II.D. Laser light sources (Sect. a - general principles, vapor phase and molecular lasers)

1. General aspects

a. Unique Properties: coherence (phase), directionality (pointing), spectral purity (frequency)

b. Stimulated emission — mechanism allows amplification of output of one transition

i. Temperature inverted levels—non-equilibrium population distribution -- $n_i > n_j$, $E_i > E_j$

---4-level system works best since lower state is continuously emptied (discuss),

4-level laser system

\[
\begin{align*}
  \text{pump} & \quad \text{laser} \\
  \text{i} & \quad \text{h} \nu = \Delta E = E_j - E_i \\
  \text{I}_c & \quad \text{I} \\

  \text{inversion: } n_i \text{ low by equil.} \\
  \text{nj created by IC} \\
  n_j > n_i \text{ - laser condition}
\end{align*}
\]
ii. Cavity construction creates standing wave—cycle light wave between mirrors, --this wave stimulates emission at the same frequency and with the same phase from the gain medium, tends to be directed out in a narrow beam by the cavity design --i.e. integral number of wavelengths between the (back-reflect & output) mirrors --gain medium needs to be excited—light or electrical discharge typical

Results: Narrow frequency distribution, defined direction and polarization —power through amplification of oscillator

1. Can make oscillator have gain if excite enough medium
2. can have separate amplifier—gain medium, no cavity

Every oscillator has 4 main parts (as seen in figure 3.1):

1. Amplifier
2. Positive resonance feedback
3. Output coupler
4. Power source

In analogy to the electronic amplifier, the laser can be described as composed of four subfigures 3.2:

1. Active medium, which serves as an optical amplifier.
2. Excitation mechanism.
3. Optical feedback.
4. Output coupler, to allow electromagnetic radiation out of the laser device.

c. Characteristics —categorize types of laser sources

- **timing**: cw — continuous wave (on all the time, DC) vs. Pulsed — down to fs ($10^{-15}$ s)
- **tune**: single or multiple lines vs. broad band (tune over 100’s - 1000’s cm$^{-1}$)
- **modes**: --transverse beam (cross-section intensity distribution), TM$_{00}$—ideal Gaussian
  --longitudinal (standing wave - each mirror at a node) – along propagation
  -- source of ultimate resolution, gain profile selects modes (by media, optics)

Longitudinal modes reflect fit of wavelength to the cavity length, gain profile

- **power**: -- cw (mW to a few W typical); exception: biggest — CO$_2$ welders (100s W)
  - also YAG based ones now

--pulsed -- can be many MW but for short pulse durations,
    high power can saturate oscillator, deplete inversion, terminate pulse
add amplifier to get highest powers (Laser fusion, Star-Wars, etc)

2. Types available

a. Gas ion -- lines or narrow bands, (HeNe — 2nd laser invented, but inefficient, low power),

  efficiency ex.: 130 mW of light require 10A to excite ion pop. At 100V = 1KW (need cool)

  HeNe typically use red line at 632.8 nm, but low power, also has IR lines: 1.15 µ, 3.39 µ

  Simple low power HeNe seal mirror to tube

  He provides excitation channel,

  Ne is gain medium, acts as 4-level system

i. Atomic ion lasers -- discharge through low pressure gas (plasma):

  \[ (\text{collision}) \rightarrow A^+ \rightarrow A^+ + h\nu \rightarrow (+e^-) \rightarrow A \]

  -- low efficiency (<0.1%) -- higher power designs are large (> m long) and need water cooling

  -- cw stable oscillator (depletes ground state), normally rare gas ions, most lines in visible

  -- power supply is expensive/ also at multiple KW needs cooling, large power drain (e.g. 220V)

  -- sensitive alignment of optics -- need very stable resonator design \( \rightarrow \) cost increase

  -- can be intracavity doubled (update) if high power (Fred design)—this is pricy (~$50 K+)

    but can be useful for spectroscopy (e.g. resonance Raman or fluorescence excitation)
SHG-second harmonic generation

--main types and transitions commonly seen:

- **Ar strongest** at 514.6, 488.8 nm + weaker blue and uv lines 351.1 and 363.8 nm

The Argon laser was invented in 1964 by William Bridges at Hughes.

Argon ion laser contains a tube filled with Argon gas which transforms into plasma in an excite (Plasma is a state of matter in which the electrons are separated from the atoms and molecules means that it contains free electrons and ions).

A schematic diagram of the energy levels of the Argon laser is shown in figure 6.4.

- Power demand is high,
  5W laser takes ~3KW
- 1m long, water cooling
- 4-level system, but multiple states populated, can operate on one or several lines

--Summary: 351.1, 363.8 (uv only high power models), 454.6, 457.9, 465.8, 476.5, 488.0, 496.5, 501.7, 514.5, 528.7, 1092.3 nm
Original - quartz tube (due to heat), now ceramic + quartz windows, BeO bore or magnet contain plasma

- **Kr** – same style - red lines strongest 647.1 nm + 568, 531, 521 nm in "yellow and green" and has uv lines at 351, 356 nm, but less efficient than Ar (costly)
  - [vis lines: 406.7, 413.1, 415.4, 468.0, 476.2, 482.5, 520.8, 530.9, 568.2, 647.1, 676.4 nm]
- **HeNe** -- 632.8 nm (Ne), low power efficiency, also near-IR lines. Lots of cheap ones available for alignment (eg. surveying) or FTIR calibration, low power, few mW.

**Less common:**
- **HeCd** -- 441 nm -- laser between energy levels of Cd⁺ ions, gain medium - ionized vapor.
  1. He excited by collisions with accelerated electrons, then they excite Cd by collisions.
  2. main application is in the optics laboratory, for fabricating holographic gratings.
- **Cu** -- pulsed green laser light at 510.6 nm and yellow laser light at 578.2 nm
  1. relatively efficient (up to 1%) for visible laser, high pulse power achieved.
  2. needs high temperature and a buffer gas like Ne
- **Au** - Gold Vapor laser - similar to Cu both in structure, and principles of operation. Red: 628 nm
- **Xe and I** lasers also have been built for research, I can be very powerful, laser fusion application
**Tuning the Laser Wavelength**

An example of such a tuning element can be seen in figure 6.17, which shows a prism inside the optical cavity.

![Diagram of laser cavity with prism](image)

Figure 6.17: Choosing a single wavelength in a tunable laser with a prism.

The dispersion of the prism causes each wavelength to bend at different angles, and only one wavelength will continue to move back and forth within the optical cavity. Moving the prism enables selecting the desired wavelength.

The pump bands are:

- [am] spectrum range which is suitable for flash-lamps.
- [am] which is suitable for diode laser pumping.

---

Longitudinal modes – group selected by gain profile, **pick single one by etalon (interference)**

![Graphs showing frequency and amplitude](image)

Normal multilongitudinal mode distribution of typical ion laser

Single longitudinal mode (or single frequency) output of ion laser using an etalon

---

**Polarization** will be in vertical plane due to Brewster angle windows, for ion lasers - relatively pure, to change it best to use a rotator (Faraday effect)
Stabilize power with a feedback system, can be very important for spectroscopy. Current control is basic, but if beam wanders the gain and output power will change.

Sealed system – windows must adjust on tube (see HeNe demo in class)

Structure of Typical Cynonics/Uniphase Argon Ion Laser Tube

### Metal-vapor lasers - comparative listing

<table>
<thead>
<tr>
<th>Laser gain medium and type</th>
<th>Operation wavelength(s)</th>
<th>Pump source</th>
<th>Applications and notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Helium-cadmium (HeCd) metal-vapor</td>
<td>441.563 nm, 325 nm</td>
<td></td>
<td>Printing and typesetting applications, fluorescence excitation examination, scientific research.</td>
</tr>
<tr>
<td>Helium-mercury (HeHg) metal-vapor</td>
<td>567 nm, 615 nm</td>
<td>Electrical discharge in metal vapor mixed with helium buffer gas</td>
<td>Rare, scientific research, amateur laser construction.</td>
</tr>
<tr>
<td>Helium-selenium (HeSe) metal-vapor</td>
<td>up to 24 wavelengths between red and UV</td>
<td></td>
<td>Rare, scientific research, amateur laser construction.</td>
</tr>
<tr>
<td>Helium-silver (HeAg) metal-vapor</td>
<td>224.3 nm</td>
<td></td>
<td>Scientific research</td>
</tr>
<tr>
<td>Neon-copper (NeCu) metal-vapor</td>
<td>248.6 nm</td>
<td>Electrical discharge in metal vapor mixed with neon buffer gas.</td>
<td>Scientific research</td>
</tr>
<tr>
<td>Copper vapor laser</td>
<td>510.6 nm, 578.2 nm</td>
<td>Electrical discharge</td>
<td>Dermatological uses, high speed photography, pump for dye lasers.</td>
</tr>
<tr>
<td>Gold vapor laser</td>
<td>627 nm</td>
<td></td>
<td>Rare, dermatological and photodynamic therapy</td>
</tr>
</tbody>
</table>
ii. **Molecular** — higher power, pulsed — 100-500 mJ/pulse — electronic transitions — vis, uv

**Excimer** -- rare gas and halogen (exciplex), excited state dimer has **no bound ground state**.

![Excimer laser diagram]

**Excimer Laser**

- **Bound excited state molecule**
- **IC create n_j**
- **Laser**
- **Disassociate**
- **Rapid dissociation**
- **Atom state**

**Transverse Discharge capacitor** through high pressure perpendicular to lasing direction

-- pulsed: moderate repetition rate and high power, fast deplete n_j
-- Beam quality poor -- transverse dye pumping OK -- can be improved (like for YAG) w/ optics
-- tunable over a short range (XeF, XeCl) by insertion of prism

**Examples:** - note specialized configurations used for **eye and other surgery** - control focus and ablation

- XeCl -- 308 nm, good for dye pump, does not photolyze dye so fast as KrCl, KrF or ArF
- XeF -- 351 nm – nuisance of handling F (passivate tube) makes less useful
- ArF -- 193 nm, good for photochem + VUV source (for photo lithography, chip design)
- F_2 -- 157 nm, good VUV (photochem, photo lithography)
- KrCl -- 222 nm and KrF -- 249 nm less commonly used
- N_2 -- "un-laser" -- super radiance 337.1 nm, 3-5 ns pulses, self terminates
  -- can be pump for (short pulse) dye lasers, low power fluorescence lifetime

<table>
<thead>
<tr>
<th>Excimer</th>
<th>Wavelength</th>
<th>Rel. Power</th>
<th>Excimer</th>
<th>Wavelength</th>
<th>Rel. Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ar_2*</td>
<td>126 nm</td>
<td></td>
<td>XeCl</td>
<td>308 nm</td>
<td>50</td>
</tr>
<tr>
<td>Kr_2*</td>
<td>146 nm</td>
<td></td>
<td>XeF</td>
<td>351 nm</td>
<td>45</td>
</tr>
<tr>
<td>F_2</td>
<td>157 nm</td>
<td>10</td>
<td>CaF_2</td>
<td>193 nm</td>
<td></td>
</tr>
<tr>
<td>Xe_2*</td>
<td>172 &amp; 175 nm</td>
<td></td>
<td>KrCl</td>
<td>222 nm</td>
<td>25</td>
</tr>
<tr>
<td>ArF</td>
<td>193 nm</td>
<td>60</td>
<td>Cl_2</td>
<td>259 nm</td>
<td></td>
</tr>
<tr>
<td>KrF</td>
<td>248 nm</td>
<td>100</td>
<td>N_2</td>
<td>337 nm</td>
<td>5</td>
</tr>
<tr>
<td>XeBr</td>
<td>282 nm</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Excimer lasers are usually operated with a pulse rate of around 100 Hz and a pulse duration of ~10 ns, although some operate as high as 8 kHz and 200 ns.
iii. Molecular—vibration-rotation (IR region)
• CO₂ --4-level system, very efficient: asymmetric stretch to bend (overtone) or sym. stretch, lower level relaxes very fast to ground state

\[ \text{CO}_2 \text{ laser levels} \]
\[ \text{each has rotations} \]

--molecular vib - rot transition (9.6-10.6 µ; --centers of bands, many lines, ~ 2 cm⁻¹ apart)

--multiple lines (coarse tune – line hop – like comb), high pressure-continuous discharge and collision excite, get ~ continuum (intensity between lines), but lots of intensity variation

-high power, can operate cw or pulsed

Many variants — CO (~5-6 µ), NO₂ (similar to CO₂), HCl (3.5-4 µ), DCI (5-5.6 µ), HBr, HF (2.5-3.3 µ), DF (3.5-4 µ),

Especially in far-IR: H₂O, CF₄ (15-17 µ), CH₃OH (37-700 µ), CH₃F (100-1200 µ)

Homework for Notes 3 (laser sources)
3. Laser light sources:

Text reading this section covers: Chapter 4-3 – pretty inadequate, out of date
Also review Kansas State web pages provided in links,
http://www.phys.ksu.edu/perg/vqm/laserweb/Preface/Toc.htm

Problems in the book
For discussion Ch. 4-18
To hand in eventually: Ch. 4 - # 2,14

More in Section 3b

Links:
Sam’s laser FAQ — general place to look up info
http://www.repairfaq.org/sam/lasersam.htm
http://www.repairfaq.org/sam/laserfaq.htm
http://www.repairfaq.org/sam/laserhen.htm#hentoc
http://www.repairfaq.org/sam/laserarg.htm#argtoc