GAS & DYE LASERS

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Gas Lasers

Most widely used lasers and most varied.

- Low power (He-Ne) to High power (CO₂) 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; \(\text{Ar}_2^*, \text{Kr}_2^*, \text{Xe}_2^*, \ldots\)
  - Rare gas Oxides; \(\text{ArO}^*, \text{KrO}^*, \text{XeO}^*, \ldots\)
  - Rare gas atom in combination with halide atom; \(\text{ArF}^*, \text{KrF}^*, \text{XeCl}^*, \ldots\)

- **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 ⇒ *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 ⇒ 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
- Output 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](image)

- 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

- 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
  - $E_6 \rightarrow E_5$ and $E_4 \rightarrow E_3$
  - $E_6 \rightarrow E_3$

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

In reality, several laser transitions $\approx$ **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** → 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 ⇒ **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.

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 740Å.

  - *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 \(\Rightarrow\) 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: 4067Å, 4131Å, 5309Å, 5682Å, 6471Å, 6764Å
    - A broader spectrum of wavelengths
- Used in multi-colour displays
  - Combination of Ar laser & Kr laser demonstrate beautiful multi coloured laser shows.

![Laser Image](image1)

![Laser Image](image2)

![Laser Warning](image3)
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°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 \( \approx 1 \text{mJ} \) and Average powers of 10-100 W
  - Output wavelengths: 5105 A\(^\circ\) (Green), 5782 A\(^\circ\) (Yellow)

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

- With electric discharge Cu-vapours excited to upper laser level \( \implies \text{Onset of Stimulated Emission} \)
- 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.
Applications:

- 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 Å

- Uses: Photodynamic therapy for destroying cancerous tissues.
Carbon Dioxide Laser

- **CO₂ 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 CO₂ 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.*
- CO₂ 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.

- Each energy state represented by three quantum numbers $(m, n, q)$ represent the amount of energy associated with each mode.
- $(0 \ 2 \ 0)$ → 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 schematic of a typical CO$_2$ laser

- A discharge tube having a bore of cross-section 1.5 cm$^2$ & length $\approx$ 25 cm
- Tube filled with a mixture of CO$_2$, N$_2$ & He gases in 1:4:5 proportions.
- 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 CO₂ laser, N₂ plays the same role as He in He-Ne laser
• Lowest vibrational levels of N₂ have nearly same energy as asymmetric mode of CO₂
• Readily transfer of energy by N₂ to CO₂ molecules in resonant collisions.
• CO₂ molecules excited to (0 0 1) E₅ level.

**E₄ & E₃ ; metastable states**

➢ P. I. established between E₅ and E₄ levels & E₅ and E₃ levels

❖ Lasing transitions:
  • E₅ → E₄ transitions at 10600 nm
  • E₅ → E₃ transitions at 9600 nm
- CO₂ molecules at E₄ & E₃ drops to E₂ through inelastic collision with He atoms
  - Decay from E₂ level to ground state to be very fast – *accumulation leads to decrease in P.I.*
  - He-atoms help to depopulate level E₂ through collisions.

- **E₂ level very close to ground state; tends to populate by thermal excitations**
  - Necessary to keep the temperature of CO₂ low
  - He has a high thermal conductivity and conduct heat away to walls and keeps CO₂ cool.

- In CO₂ Lasers; N₂ 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\textsubscript{2} laser

- Most efficient structure to produce a compact CO\textsubscript{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\textsubscript{2} laser

- An Electric discharge; not only way to produce P.I. In CO\textsubscript{2} gas

- Rapidly flowing hot, high pressure CO\textsubscript{2} gas is *allowed to expand supersonically* through an expansion nozzle into a low pressure region.

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

  \[ \implies \text{P.I. Condition is attained} \]

- Design produces CW output > 100 kW
TEA CO$_2$ lasers

- Laser operates at a gas pressure of \( \approx 1 \) 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](image)

**Application of CO$_2$ lasers**

- **Material processing:** cutting, drilling, welding, etching, melting, annealing, hardening etc.

- Medical applications such as cutting, crushing etc.
**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 ⇒ *repel one another in atomic distances.*

- An excitation modify the state of atoms and there appears an attractive force with other atoms.

- Such molecules which exist only in excited state

  ⇒ **Excited state dimers** or **Excimers**

- Atoms of inert gases can be bound to molecules by imparting energy to them.
Excimer State; *A metastable state*

- When atoms are bound together in the excited state ⇒ *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 ⇒ 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
    ⇒ 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*,

### Major Applications:

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

<table>
<thead>
<tr>
<th>Excimer Lasers</th>
<th>Wavelength (Å)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ar$_2^*$</td>
<td>1260</td>
</tr>
<tr>
<td>ArCl*</td>
<td>1750</td>
</tr>
<tr>
<td>ArF*</td>
<td>1930</td>
</tr>
<tr>
<td>KrCl*</td>
<td>2220</td>
</tr>
<tr>
<td>KrF*</td>
<td>2490</td>
</tr>
<tr>
<td>XeCl*</td>
<td>3080</td>
</tr>
<tr>
<td>XeF*</td>
<td>3500</td>
</tr>
</tbody>
</table>
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 \(\mu\)m
  - DF (Deuterium Fluoride) \(\Rightarrow\) Output wavelength range 3.5 to 4.2 \(\mu\)m

  - 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 continues until all the molecular $H_2$ & $F_2$ are consumed.

- **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 ⇒ 400J in 10 μs pulses
    - **CW dye laser**: pumped by other CW laser (Ar– ion) ⇒ Output Power ≈ 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 states; $S_0, S_1, S_2$
  - Triplet states; $T_1 & T_2$
- Transitions from singlet states to triplet states ⇒ **forbidden**

- 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 ⇒ 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
<table>
<thead>
<tr>
<th>Dye</th>
<th>Peak wavelength (nm)</th>
<th>Tuning range (nm)</th>
<th>Pump Source</th>
<th>Solvent</th>
</tr>
</thead>
<tbody>
<tr>
<td>p-Terphenyl</td>
<td>340</td>
<td>323-346</td>
<td>KrF (249 nm)</td>
<td>Cyclohexane</td>
</tr>
<tr>
<td></td>
<td>340</td>
<td>333-348</td>
<td>Nd-YAG (266 nm)</td>
<td>Cyclohexane</td>
</tr>
<tr>
<td></td>
<td>341</td>
<td>334-347</td>
<td>XeCl (308 nm)</td>
<td>Cyclohexane</td>
</tr>
<tr>
<td></td>
<td>341</td>
<td>335-355</td>
<td>Flashlamp</td>
<td>Dimethylformamide</td>
</tr>
<tr>
<td></td>
<td>341</td>
<td>335-349</td>
<td>XeCl (308 nm)</td>
<td>p-Dioxane</td>
</tr>
<tr>
<td>Stilbene 420</td>
<td>424</td>
<td>410-454</td>
<td>XeCl (308 nm)</td>
<td>Ethanol/H₂O, 9:1</td>
</tr>
<tr>
<td></td>
<td>424</td>
<td>411-436</td>
<td>Nd-YAG (355 nm)</td>
<td>Methanol</td>
</tr>
<tr>
<td></td>
<td>425</td>
<td>400-460</td>
<td>N₂ (337 nm)</td>
<td>Ethanol/H₂O, 1:4</td>
</tr>
<tr>
<td></td>
<td>425</td>
<td>405-467</td>
<td>XeCl (308 nm)</td>
<td>Ethanol</td>
</tr>
<tr>
<td></td>
<td>425</td>
<td>408-453</td>
<td>N₂ (337 nm)</td>
<td>Methanol</td>
</tr>
<tr>
<td></td>
<td>432</td>
<td>406-448</td>
<td>Ar (uv)</td>
<td>Ethylene glycol / Methanol, 9:1</td>
</tr>
<tr>
<td></td>
<td>445</td>
<td>421-468</td>
<td>N₂ (337 nm)</td>
<td>H₂O</td>
</tr>
<tr>
<td></td>
<td>449</td>
<td>420-470</td>
<td>Ar (uv)</td>
<td>Ethylene glycol</td>
</tr>
</tbody>
</table>
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**.

<table>
<thead>
<tr>
<th>Dye</th>
<th>λ (nm)</th>
<th>Gain Medium</th>
<th>Laser Type</th>
<th>Solvent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rhodamine 590</td>
<td>560</td>
<td>548-580</td>
<td>Nd-YAG(532 nm)</td>
<td>Methanol</td>
</tr>
<tr>
<td>(Rhodamine 6G)</td>
<td>572</td>
<td>564-600</td>
<td>Copper vapor</td>
<td>Ethanol</td>
</tr>
<tr>
<td>579</td>
<td>568-605</td>
<td>N₂ (337 nm)</td>
<td>Ethanol</td>
<td></td>
</tr>
<tr>
<td>583</td>
<td>566-610</td>
<td>XeCl (308 nm)</td>
<td>Methanol</td>
<td></td>
</tr>
<tr>
<td>587</td>
<td>565-615</td>
<td>Flashlamp</td>
<td>Methanol</td>
<td></td>
</tr>
<tr>
<td>590</td>
<td>570-650</td>
<td>Ar (458, 514 nm)</td>
<td>Ethylene glycol</td>
<td></td>
</tr>
<tr>
<td>596</td>
<td>577-614</td>
<td>Flashlamp</td>
<td>Methanol/H₂O, 1:3</td>
<td></td>
</tr>
<tr>
<td>602</td>
<td>560-654</td>
<td>Kr (blue-green)</td>
<td>Methanol/Ethylene glycol mixture</td>
<td></td>
</tr>
<tr>
<td>610</td>
<td>585-633</td>
<td>Flashlamp</td>
<td>4% Ammonyx LO in H₂O</td>
<td></td>
</tr>
</tbody>
</table>
References:

1. LASERS: Theory and Applications; MN Avadhanulu, S. Chand & Company Ltd.

2. Lasers & Optical Instrumentation; S.Nagabhusana and N. Sathyanarayana, IK International Publishing House (P) Ltd.


4. www.Google.co.in/Search engine
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