# CHEM 524 - Course Outline (Sect. 3)

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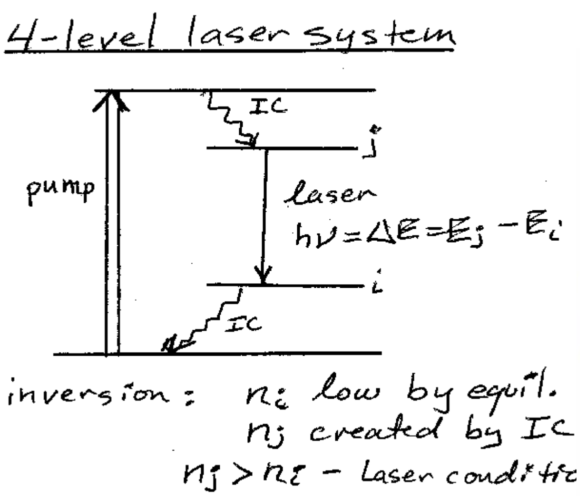
**II.D. Laser light sources** (general Laser Handout, p.2, from class, very old but possibly useful outline of IR lasers)

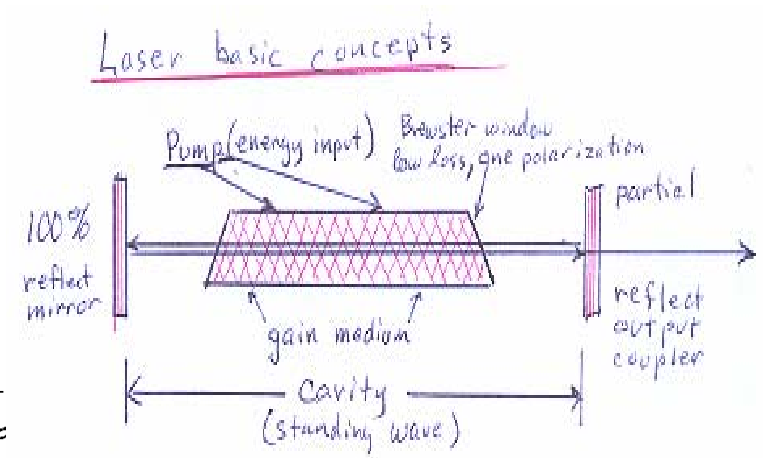
**1. General aspects**

**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,




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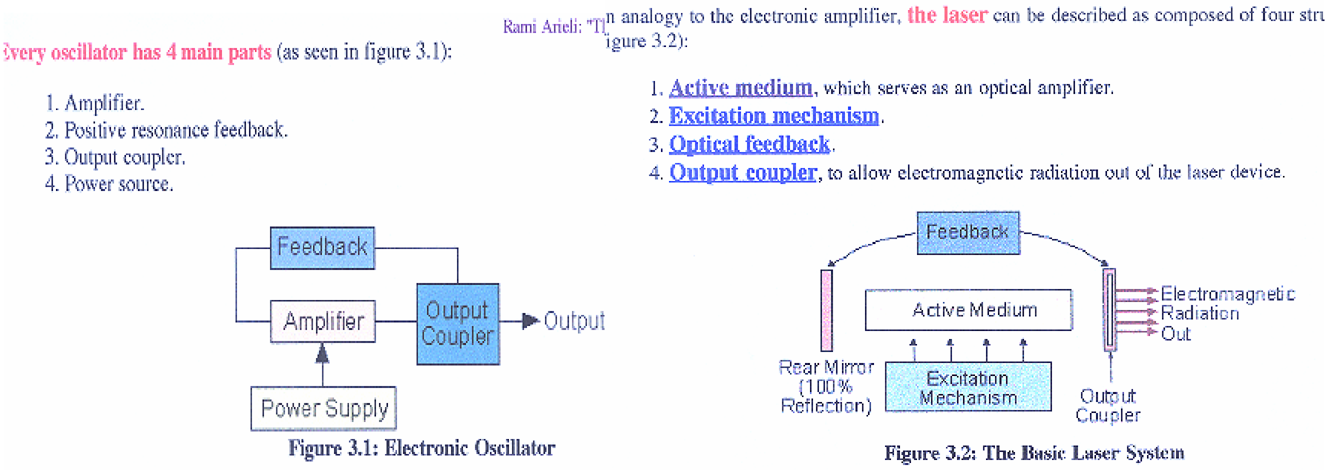
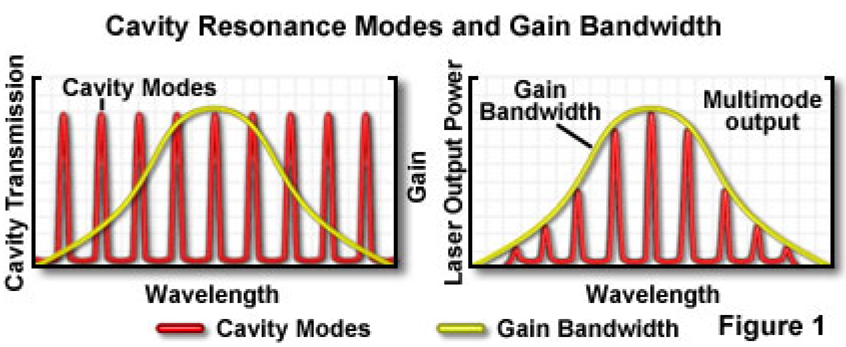
- --Results: Narrow frequency distribution, defined direction and polarization—power through amplification of oscillator




**c.** Characteristics —categorize types of laser sources

- *timing*: cw — continuous wave 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 (cross-section intensity distribution), $TM_{oo}$–ideal Gaussian

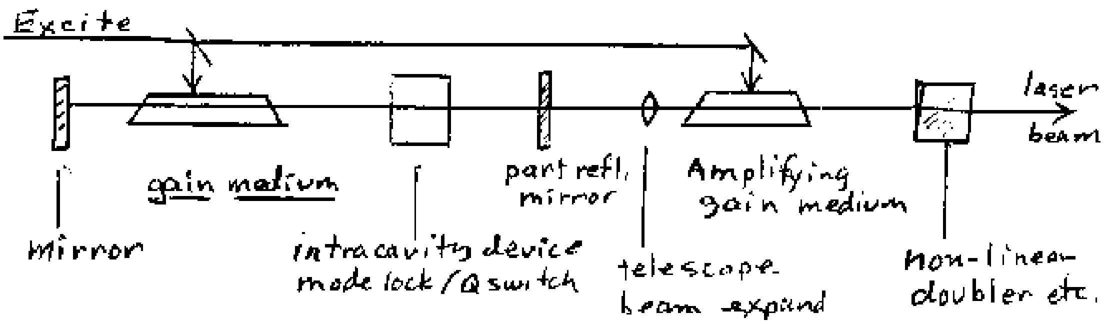
  --longitudinal (standing wave - each mirror at a node)-- source of ultimate resolution, gain profile selects modes




- *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, can saturate oscillator, deplete inversion, terminate pulse

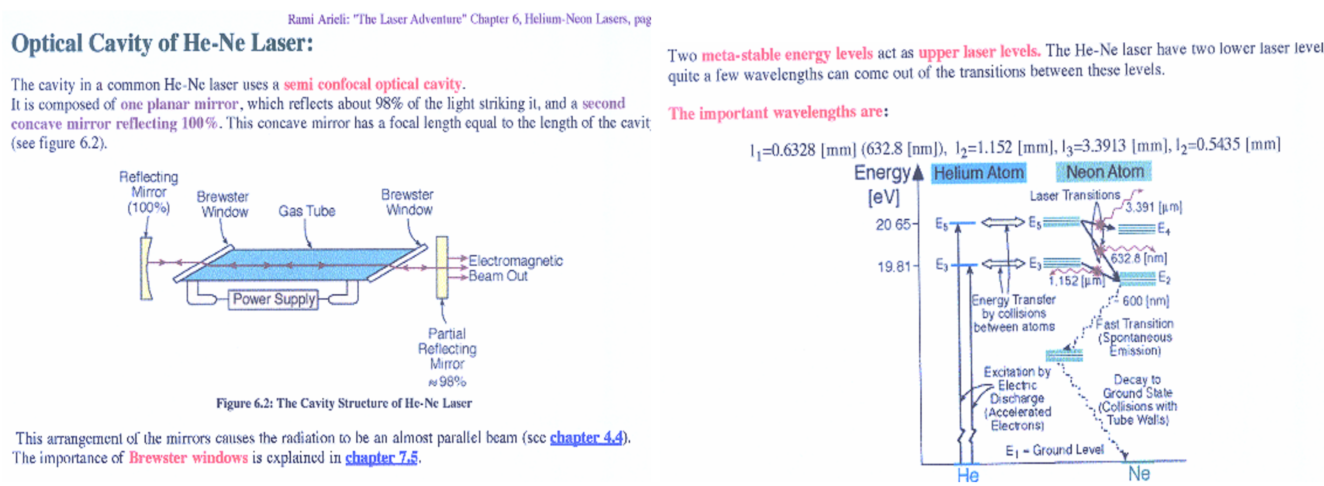
  --add amplifier to get highest powers (Laser fusion, Star-Wars,etc)




Typical Laser source components (single frequency)

## 2. Types available

**a. Gas ion** -- lines or narrow bands, (HeNe —2nd laser invented, even though inefficient.), figure L-3



Rami Arieli: "The Laser Adventure" Chapter 6, Helium-Neon Lasers, pag

**Optical Cavity of He-Ne Laser:**

The cavity in a common He-Ne laser uses a **semi confocal optical cavity**.
It is composed of **one planar mirror**, which reflects about 98% of the light striking it, and a **second concave mirror reflecting 100%**. This concave mirror has a focal length equal to the length of the cavit (see figure 6.2).



**Figure 6.2: The Cavity Structure of He-Ne Laser**

This arrangement of the mirrors causes the radiation to be an almost parallel beam (see chapter 4.4).
The importance of **Brewster windows** is explained in chapter 7.5.

Two **meta-stable energy levels** act as **upper laser levels.** The He-Ne laser have two lower laser levels quite a few wavelengths can come out of the transitions between these levels.

**The important wavelengths are:**

$l_1$=0.6328 [mm] (632.8 [nm]), $l_2$=1.152 [mm], $l_3$=3.3913 [mm], $l_2$=0.5435 [mm]



**He provides excitation channel, Ne is gain medium, acts as 4-level system**

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

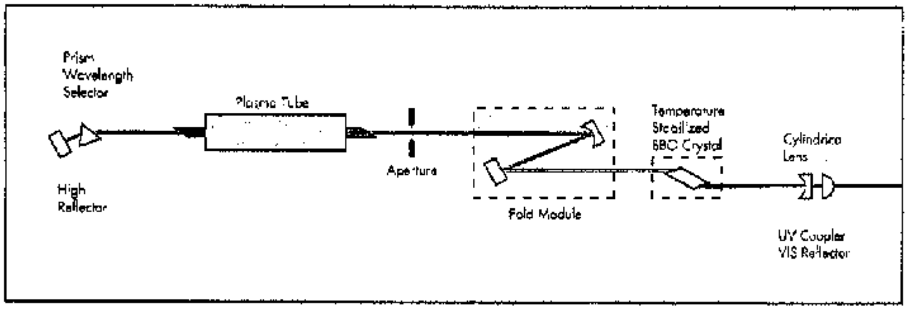
(collision) --> $A^{\pm *}$ -- > $\mathbf{A^{\pm}}$**+hν** — > (+$e^-$) -- > A

--low efficiency (<0.1%)

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

--power supply is expensive/sensitive alignment of optics

--can be intracavity doubled(update) if high power (Fred design)—this is pricy but can be valuable (e.g. resonance Raman)




Fredlaserdesign/BBOdouble

**Innova 90C FreD**

| Output Power Specifications | SHG[1] | | Fundamental[2] | |
|---|---|---|---|---|
| | Wavelength (nm) | Power (W) | Wavelength (nm) | Power (W) |
| | | | Multiline Visible | 5.00 |
| | 264.3 | 0.02 | 528.7 | 0.35 |
| | 257.2 | 0.10 | 514.5 | 2.00 |
| | 250.8 | 0.015 | 501.7 | 0.40 |
| | 248.2 | 0.06 | 496.5 | 0.60 |
| | 244.0 | 0.10 | 488.0 | 1.50 |
| | 238.2 | 0.03 | 476.5 | 0.60 |
| | 229.0 | 0.01 | 457.9 | 0.35 |
| | | | Multiline UV[3] | 0.4 |
| **Beam Parameters[4]** | **SHG** | | **Fundamental (514.5 nm)** | |
| Beam Diameter (mm) | 0.6-0.9[5] | | 1.7[5] | |
| Beam Divergence[1] (mrad) | 0.5-0.85 | | 0.5 | |
| Output Polarization | 100:1 horizontal | | 100:1 vertical | |
| Power Stability[8] | ±1.0% | | ±0.5% | |

--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.

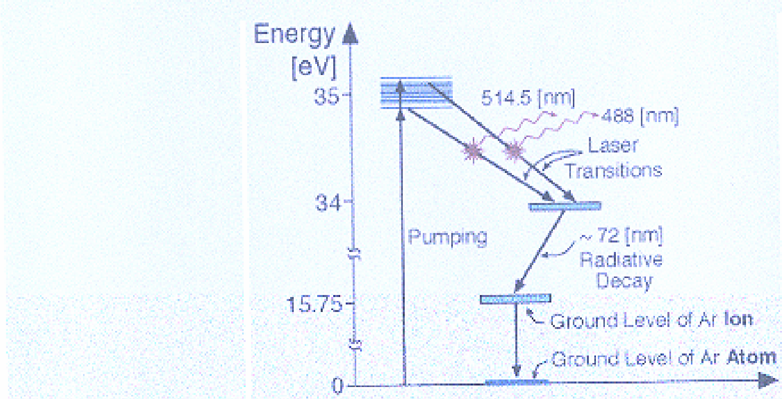
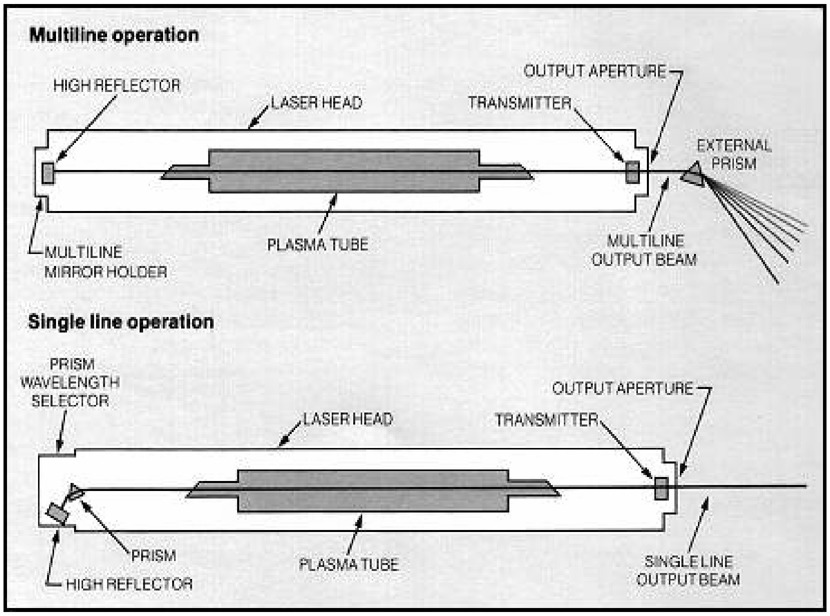



**Figure 6.4: Energy Level Diagram of Ion Argon Laser.**




- **Kr** red lines strongest 647.1 nm + 568, 531, 521 nm in "yellow and green" and uv lines at 351, 356 nm, but less efficient than Ar (costly)
- **HeNe** -- 632.8 nm (Ne), low power efficiency, also near-IR lines. Lots of cheap ones available for alignment (eg. surveying) or FTIR calibration.
- **HeCd** -- 441 nm -- laser occurs between energy levels of **Cadmium ions**, **lasing medium is ionized metal vapor**.
    1. Helium atoms are excited by collisions with accelerated electrons, and than they pass their energies to Cadmium atoms by collisions..
    2. the main application of the He-Cd laser 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. relative high efficiency (up to 1%) for lasers in the visible spectrum range, and the high pulse power achieved.
    2. needs high temperature and a buffer gas like Ne
- Au - Gold Vapor laser is very similar to **Cu** both in structure, and principles of operation.
    1. replace the solid Copper by pure Gold.
    2. The wavelength of Gold lasers is Red: 628 [nm].

Rami Arieli: "The Laser Adventure" Chapter 6.2.

## Tuning the Laser Wavelength

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

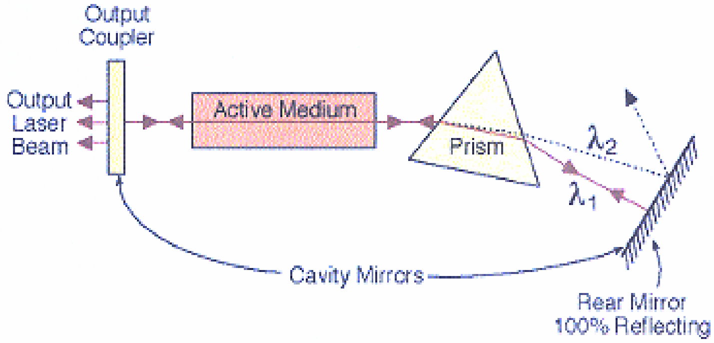


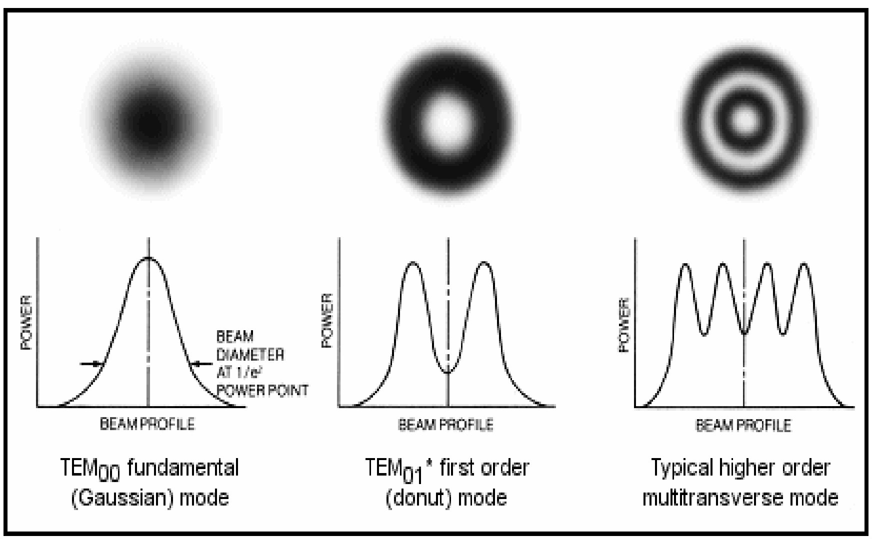

**Figure 6.17:** Choosing a single wavelength in a tunable laser with a prism.

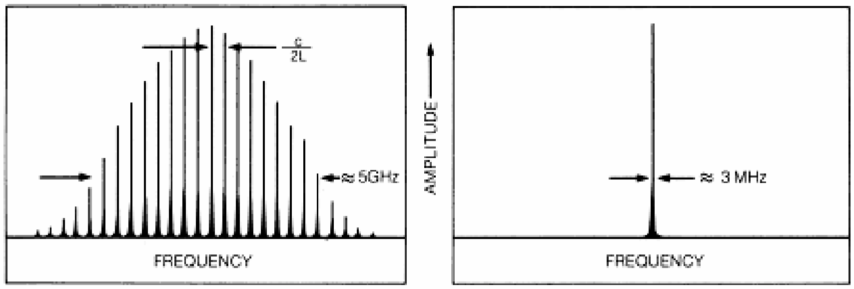
**The dispersion of the prism cause each wavelength to bend at different angle, and only one wavelength will continue to move back and forth within the optical cavity.**
**Moving the prism enable selecting the desired wavelength.**

**The pump bands are:**

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

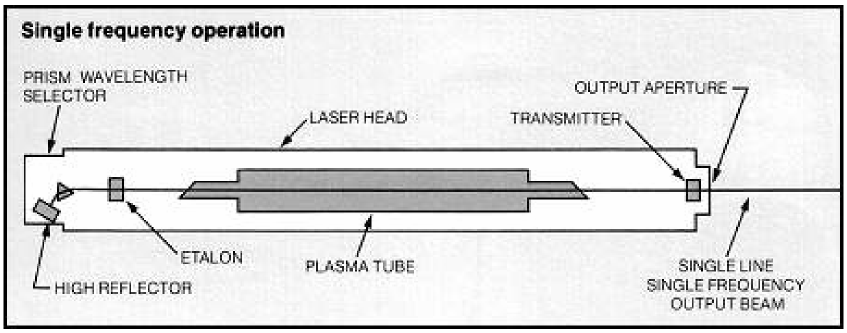
Laser modes—transverse affect shape of beam and focus






Normal multilongitudinal mode distribution of typical ion laser

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

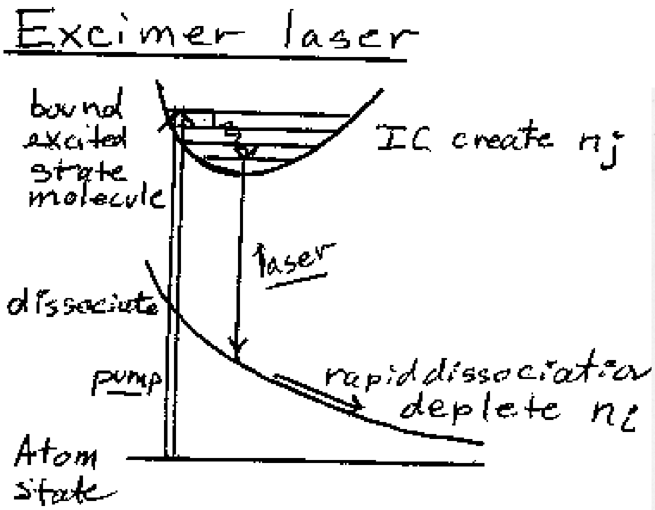


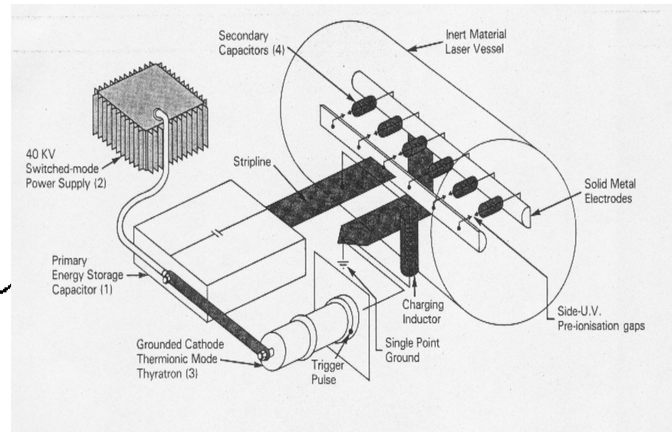

# Metal-vapor lasers

| Laser gain medium and type | Operation wavelength(s) | Pump source | Applications and notes |
|---|---|---|---|
| Helium-cadmium (HeCd) metal-vapor laser | 441.563 nm, 325 nm | Electrical discharge in metal vapor mixed with helium buffer gas | Printing and typesetting applications, fluorescence excitation examination, scientific research. |
| Helium-mercury (HeHg) metal-vapor laser | 567 nm, 615 nm | | Rare, scientific research, amateur laser construction. |
| Helium-selenium (HeSe) metal-vapor laser | up to 24 wavelengths between red and UV | | Rare, scientific research, amateur laser construction. |
| Helium-silver (HeAg) metal-vapor laser[1] | 224.3 | | Scientific research |
| Neon-copper (NeCu) metal-vapor laser[1] | 248.6 | Electrical discharge in metal vapor mixed with neon buffer gas. | Scientific research |
| Copper vapor laser | 510.6 nm, 578.2 nm | Electrical discharge | Dermatological uses, high speed photography, pump for dye lasers. |
| Gold vapor laser | 627 nm | | Rare, dermatological and photodynamic therapy uses. |

**ii. Molecular --**higher power, pulsed — 100-500 mJ/pulse

**Excimer** --rare gas and halogen, excited state dimer has no bound ground state,




Transverse Discharge capacitor through high pressure perpendicular to lasing direction

-- pulsed: high rep. rate and high power, fast deplete $n_j$

-- Beam quality poor-- but OK for transverse dye pumping-- can be improved (like for YAG) w/special optics

- XeCl -- 308 nm, good for dye pump, does not photolyze dye so fast
- XeF -- 351 nm
- ArF -- 193 nm, good for photochem + VUV source (now used for photo lithography for chip design)
- $F_2$ -- 157 nm, good VUV (photochem, photo lithography)
- KrCl -- 222 nm and KrF -- 249 nm less comonly used
- $N_2$ -- "un-laser" -- super radiance 337.1 nm, 3-5 ns pulses -- can be good pump for dye lasers, low power fluorescence

| Excimer | Wavelength | Relative Power | Excimer | Wavelength | Relative Power |
|---|---|---|---|---|---|
| $Ar_2$* | 126 nm | | XeCl | 308 nm | 50 |
| $Kr_2$* | 146 nm | | XeF | 351 nm | 45 |
| $F_2$ | 157 nm | 10 | $CaF_2$ | 193 nm | |
| $Xe_2$* | 172 & 175 nm | | KrCl | 222 nm | 25 |
| ArF | 193 nm | 60 | $Cl_2$ | 259 nm | |
| KrF | 248 nm | 100 | $N_2$ | 337 nm | 5 |
| XeBr | 282 nm | | | | |

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.

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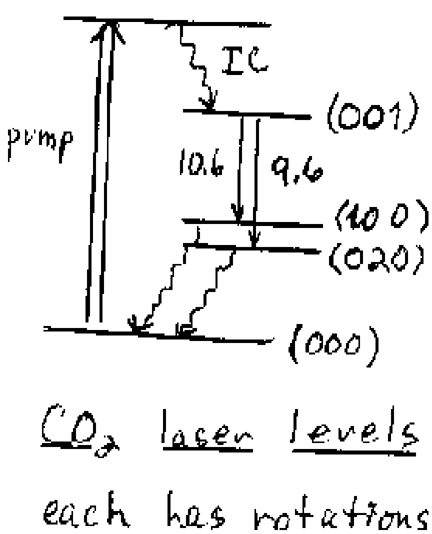
### iii. Molecular—vibration-rotation (IR region)

• $CO_2$ --4-level system, very efficient: asymmetric stretch to bend (overtone) or sym. stretch, lower level relaxes very fast to ground state



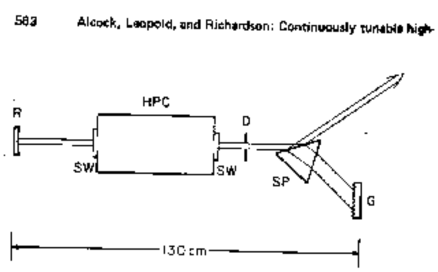




FIG. 2. Resonator configuration employed for continuously tunable laser. R—5-m gold mirror; SW—NaCl window; HPC—high-pressure chamber; D—diaphragm; SP—NaCl prism; G—grating.

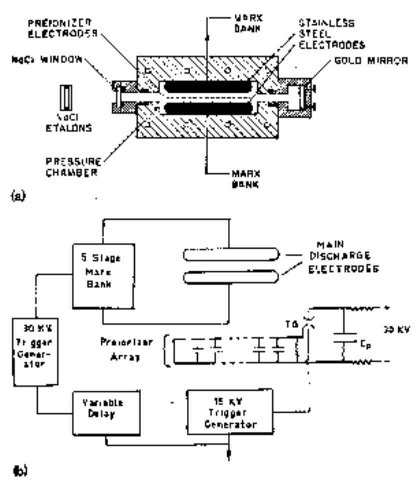



FIG. 1. (a) Cross section of high-pressure $CO_2$ laser showing location of main discharge electrodes immediately above the preionizer array. (b) Schematic diagram of preionizer and main discharge circuits.

**--molecular *vib - rot* transition (9.6-10.6 μ; --centers of bands, many lines, ~ 2 $cm^{-1}$ apart)**

--multiple line (coarse tune – line hop), high pressure more continuous discharge and collision excite, almost get a continuum, lots of intensity variation

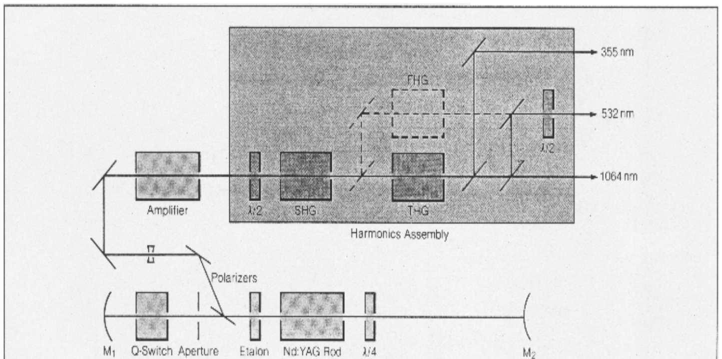
-high power, can operate cw or pulsed

**Many variants--CO, $NO_2$, HCl, HBr, $H_2O$, HF**

**b.Solid state --** note 1st laser was "ruby"($Cr^{+3}$ in $Al_2O_3$) T. Maiman, 1960

-- red, pulsed, inefficient, (2nd HeNe — also inefficient.)

• **[$Nd^{+3}$ YAG]** **-dominate -- work horse of pulsed laser field— can pump other devices**



Optical Schematic MY-Series Pulsed Nd:YAG Laser

IR oscillator -- fundamental oscillation at **1.06 μ** -- high power, good efficiency (double to 532 nm, triple to 353nm, quadruple to 266 nm, etc.)

--Originally --

flashlamp pumped-- Xe discharge lamp

Rami Arieli: "The Laser Adventure" Section 6.2.2 p

## Energy Level Diagram of Nd-YAG laser

The energy level diagram of a Nd-YAG laser can be seen in figure 6.15.

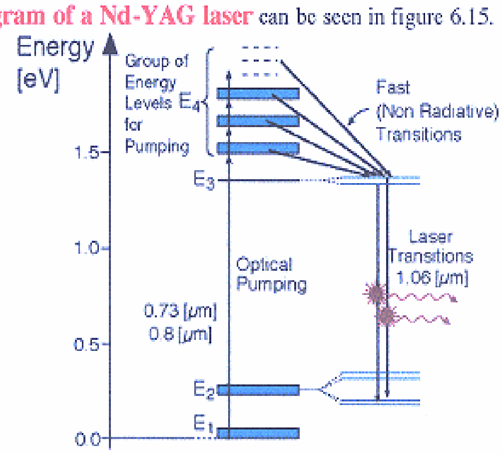


**Figure 6.15: Energy Level Diagram of a Nd-YAG Laser**

As can be seen from the energy level diagram, Nd lasers are four level lasers.

Nd ions have two absorption band, and excitation is done by optical pumping, either by flash lamps f pulsed lasers, or by arc lamps for continuous wave lasers.

From these excited energy levels, the Nd ions are transferring into the upper laser level by a non radiativ transition.

The stimulated emission is from the upper laser level to the lower laser level, and the wavelengths of tl emitted photons are around 1.06 [mm].

From the lower laser level, a non-radiative transition to the ground level.

# Arrangement of Pump and Laser Rod

There are many ways to transfer as much pump light as possible from the lamp to the active medium. The most common method is to use an **elliptic optical cavity** (A cavity created by an ellipsoid of revolution).

The lamp is at one focus of the **ellipsoid**, and the rod of the active medium at another, as described in Figure 6.12.

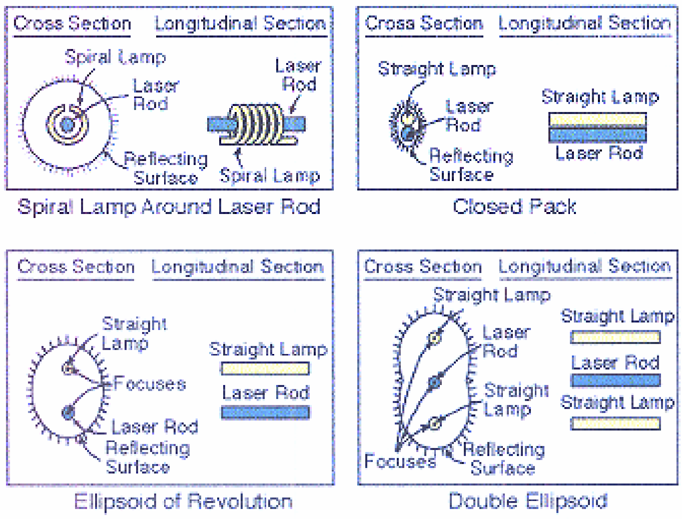


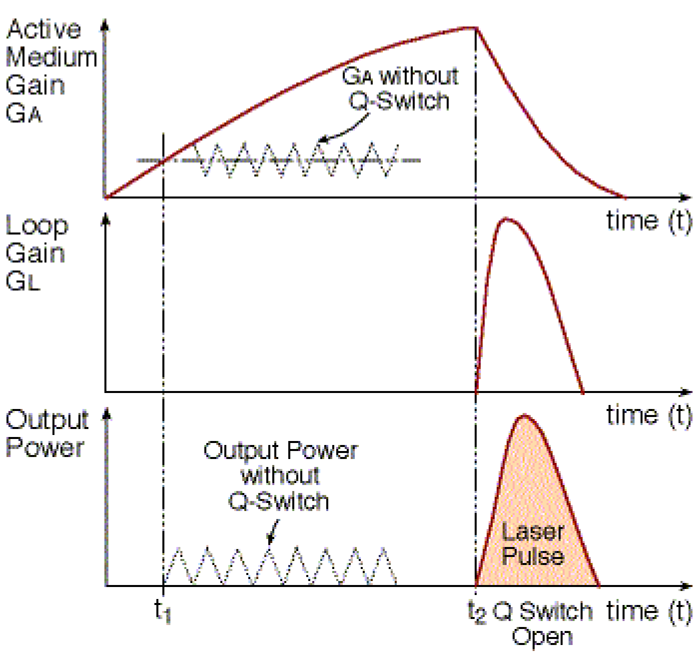

**Figure 6.12: Methods of Optical Pumping of Solid State Lasers.**

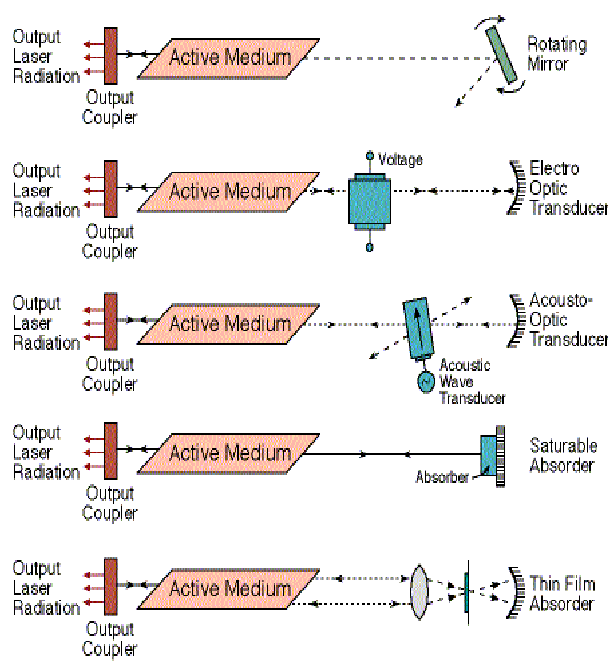
The inner surface of the cavity are coated with a reflective coating (usually Gold), such that all the radia emitted from the lamps ended at the active medium.

-- can be diode laser pumped -- beam quality high, power high

-- need Q-switch to control pulse (8-12 ns), different types

--traditional pulsed at only a modest rep rate (few Hz)



--power 100’s mJ/pulse, but with an amplifier get more,

non linear crystals— high efficiency conversion of frequency

--double (532nm), triple (355nm=fundamental+doupled), quadruple (266nm)

-- now available at MHz rate pulses (mode lock, Δt ~ ps, T=2nL/c – make round trip pulse be in phase, constructive interference, done with acousto-optic modulator at MHz rates

--and even cw (lower peak power, high average power)

• Other host materials possible:

Glass, larger gain medium inc. Conc., problem of heat, low rep.rate

YLF another crystal host

• Other ions and materials available, typically Rare Earth ion (e.g. Ho) & near IR lines

# Solid-state lasers

*Main article: Solid-state laser*

| Laser gain medium and type | Operation wavelength(s) | Pump source | Applications and notes |
|---|---|---|---|
| Ruby laser | 694.3 nm | Flashlamp | Holography, tattoo removal. The first type of visible light laser invented; May 1960. |
| Nd:YAG laser | 1.064 µm, (1.32 µm) | Flashlamp, laser diode | Material processing, rangefinding, laser target designation, surgery, research, pumping other lasers (combined with frequency doubling to produce a green 532 nm beam). One of the most common high power lasers. Usually pulsed (down to fractions of a nanosecond) |
| Er:YAG laser | 2.94 µm | Flashlamp, laser diode | Periodontal scaling, Dentistry |
| Neodymium YLF (Nd:YLF) solid-state laser | 1.047 and 1.053 µm | Flashlamp, laser diode | Mostly used for pulsed pumping of certain types of pulsed Ti:sapphire lasers, combined with frequency doubling. |
| Neodymium doped Yttrium orthovanadate ($Nd:YVO_4$) laser | 1.064 µm | laser diode | Mostly used for continuous pumping of mode-locked Ti:sapphire or dye lasers, in combination with frequency doubling. Also used pulsed for marking and micromachining. A frequency doubled $nd:YVO_4$ laser is also the normal way of making a green laser pointer. |
| Neodymium doped | ~1.060 µm (~530 | laser diode | Nd:YCOB is a so called "self-frequency doubling" or |

| | | | |
|---|---|---|---|
| yttrium calcium oxoborate Nd:$YCa_4O(BO_3)_3$ or simply Nd:YCOB | nm at second harmonic) | | SFD laser material which is both capable of lasing and which has nonlinear characteristics suitable for second harmonic generation. Such materials have the potential to simplify the design of high brightness green lasers. |
| Neodymium glass (Nd:Glass) laser | ~1.062 µm (Silicate glasses), ~1.054 µm (Phosphate glasses) | Flashlamp, laser diode | Used in extremely high power (terawatt scale), high energy (megajoules) multiple beam systems for inertial confinement fusion. Nd:Glass lasers are usually frequency tripled to the third harmonic at 351 nm in laser fusion devices. |
| Titanium sapphire (Ti:sapphire) laser | 650-1100 nm | Other laser | Spectroscopy, LIDAR, research. This material is often used in highly-tunable mode-locked infrared lasers to produce ultrashort pulses and in amplifier lasers to produce ultrashort and ultra-intense pulses. |
| Thulium YAG (Tm:YAG) laser | 2.0 µm | Laser diode | LIDAR. |
| Ytterbium YAG (Yb:YAG) laser | 1.03 µm | Laser diode, flashlamp | Optical refrigeration, materials processing, ultrashort pulse research, multiphoton microscopy, LIDAR. |
| Ytterbium:$_2O_3$ (glass or ceramics) laser | 1.03 µm | Laser diode | ultrashort pulse research, [2] |
| Ytterbium doped glass laser (rod, plate/chip, and fiber) | 1. µm | Laser diode. | Fiber version is capable of producing several-kilowatt continuous power, having ~70-80% optical-to-optical and ~25% electrical-to-optical efficiency. Material processing: cutting, welding, marking; nonlinear fiber optics: broadband fiber-nonlinearity based sources, pump for fiber Raman lasers; distributed Raman amplification pump for telecommunications. |
| Holmium YAG (Ho:YAG) laser | 2.1 µm | Laser diode | Tissue ablation, kidney stone removal, dentistry. |
| Cerium doped lithium strontium(or calcium) aluminum fluoride (Ce:LiSAF, Ce:LiCAF) | ~280 to 316 nm | Frequency quadrupled Nd:YAG laser pumped, excimer laser pumped, copper vapor laser pumped. | Remote atmospheric sensing, LIDAR, optics research. |

| | | | |
|---|---|---|---|
| Promethium 147 doped phosphate glass ($^{147}Pm^{+3}$:Glass) solid-state laser | 933 nm, 1098 nm | ?? | Laser material is radioactive. Once demonstrated in use at LLNL in 1987, room temperature 4 level lasing in $^{147}$Pm doped into a lead-indium-phosphate glass étalon. |
| Chromium doped chrysoberyl (alexandrite) laser | Typically tuned in the range of 700 to 820 nm | Flashlamp, laser diode, mercury arc (for CW mode operation) | Dermatological uses, LIDAR, laser machining. |
| Erbium doped and erbium-ytterbium codoped glass lasers | 1.53-1.56 µm | Laser diode | These are made in rod, plate/chip, and optical fiber form. Erbium doped fibers are commonly used as optical amplifiers for telecommunications. |
| Trivalent uranium doped calcium fluoride ($U:CaF_2$) solid-state laser | 2.5 µm | Flashlamp | First 4-level solid state laser (November 1960) developed by Peter Sorokin and Mirek Stevenson at IBM research labs, second laser invented overall (after Maiman's ruby laser), liquid helium cooled, unused today. [1] |
| Divalent samarium doped calcium fluoride ($Sm:CaF_2$) laser | 708.5 nm | Flashlamp | Also invented by Peter Sorokin and Mirek Stevenson at IBM research labs, early 1961. Liquid helium cooled, unused today. [2] |
| F-center laser. | 2.3-3.3 µm | Ion laser | Spectroscopy |

**c. Non-linear Devices** —transform — one frequency in,different ones out, but depend on high power, index match of input and output frequency and **k**-vector-- figure L-17

IR:

- Optical parametric oscillator: $\omega_\pi = \omega_\iota + \omega_\sigma$ --$LiNbO_3$ typical at YAG (1-4 µ)
- Difference crystal: $\omega_3 = \omega_1 - \omega_2$ -- tune $\omega_3$ output by tune $\omega_2$ vs. $\omega_1$ figure L-16

UV/vis:

- Sum or Doubler setup, results, in shift of frequency: $\omega_3 = \omega_1 + \omega_2$ or $\omega_0 = 2\omega_\iota$
  - use crystal with non-isotropic susceptibility, eg. KDP, KD*P, BBO (uv)
- Tripler (gas)––pass laser (focus) inot gas with 3rd order susceptibility--Typical use a very polarizable rare gas, eg. Xe
  - Results in output at tripled frequency (non-linear): $\omega_0 = 3\omega_\iota$
- Raman shift-pass laser ($\nu_0$) through gas cell, output contains frequencies shifted by Raman effect (stokes, decrease ν, anti-Stokes, increase ν)

- $\omega_0 = \omega_\iota \pm n\omega_{vib}$ -- often use $H_2$ since $\omega_{vib}$ ~4000 $cm^{-1}$
- setup,, multiple frequency shifts, Results, again,:

**d. Diode lasers** -- variously tunable, visible and IR

• Diode: vis to IR, depends on composition (band gap) low power, tune each over narrow band by current and temperature variation,

--this has been major growth area in lasers for past decade due to optoelectronics

--Very efficient (~20%), high reliability, low power, long lived, cheap

--See Kansas State site: (and following sequential pages) and Florida State diode section:

semiconductor has energy gap, electrons change level can emit light,- p-n junction diode, if forward bias can create current flow and radiation

degree of bias means spontaneous or stimulated emission

--multilayer chip (crystal), — size ~1 mm cavity, beam ~f/1, various layer patterns (heterostructures) improve efficiency, small packages

--Ga (In) As -- vis and near IR, moderate power (100's mW to multiple W), --fiber optic communication

--Pb (Sn) Te -- near to mid IR (3-30 μ) power~1 mW (cw) — high resolution IR absorption spectroscopy, remote sense

Modes — each very narrow, separated by few $cm^{-1}$, hop between

oscillate on (5-10) at a time, add monochromator for single mode

--change composition for other regions

--each crystal tune ~100 $cm^{-1}$ by temperature (T)

--each mode tune ~2 $cm^{-1}$ by current (I) until hop

**e. Tunable visible lasers/ vibronic lasers (include-- Ti:sapphire and F-center)**

• Dye laser -- pseudo four-level (fast relax vibration in ground. state.),

Timing-- mimic time character of pump:

-- Pulsed mode--excite with pump laser(YAG double/triple or excimer) or flash lamp (rare these days)

--or operate cw ($Ar^+$ion laser pump, or cw YAG doubled is typical)

Tune (with grating/prism/etalon) over fluorescence band — smooth, width depend on vibronic envelope

--Big shifts -- change dye (400-700 possible, near IR very unstable)

--Relatively high efficiency (~10% ofpump power with rhodamine)

Transverse or longitudinal pump -- powerdepends on pump

--for very high powers need amplifier stage avoid saturation,

Major resource for spectroscopy, resolution can be high

--Can be operated at very high resolution with accessory tuning --Designs: jet (cw), ring (traveling wave). etalon tune modes, transverse + amplifier

- Ti: Sapphire -- solid state --dye-like laser, capable of fsec operation

– Absorb ~500 nm, emit in red tunability into near IR, specifications

--very high efficiency and power capability

--particularly used for cw with Ar ion pump or doubled YAG pump,

--convert to fsec laser with mode-lock operation

- F-center -- near IR, cw, needs to be cooled

-- excite with laser, operate like dye laser, tune w/grating— limited (~100 $cm^{-1}$)

— change xtal for bigger shift, F-center: $M^+X^-$ xtal $e^-$ trap

**Assigned homework (all part of #1)** for Section3 – Laser Light Sources:

**3. Laser light sources**: Read and study the text, Chap 4-3, and the Kansas State site suggested in the notes, plus handouts on theory.

**Homework** for discussion only: Chap. 4: 2, 18

* **Problems to hand in**: Chap 4: 14, Plus those below:

a. from O. Svelto and D.C. Hanna (trans.) *Principles of Lasers, 2nd Edition*, Plenum, 1982.

6.15 Collision broadening of the $CO_2$ laser transition is $\Delta\nu_e = 7.58\,(X_{CO_2} + 0.73\,X_{N_2} + 0.6\,X_{He})\,p\,(300/T)^{1/2}$ in MHz, where X is partial function of each component and p is total pressure. If the ratio of $CO_2$:$N_2$:He is 1:1:8 calculate p when all rotational lines merge together.

(HINT: For $CO_2$ energy levels you will need B, the rotational constant—look it up or calculate it.)

1.4 If two levels at $300^o$ K are in thermal equilibrium with $n_2/n_1 = 1/e$, calculate the frequency of the transition from $1 \rightarrow 2$. In what part of the spectrum does this occur?

2.0 Calculate the number of longitudinal modes that occur in $\Delta\lambda$=1 nm at $\lambda^0$=1.06 $\mu$ for a 1 m long laser cavity.

**b. Question 4.4: Ar+ Ion laser** (from Kansas State site)

The difference between adjacent modes in Ar+ Ion laser is 100 MHz. The mirrors are at the end of the laser tube.

**Calculate:**

1. The length of the laser cavity.
2. The mode number of the wavelength 488 [nm].
3. The change in difference between adjacent modes when the tube is shortened to half its length.

## WebLinks,

laser companies, leads to details, drawings, explanations—good source of what is available

Other sites, background information ***Recommend reading through these***::

Kansas State short laser course, very good, but a bit difficult to navigate,

summary of principles in outline form (then detailed discussion if you follow the pointed hands on left, click on it not the links) with glossary (click on linked words)

http://www.phys.ksu.edu/perg/vqm/laserweb/Preface/Toc.htm

Fraunhofer laser review—German source (in English) hitting main topics with linked pages, terse some nice concepts http://www.ilt.fraunhofer.de/eng/100048.html

Sam's Laser FAQ, a hobbyist site, lots of safety and some diagrams:

http://www.eio.com/repairfaq/sam/lasersam.htm

Florida State Notes on laser operation and design with interactive sections on various lasers

http://micro.magnet.fsu.edu/primer/lightandcolor/laserhome.html