A change in the method of excitation enhances some important aspects of laser performance.

Gas Transport Lasers.

- Build-up of the waste heat sets a fundamental limit to the average output power.
- Collisions that destroy vibrationally excited molecules cause T<br>
- T<br> reduces the Dν through thermal excitation of the lower laser level.
- T<br> reduces the gain through increase in the Doppler width.
- Thermal lensing

In a cylindrical, gas discharge laser, heat must be removed by transport of hot particles to the cooled tube walls.
- Diffusion controls the way hot particles reach the tube walls.
- Characteristic time for this process is the thermal conduction time,

\[ T_0 \approx \frac{D^2}{C} \]

D = diameter, \( C \) = mean velocity of gas particles,
A = mean free path of the particles.

When only thermal conduction is the only means to remove waste heat, there is an upper limit of 1 kW for the input power, regardless of the tube.

1) Lower limit ~ 300 W/m<sup>2</sup> (for Cap-30x) 2) Saturation intensity ~ 60 W/m<sup>2</sup>
In a gas-transport laser by flowing gas through the system we can improve laser operation in a number of ways.

Fig. 11.1. Some examples of gas transport laser geometries: (a) axial flow laser \((L,U)_x\), geometry-resonator axis; current direction and gas velocity are in common axial direction; (b) transverse flow laser; (c) flow-mixing laser.

(i) the gas flow provides convective cooling. Waste heat is removed at a rate determined by the residence time of particles in the system, \(f(U)\) dimension over which particles flow through the system.

(ii) the gas flow removes particles in the lower laser level. Power output capacity.

(iii) removes decomposition products of the discharge.

(iv) gas flow is used for mixing the laser gases or the heating species. (flow mixing laser).

Classification according to the relative directions of the laser axis \((L)\), current flow \((I)\) and gas velocity \((U)\).
Fig. 11.2. $(L)_x (I_0)_z$ gas transport laser geometry, where $L$ is the laser beam direction, $I$ the current direction and $V$ the gas flow velocity direction. The gas flow passes through the grid or mesh electrodes.

Classification according to the relative directions of the laser axis

- current flow $(I)_x$
- gas velocity $(V)_z$

$(L)_x (I_0)_z$
• When gas transport techniques are used in a laser oscillator, the output transverse mode pattern can become unsymmetrical because the system lacks cylindrical symmetry and can be influenced by flow distortion.

• For improved beam geometry, the gas transport device is used as an amplifier for the beam from an oscillator.
Gas transport CO₂ lasers provide large power output from relatively small packages.

Part ~ 1 kW for CO₂ laser of 0.5 m in length.
Gas Dynamic Lasers

- In the gas transport lasers the main purpose of the gas flow is to remove waste heat generated from the primary electrical excitation.
- In gas dynamic lasers the population inversion itself is produced as a result of the flow of gas from a high to a low pressure region.
- The inversion is produced "gas dynamically" by the rapid expansion of the gas, the subsequent gas flow also removes waste heat and reaction products from the gain region.
- If the expansion of the gas is rapid through a supersonic nozzle cooling always occurs, and is very efficient.
- Expansion of a hot molecular gas through a supersonic nozzle channels the random kinetic motion of the hot molecules into directed motion in the direction of the flow. Since energy must be conserved, the random component of molecular velocity must decrease, and the gas cools translationally. The rotational temperature remains in equilibrium with the translational temperature, so it also falls.
- A population inversion can result if excitation remains frozen in higher vibrational levels, while at the same time lower vibrational levels lose population through collisions.

\[
\frac{N_2}{N_1(000)} = \frac{2a}{2a - 4k} \text{ K line.}
\]

- \(N_1\) falls rapidly through collisions.
- \(N_2\) is not efficiently relaxed by collision.
The water vapor is added to the gas mix because it is particularly efficient at relaxing the CO₂ lower laser levels.

- vibrationally excited N₂ also persists downstream of the nozzle and assists in population of the CO₂ upper laser level.
Fig. 11.7. (a) Partition of energy in the gas dynamic laser arrangement shown in Fig. (11.6). (b) Relative population of upper and lower CO₂ laser levels.

Fig. 11.8. Schematic arrangement of a high power, multinozzle gas dynamic laser.[1,4]

- The energy theoretically available from such a laser is essentially that energy stored in the vibrationally excited hot nitrogen and in the asymmetric stretching mode of CO₂: 3.5 x 10⁸ J/kg of gas 10% CO₂, 90% N₂ at \( T = 14000 \) K.
- \( T = 14000 \) K is achieved by electrical heating or burning of appropriate hydrocarbon fuels: acetylene and propane, CO, CO₂, N₂, O₂, H₂ (pulsed operation).
- The gasdynamic CO₂ laser is the highest power CW laser currently operating. \( P_{\text{cw}} = 5 \text{MW} \).
High Pressure Pulsed Gas Lasers

- These lasers are called TEA lasers – transversely excited atmospheric pressure lasers.
- Their development arose from a desire to obtain larger power outputs from CO₂ lasers.
- Conventional discharge excited lasers generally operate at relatively low pressures (< 50 Torr), since it is only at such P that a stable, uniform glow discharge can be excited in a longitudinal excited discharge.
- Increase of pressure in the discharge leads to the formation of narrow current bearing filaments, sparks, arcs or lightning streamers.
- At high pressures, the E/D value of the discharge may become too low for efficient excitation of the laser levels.
- Transverse excitation overcomes this problem as the applied voltage acts across a smaller dimension of the laser structure.
- If uniform transverse excitation of a high pressure discharge can be achieved, the possibility of large laser powers exists as there are many more laser molecules available in the gas – if they can be excited.
- The problem of filament formation can be overcome in the case of transverse pulsed excitation.
- To prevent filament formation in pulsed excitation, severe methods are used. They excite the gas in a way to encourage uniform, glow discharge excitation and discourage the formation of filaments.
Fig. 11.9.
(a) Plane-parallel electrodes have a high field at their edges; (b) a double Rogowski profile has a uniform field between the electrodes; (c) Rogowski profiles - the equipotentials of a two-dimensional parallel plate capacitor. The potential of each profile satisfies $V = rV_0$.

**Rogowski profile electrodes.**

- If a transversely excited laser structure is constructed like a large plane-parallel capacitor, sparks will form at the edges of the electrodes because edge effects cause the $E$ field to be higher there.

  - To prevent this the electrodes must be curved away at the edges in a way that ensures $E$ is near higher than in the center.

- **Rogowski profile** - Two electrodes curved away at the edges in one electrode is larger than second one.

  Actually voltage is 20-50 kV
In a transversely excited structure, a uniform discharge can be encouraged to form by the use of preionization techniques. Some charge carriers are injected into the space between the main electrodes just prior to application of excitation voltage pulse. Preionization can be provided by arrays of insulated trigger wires placed near the cathode, which are excited by a high voltage pulse and lead to production of a corona discharge near the surface of the electrode.
Fig. 11.11 TEA CO₂ laser structure using ultraviolet photo-preionization with a spark array. Typical dimensions are shown.

- Preionization can be provided by firing an array of sparks below a mesh anode or at the rear of the structure. These sparks feed energetic UV photons into the laser gas causing photoionization.

\[ E = 35 \text{mJ} \quad T = 100 \mu s \quad P = 10 \text{MW} \]
**Beam preionization and excitation.**

- High energy $e$ beams can be used both as a means for preionizing a large volume of high pressure gas and as a primary excitation source in a high pressure gas laser.
- Apply a large voltage pulse $>100$ kV between a knife-edge cathode a thin metal foil anode in a vacuum.
- Electrons are drawn from the cathode by field emission and accelerated towards anode.
- High energy $e$ penetrate the foil and preionize to excite a volume of high pressure gas.

- In T$E$A lasers, it is uncommon for $V$ and pressure condition necessary for uniform and efficient discharge operation to be the same as $V$ and pressure conditions which provide the optimum $E/P$, ratio for excitation of the upper laser level.
- An $e$ beam pulser/sustainer arrangement is used.
- The $e$ beam energy is chosen to provide uniform penetration of $e$ through the volume.
after preionization has occurred, the main discharge capacitor is able to provide current to the discharge.

**Fig. 11.13.** Transverse cross-section of an e-beam pulser/sustainer laser.

**Fig. 11.14.** Energy level diagram for the N₂ molecule showing an excitation pathway and a laser transition from the upper level (C^3Π_u/v'' = 0) to the lower level (B^3Π_g/v'' = 0) at 337 nm.

- Use fast pulse electric discharge or e-beam pumping to excite laser action in electron transit in UV.
- Fast pulse, high power excitation is required because:
  a) The upper level is short lived.
  b) The lower level may be longer lived than the upper level.
  c) Laser threshold requires to achieve gain at a short wavelength.

N₂: UV pulse peeks in pulses 10-20 μs long.
CO: λ = 190 nm
H₂: λ = 160 nm.
There are lasers where transition occurs between 2 electronic states, the lower of which is unbound.
The lower laser level produced by stimulated emission
flies apart on the time scale of a molecular vibration
($\approx 10^{-13}$ s), very efficient way to depopulate the laser
level and provide perfect pop. inversion.

Although the rare gases do not form stable molecules such
as He$_2$, Ne$_2$, etc., called dimers in the ground state, these
molecules are known to exist in excited electronic states.

Excimers — contraction from excited dimer

Xe$_2^+$ excimer laser, excited by high energy e-beam,
using high pressure xenon (7-30 atm)

\[
\begin{align*}
Xe + e &\rightarrow Xe^+ \\
Xe^+ + Xe + Xe &\rightarrow Xe_2^+ + Xe \\
Xe_2^+ &\rightarrow Xe_2 + hv \\
Xe_2 &\rightarrow Xe + Xe
\end{align*}
\]

Laser is tunable
over a small range
near 171.6 nm.

$^1\Sigma_u^+ \rightarrow ^3\Sigma_u^+$ — the observed line is very broad. \(\Rightarrow\) AN shoulder

eat large \(\Rightarrow\) pulsed excitation is needed.

CW — impossible.
Most excimer lasers use transitions between an excited bound state of a molecule formed from 2 different atoms (rare gas & halogen) and the unbound (repulsive) ground state of the molecule. Molecules are not strictly dimers, they should call exciplex, excited complex.

Table 11.1. Exciplex Lasers.

<table>
<thead>
<tr>
<th>Exciplex molecule</th>
<th>Principal laser wavelengths (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ArCl</td>
<td>169, 175</td>
</tr>
<tr>
<td>ArF</td>
<td>193.3</td>
</tr>
<tr>
<td>ArO</td>
<td>558</td>
</tr>
<tr>
<td>HgBr</td>
<td>499–504.6</td>
</tr>
<tr>
<td>HgCl</td>
<td>551.6–559</td>
</tr>
<tr>
<td>KrCl</td>
<td>222</td>
</tr>
<tr>
<td>KrF</td>
<td>248.4–249.1</td>
</tr>
<tr>
<td>KrO</td>
<td>557.81</td>
</tr>
<tr>
<td>XeBr</td>
<td>281.8</td>
</tr>
<tr>
<td>XeCl</td>
<td>307–308.43</td>
</tr>
<tr>
<td>XeF</td>
<td>348.8–354.0, 483, 486</td>
</tr>
<tr>
<td>XeO</td>
<td>537.6, 544.2</td>
</tr>
<tr>
<td>KrF</td>
<td>430</td>
</tr>
<tr>
<td>Xe2Cl</td>
<td>518</td>
</tr>
</tbody>
</table>

Lasers are attractive because of large energy outputs and good electrical efficiency. E-beam excitation of Ar F produces 554 nm 92% at 166 W.

TEA type excitation.

Large pressure of the rare gas with a much smaller amount of the halogen.
Photodissociation Lasers

Lasers in which an UV flashlamp or the Sun is used to decompose (photolyse) a molecule into fragments, one of which is produced in an excited state. Example: atomic iodine photodissociation laser.

\[ \text{i-C}_3\text{F}_7\text{I} \rightarrow \text{i-C}_3\text{F}_7 + \text{I}^* \]

\[ \text{I}^* \rightarrow \text{I} \] (ground state) + \( \text{hv} (\lambda = 1.315 \mu\text{m}) \)

3 level system? The lower laser level is the atomic ground state.

No since \( \text{I} + \text{i-C}_3\text{F}_7 + \overline{\text{M}} \rightarrow \text{i-C}_3\text{F}_7\text{I} + \overline{\text{M}} \)

can gas atom added in the laser mixture.

I + I \rightarrow \text{I}_2 + \overline{\text{M}} should be removed. It makes laser action less efficient.

Iodine lasers yielded energies \( 1 \text{ to 9} \text{ in} \text{ J} \), \( \text{P} = 10^{12} \text{ W} \)

Technologically similar to optically pumped solid state lasers.

Can operate in CW mode provided the laser gas is recirculated and the iodine is removed.
Chemical Lasers

The reaction of two or more molecules leads to the generation of reaction products in excited states, which is possible on vibrational transitions.

- Laser oscillates in possible on vibrational transitions.

- \( H_2 + e \rightarrow 2H + e \)

- \( H + F_2 \rightarrow HF(v^* = 1, 2, 3) + F + 14.24 \text{ eV} \)

- \( F + H_2 \rightarrow HF(v^* = 1, 2, 3) + H + 13.65 \text{ eV} \)

- Cyclically repeat constituent chain reaction.

- The reaction between \( H_2 \) and \( F_2 \) is violent, like a bomb. 4kV in 25μs have been obtained.

- CW is also possible.
Mirage Chemical Laser. (New Mexico)
P = 2 MW cw for shooting down missiles.

A mixture of ethylene (C₂H₄), nitrogen trifluoride (NF₃) and helium is burned to generate fluorine atoms that then react with deuterium to generate vibrationally excited DF in a supersonic flow from a bank of nozzles.

N₂H₄ - high pressure hydrazine is injected to provide momentum to the gas flow and remove gases downstream.

CO chemical laser.

C₂H₂ + O₂ → CO₂ + S
C₂H₂ + O₂ → CO(ν₄)+ S₂ + 36 eV

700 W output power.

HCl chemical laser.

H + Cl₂ → HCl (ν₄, ν₄) + CE ⋆ 3.57-4.11 μm
CE + H₂ → HCl (ν₄) + H

Chemical iodine laser

Based on generation of electronically excited iodine atoms as a result of reactions:

O₂ (ⁿ₄) + I₂ (𝜃) → O₂ (ⁿ₄, S₁g) + I₂ (ⁿ₄, S₁g, ground)
O₂ (ⁿ₄) + I₂ → O₂ (ⁿ₄, S₁g) + 2I (²P₃/₂, ground)
O₂ (ⁿ₄) + I (²P₃/₂, ground) → O₂ (ⁿ₄) + I (²P₃/₂)

O₂ (ⁿ₂) is generated in reaction: CE + HCl + O₂ + 2NaCl → O₂(ⁿ₂)+ C₂H₂ (g) + ECE.
**Far-Infrared Lasers**

Fig. 11.19. Schematic variation of the power output of a far-infrared laser as the length of the resonator is adjusted.

Fig. 11.20. (a) Far-infrared laser pumped by a CO$_2$ laser that enters through a hole in one of the resonator mirrors. (b) Far-infrared waveguide laser design.

- FIR are molecular gas lasers in which a laser transition occurs between two rotational levels associated with the same vibrational level.
- Features:
  1. Because of their long $\tau$ → narrow linewidth.
  2. Usually only one axial mode of a resonator lies under the gain profile. We have to adjust $\zeta$ so that $\frac{\pi c}{2L} = \alpha$.
- In order to minimize diffraction losses, characterized by Fresnel $\# \frac{L}{\pi} D$, relatively large diameters of the tubes $D$ are used.
<table>
<thead>
<tr>
<th>Molecule</th>
<th>Wavelength (µm)</th>
<th>Typical power output (mW)</th>
<th>Pump laser and wavelength (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NH₃</td>
<td>81.5</td>
<td>50</td>
<td>N₂O 10.78</td>
</tr>
<tr>
<td>^1⁵NH₃</td>
<td>152.9</td>
<td>200</td>
<td></td>
</tr>
<tr>
<td>^1⁰BCl₃</td>
<td>19.4</td>
<td>50</td>
<td>^1³CO₂ 10.78</td>
</tr>
<tr>
<td></td>
<td>19.1</td>
<td>50</td>
<td>CO₂</td>
</tr>
<tr>
<td></td>
<td>18.3</td>
<td>50</td>
<td>CO₂</td>
</tr>
<tr>
<td>^1¹BCl₃</td>
<td>20.6</td>
<td>100</td>
<td>CO₂</td>
</tr>
<tr>
<td></td>
<td>20.2</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>CH₃F (methyl fluoride)</td>
<td>372.68</td>
<td>10</td>
<td>CO₂ 10.16</td>
</tr>
<tr>
<td></td>
<td>192.78</td>
<td>10</td>
<td>CO₂ 10.17</td>
</tr>
<tr>
<td>HCOOH (formic acid)</td>
<td>513.0157</td>
<td>5</td>
<td>CO₂ 9.23</td>
</tr>
<tr>
<td></td>
<td>302.2781</td>
<td>5</td>
<td>CO₂ 9.27</td>
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<tr>
<td>HCOOD</td>
<td>926.2087</td>
<td>10</td>
<td>CO₂ 10.29</td>
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<tr>
<td></td>
<td>919.9355</td>
<td>10</td>
<td>CO₂ 10.17</td>
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<tr>
<td>DCOOH</td>
<td>380.5654</td>
<td>10</td>
<td>CO₂ 10.30</td>
</tr>
<tr>
<td>CH₃Cl (methyl chloride)</td>
<td>334.0</td>
<td>50</td>
<td>CO₂ 9.75</td>
</tr>
<tr>
<td>CH₂F₂ (difluoromethane)</td>
<td>214.5791</td>
<td>500</td>
<td>CO₂ 9.20</td>
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<tr>
<td>CH₃⁷⁹Br</td>
<td>414.98</td>
<td>20</td>
<td>CO₂ 10.38</td>
</tr>
<tr>
<td>CH₃I (methyl iodide)</td>
<td>1253.738</td>
<td>10</td>
<td>CO₂ 10.72</td>
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<td>CH₃OH (methanol)</td>
<td>170.57637</td>
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<td>CO₂ 9.69</td>
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<td>164.7832</td>
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<td>118.8349</td>
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<td>96.52239</td>
<td>20</td>
<td>CO₂ 9.33</td>
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