Ethylene glycol / Methanol, 9:1
	445	421-468	N_2 (337 nm)	H_2O
	449	420-470	Ar (uv)	Ethylene glycol

Table contd…

Rhodamine 590	560	548-580	Nd-YAG(532 nm)	Methanol
(Rhodamine 6G)	572	564-600	Copper vapor	Ethanol
	579	568-605	N_2 (337 nm)	Ethanol
	583	566-610	XeCl (308 nm)	Methanol
	587	565-615	Flashlamp	Methanol
	590	570-650	Ar (458, 514 nm)	Ethylene glycol
	596	577-614	Flashlamp	Methanol/H_2O, 1:3
	602	560-654	Kr (blue-green)	Methanol/Ethylene glycol mixture
	610	585-633	Flashlamp	4% Ammonyx LO in H_2O

- **Dye lasers are exclusively used in some areas, e.g. pumping solid state lasers, spectroscopy with wavelengths which are otherwise hard to generate. They are also particularly suitable for Intracavity Laser Absorption Spectroscopy.**

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