

# CHEM 524 - Course Outline (Sect. 3-b – solid state lasers)

For Html Version of This Set of Notes from 2005, with Linked FIGURES [CLICK HERE](#)

**b.Solid state** -- note 1<sup>st</sup> laser was "ruby"(Cr<sup>+3</sup> in Al<sub>2</sub>O<sub>3</sub>)

by Ted Maiman, 1960, Hughes Lab.

- red, 694.3 nm, pulsed, ~msec,
- inefficient, three level system, self-absorbent rod
- Xe flash lamp pump, original rod ends polish/silvered

• **Nd<sup>+3</sup>YAG** -dominate -- work horse of pulsed laser field

— often to pump other devices – non-linear xtal, dyes, shifter

**IR oscillator** -- **fundamental - 1.06 μ** -- high power, good efficiency

(double to 532 nm, triple to 353nm, quadruple

## Arrangement of Pump and Laser Rod

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

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

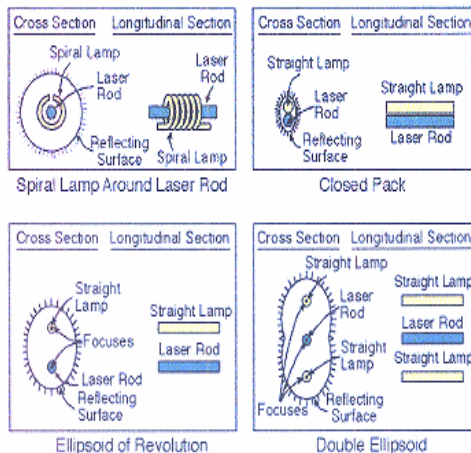


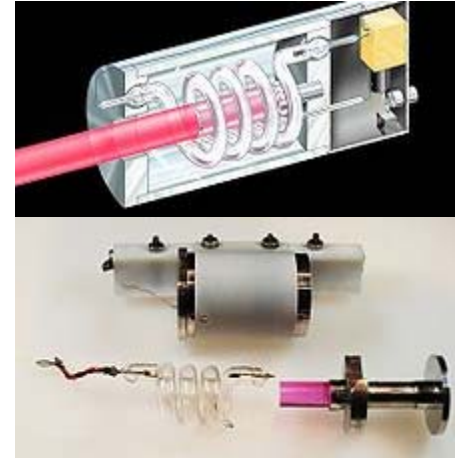
Figure 6.12: Methods of Optical Pumping of Solid State Lasers.

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

to 266 nm, etc.) – green, near uv, deep uv

Originally -- flashlamp pumped

- Xe discharge, broad pump, but absorb narrow
- various cavity designs for transfer excite
- Levels have slight variation
- different host matrices (xtal) can affect



Kamr Arnet: "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.

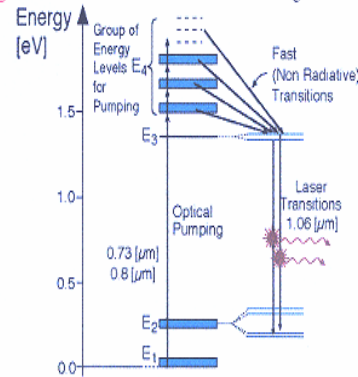


Figure 6.15: Energy Level Diagram of a Nd-YAG Laser

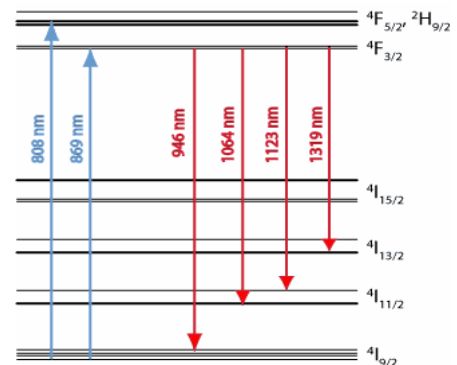
As can be seen from the energy level diagram, Nd lasers are **four level lasers**.

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 radiati  
transition.

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

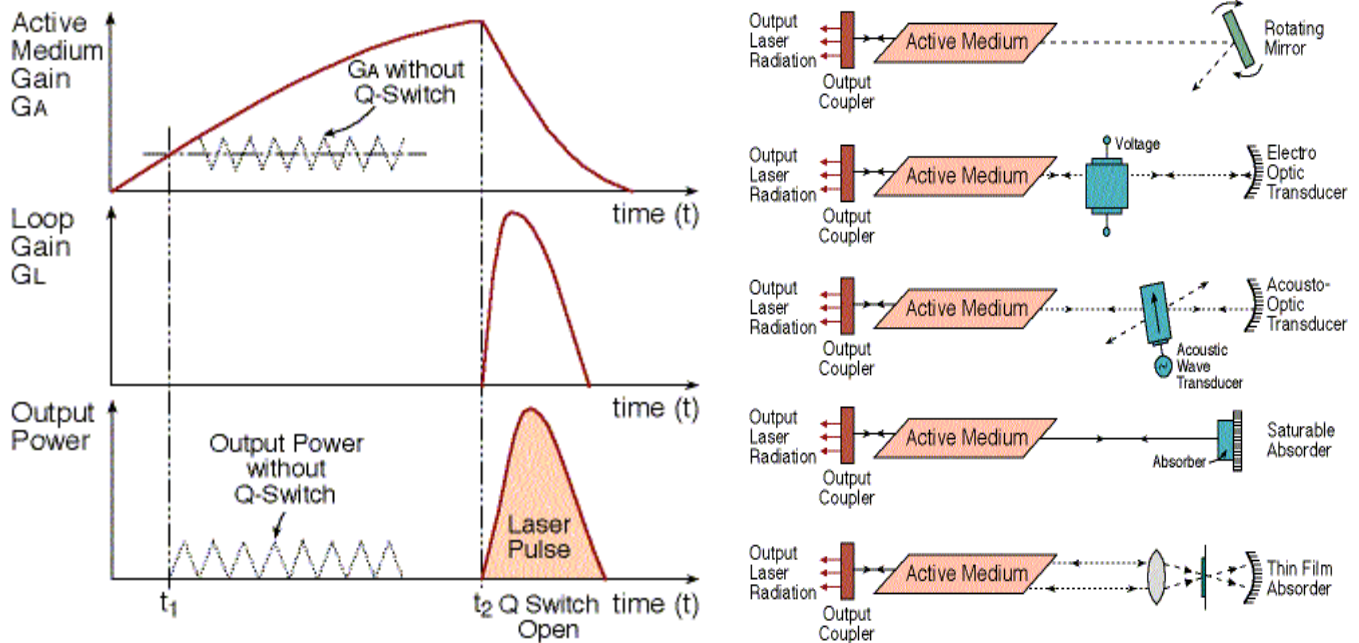
From the lower laser level, a non-radiative transition to the ground level.



Alternate-- can diode laser pump -- beam quality & power high – efficient **hit absorbance**

Pulse operation -- [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

frequency conversion (**Sect. c below**)

--double (532nm), triple (355nm =

fundamental+doupled),

or quadruple (266nm)

-- now available at **MHz rate** pulses

(mode lock,  $\Delta t \sim ps$ ,  $T=2nL/c$  – make round trip pulse be in phase, constructive

interference, done with acousto-optic modulator at MHz rates

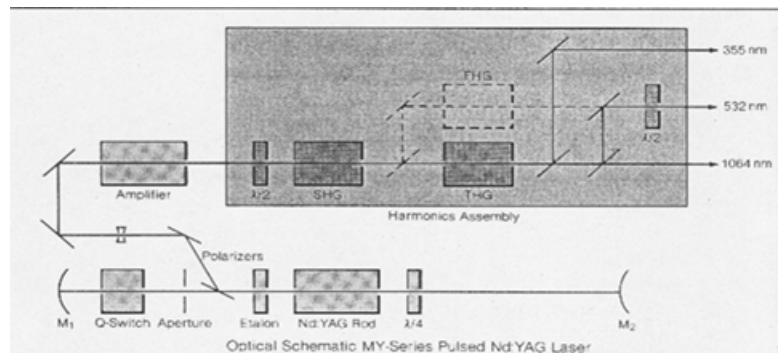
--and even **cw** (lower peak power, high average power)

• **Other host materials** possible: YLF and  $YVO_4$  other crystal hosts

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

• 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
<a href="#">Ruby laser</a>	694.3 nm	Flashlamp	<a href="#">Holography</a> , <a href="#">tattoo</a> removal. The first visible light laser invented; <a href="#">1960</a> . Material processing, <a href="#">rangefinding</a> , laser target designation, surgery,
<a href="#">Nd:YAG laser</a>	1.064 $\mu\text{m}$ , (1.32 $\mu\text{m}$ )	Flashlamp, <a href="#">laser diode</a>	research, pumping other lasers (combined with <a href="#">frequency doubling</a> to produce a green 532 nm beam). One of the most common high power lasers. Usually pulsed (down to fractions of a nanosec)
<a href="#">Er:YAG laser</a>	2.94 $\mu\text{m}$	Flashlamp, <a href="#">laser diode</a>	Periodontal scaling, <a href="#">Dentistry</a>
<a href="#">Neodymium YLF (Nd:YLF) solid-state laser</a>	1.047 and 1.053 $\mu\text{m}$	Flashlamp, laser diode	Mostly used for pulsed pumping of certain types of pulsed <a href="#">Ti:sapphire</a> lasers, combined with <a href="#">frequency doubling</a> .
<a href="#">Neodymium doped Yttrium orthovanadate (Nd:YVO<sub>4</sub>) laser</a>	1.064 $\mu\text{m}$	laser diode	Mostly used for continuous pumping of <a href="#">mode-locked</a> Ti:sapphire or dye lasers, in combination with <a href="#">frequency doubling</a> . Also used pulsed for marking and micromachining. A frequency doubled nd:YVO <sub>4</sub> laser is also the normal way of making a <a href="#">green laser pointer</a> .
<a href="#">Nd doped yttrium calcium oxoborate Nd:YCa<sub>4</sub>O(BO<sub>3</sub>)<sub>3</sub> or simply Nd:YCOB</a>	~1.060 $\mu\text{m}$ (~530 nm, 2 <sup>nd</sup> harm)	laser diode	Nd:YCOB is a so called "self-frequency doubling" or SFD laser material which is both capable of lasing and which has nonlinear characteristics suitable for <a href="#">second harmonic generation</a> . Such materials have the potential to simplify the design of high brightness green lasers.
<a href="#">Neodymium glass (Nd:Glass) laser</a>	~1.062 $\mu\text{m}$ ( <a href="#">Si-O glasses</a> ), ~1.054 $\mu\text{m}$ ( <a href="#">P-O glasses</a> )	Flashlamp, laser diode	Used in extremely high power ( <a href="#">terawatt</a> scale), high energy ( <a href="#">megajoules</a> ) multiple beam systems for <a href="#">inertial confinement fusion</a> . Nd:Glass lasers are usually <a href="#">frequency tripled</a> to the <a href="#">third harmonic</a> at 351 nm in laser fusion devices.
<a href="#">Titanium sapphire (Ti:sapphire) laser</a>	650-1100 nm	Other laser	Spectroscopy, <a href="#">LIDAR</a> , research. This material is often used in highly-tunable <a href="#">mode-locked infrared</a> lasers to produce <a href="#">ultrashort pulses</a> and in amplifier lasers to produce ultrashort and ultra-intense pulses.
<a href="#">Thulium YAG (Tm:YAG) laser</a>	2.0 $\mu\text{m}$	Laser diode	<a href="#">LIDAR</a> .
<a href="#">Ytterbium YAG (Yb:YAG) laser</a>	1.03 $\mu\text{m}$	Laser diode, flashlamp	<a href="#">Optical refrigeration</a> , materials processing, ultrashort pulse research, multiphoton microscopy, <a href="#">LIDAR</a> .
<a href="#">Ytterbium:2O<sub>3</sub> (glass or ceramics) laser</a>	1.03 $\mu\text{m}$	Laser diode	ultrashort pulse research, <sup>[2]</sup>
<a href="#">Ytterbium doped glass</a>	1. $\mu\text{m}$	Laser diode.	Fiber version is capable of producing several-kilowatt continuous power,

laser (rod, plate/chip, and fiber)

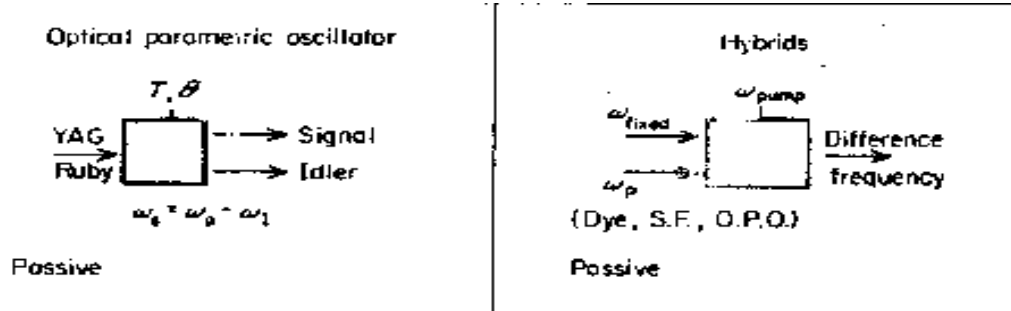
having ~70-80% optical-to-optical and ~25% electrical-to-optical efficiency. Material processing: cutting, welding, marking; nonlinear fiber optics: broadband fiber-nonlinearity based sources, pump for fiber [Raman lasers](#); distributed Raman amplification pump for [telecommunications](#).

<a href="#">Holmium</a> YAG (Ho:YAG) laser	2.1 $\mu\text{m}$	Laser diode	Tissue ablation, <a href="#">kidney stone</a> removal, <a href="#">dentistry</a> .
<a href="#">Cerium</a> doped <a href="#">lithium strontium</a> (or <a href="#">calcium</a> ) <a href="#">aluminum fluoride</a> (Ce:LiSAF, Ce:LiCAF)	~280 to 316 nm	UV laser pump, Nd:YAG -4th, <a href="#">excimer</a> , Cu	Remote atmospheric sensing, <a href="#">LIDAR</a> , optics research.
<a href="#">Promethium</a> 147 doped <a href="#">phosphate glass</a> ( $^{147}\text{Pm}^{+3}$ :Glass)	933 nm, 1098 nm	??	Laser material is radioactive. Once demonstrated in use at <a href="#">LLNL</a> in <a href="#">1987</a> , room temperature 4 level lasing in $^{147}\text{Pm}$ doped into a lead- <a href="#">indium</a> -phosphate glass <a href="#">étalon</a> .
<a href="#">Chromium</a> doped <a href="#">chrysoberyl</a> ( <a href="#">alexandrite</a> ) laser	Tuned in the range of 700 to 820 nm	Flashlamp, laser diode, <a href="#">Hg arc</a> ( <a href="#">cw</a> )	<a href="#">Dermatological</a> uses, <a href="#">LIDAR</a> , laser machining.
<a href="#">Erbium</a> and Er:Yb codoped glass lasers	1.53-1.56 $\mu\text{m}$	Laser diode	These are made in rod, plate/chip, and optical fiber form. Erbium doped fibers are commonly used as <a href="#">optical amplifiers</a> for <a href="#">telecommunications</a> .
Trivalent <a href="#">uranium</a> doped <a href="#">calcium fluoride</a> (U:CaF <sub>2</sub> ) solid-state	2.5 $\mu\text{m}$	Flashlamp	First 4-level solid state laser (November 1960) developed by Peter Sorokin and Mirek Stevenson at <a href="#">IBM</a> research labs, second laser invented overall (after Maiman's ruby laser), <a href="#">liquid helium</a> cooled, unused today. <a href="#">[1]</a>
Divalent <a href="#">samarium</a> doped <a href="#">calcium fluoride</a> (Sm:CaF <sub>2</sub> ) laser	708.5 nm	Flashlamp	Also invented by Peter Sorokin and Mirek Stevenson at <a href="#">IBM</a> research labs, early 1961. <a href="#">Liquid helium</a> cooled, unused today. <a href="#">[2]</a>
<a href="#">F-center</a> laser.	2.3-3.3 $\mu\text{m}$	Ion laser	Spectroscopy ( <a href="#">act like dye laser, broad band emit, select <math>\lambda</math> with grating</a> )

c. **Non-linear Devices** —not lasers, but transform — one frequency in, different ones out, but depend on high power, index match of input and output frequency and **k-vector**--

IR:

- **Optical parametric oscillator**: --LiNbO<sub>3</sub> typical at YAG (1-4 μ), can use BBO in vis



**FIGURE 2. Principal mechanisms used for tunable infrared lasers since 1970.**

OPO:  $\omega_s + \omega_i = \omega_p$  : Input pump  $\omega_p$  and out put **signal**  $\omega_s$  (higher freq.) and **idler**  $\omega_i$

Can use to get tunable IR (Yag pump) or vis (double pump) with relatively high intensity

To get gain at  $\omega_s + \omega_i$  need to put crystal (non-linear,  $\chi^{(2)}$ ) in a cavity (oscillator) for both

This transfer energy (field strength) form pump to desired outputs

Tune by changing **phase matching**—  $k_s + k_i = k_p$  --typically by angle, but also temperature

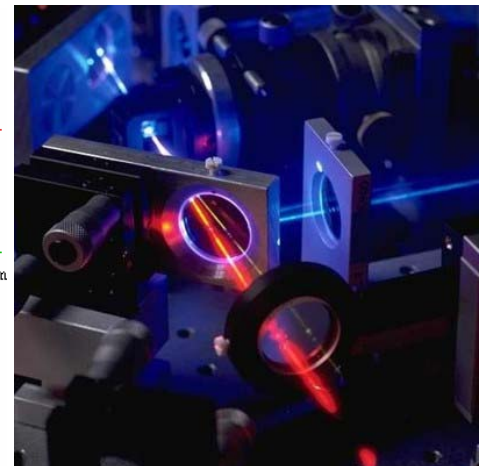
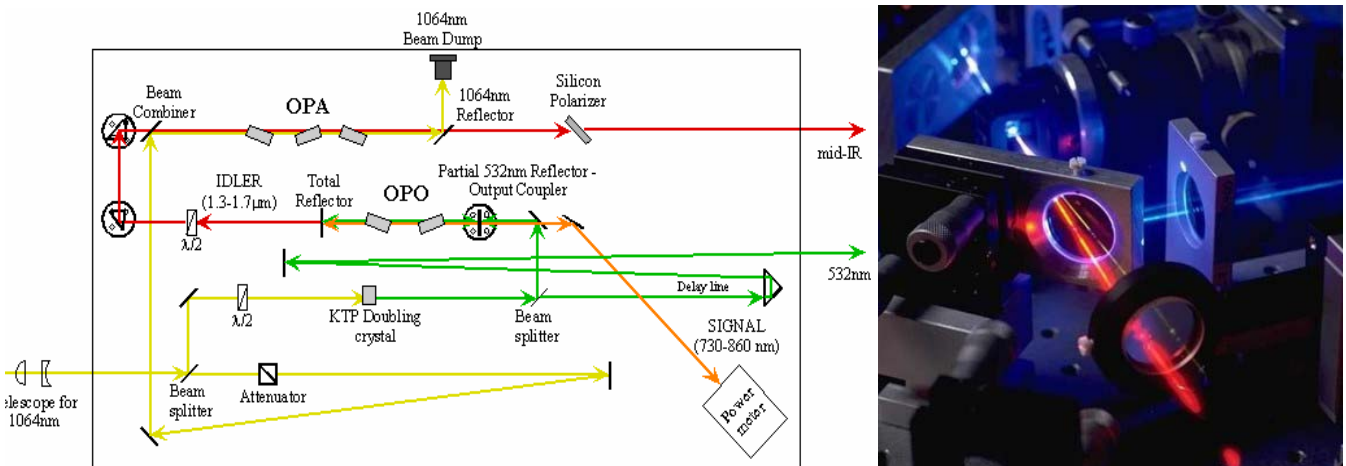
Mode hopping can be a problem for continuous tuning

Optical Parametric Amplifiers – common commercial term, seems to operate essentially the same

Big deal is high power OK, since total conversion of photon in to two photon out

Also possible to make a fiber OPA, here operate with four waves and use  $\chi^{(3)}$

Example OPO/OPA setup at Tufts Univ (Prof. Mary Shultz):

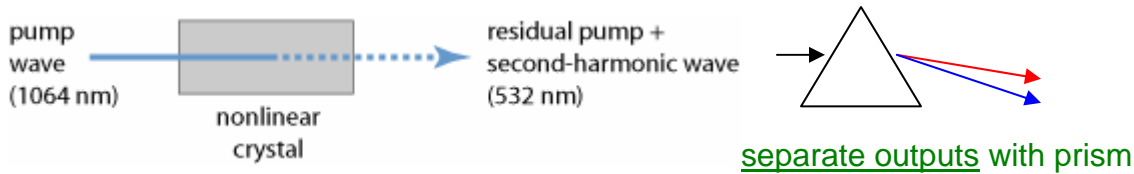


- **Difference crystal**:  $\omega_3 = \omega_1 - \omega_2$  -- tune  $\omega_3$  output by tune  $\omega_2$  vs.  $\omega_1$

1. use variety of non-linear crystals ( $\chi^{(2)}$  dependent, birefringent) and phase match

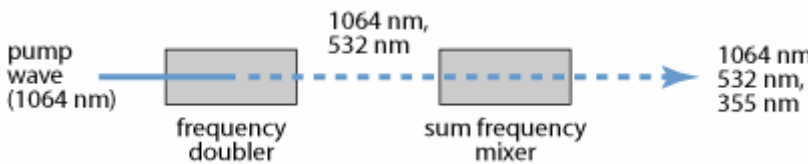
UV/vis:

- Sum or Doubler setup, results, in shift of frequency:  $\omega_3 = \omega_1 + \omega_2$  **OR**  $\omega_0 = 2\omega_1$ 
  - use crystal with non-isotropic susceptibility, eg. KDP, KD\*P, BBO (uv)



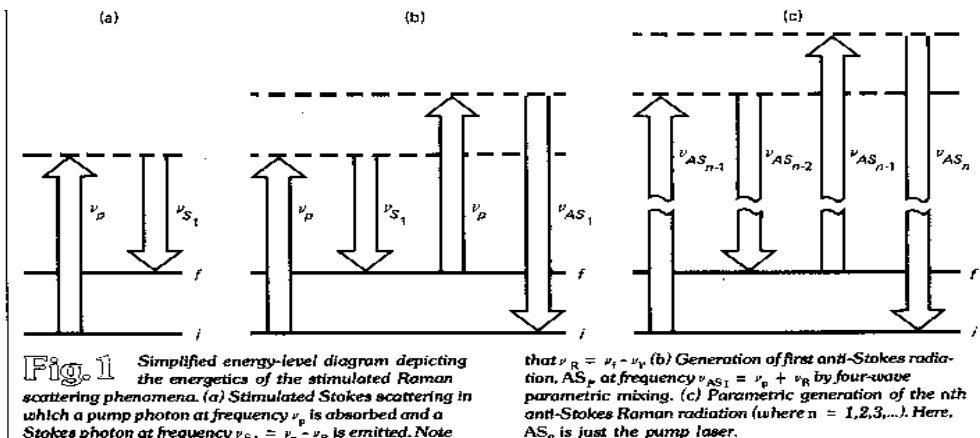
Control function by which frequencies are phase matched (angle, temperature):  $k_s + k_i = k_p$

Frequency tripling is usually realized as a cascaded process, beginning with frequency doubling of the input beam and subsequent sum frequency generation of both waves, with both processes being based on nonlinear crystal materials with a  $\chi^{(2)}$  nonlinearity. (See Previous Laser setup)



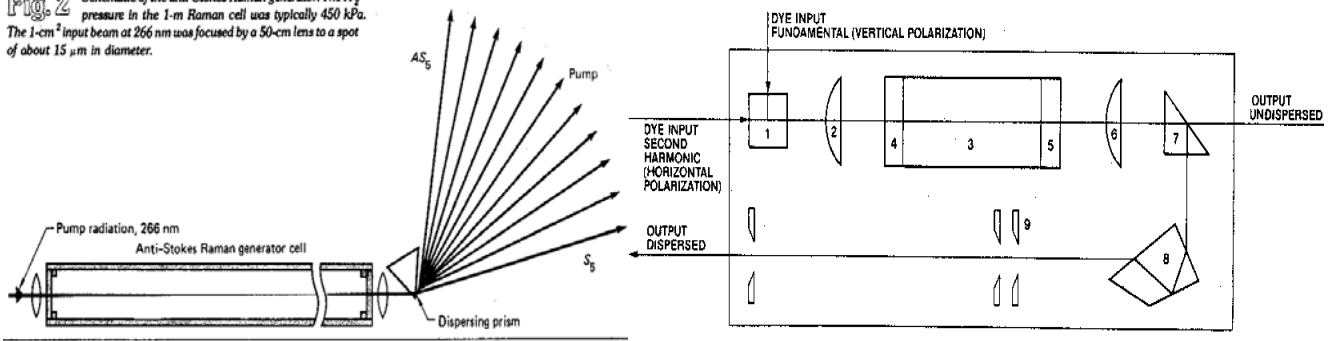
**Figure 1:** infrared input beam at 1064 nm generates a green 532-nm wave, and these two mix in a second crystal to obtain 355-nm light.

- Tripler (gas)—pass laser (focus) into gas with 3rd order susceptibility,  $\chi^{(3)}$ 
  - --Typical use a very polarizable rare gas, eg. Xe
  - Results in output at tripled frequency (non-linear):  $\omega_0 = 3\omega_1$
  -
- Raman shift-pass laser ( $\nu_0$ ) through gas cell, output contains frequencies shifted by Raman effect (Stokes, decrease  $\nu$ , anti-Stokes, increase  $\nu$ )
  - $\omega_0 = \omega_1 \pm n\omega_{vib}$  -- often use  $H_2$  since  $\omega_{vib} \sim 4000 \text{ cm}^{-1}$ , alternative  $D_2$  or  $CH_4$
  - setup., multiple frequency shifts, Results, again,:
  - Shift by multiple units of  $\nu_{vib}$ , due to re-pump with  $\nu_S$  or  $\nu_{AS}$





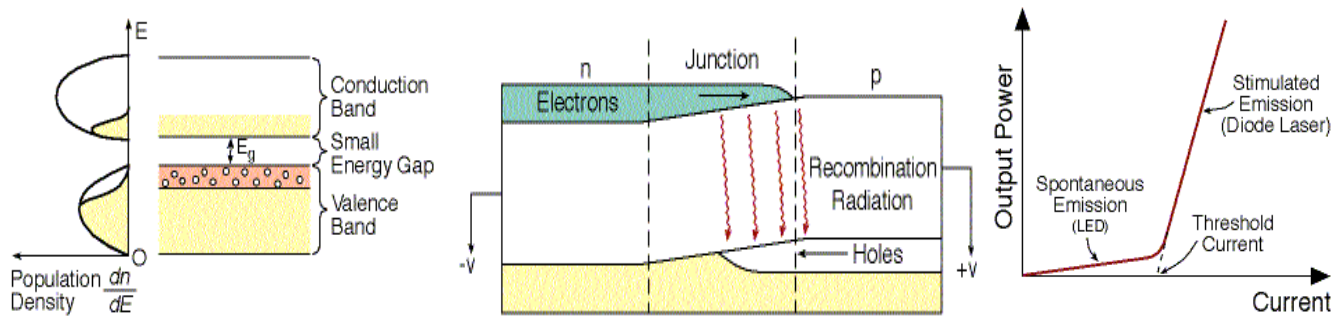
**Fig. 2** Schematic of the anti-Stokes Raman generator. The  $H_2$  pressure in the 1-m Raman cell was typically 450 kPa. The  $1\text{-cm}^2$  input beam at 266 nm was focused by a 50-cm lens to a spot of about  $15\ \mu\text{m}$  in diameter.



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

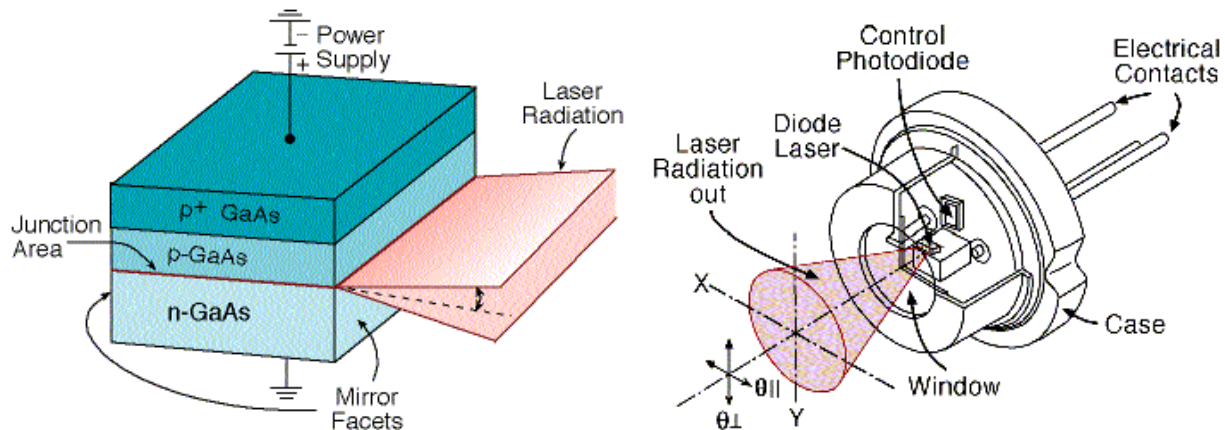
**Diode:** vis to IR, depends on composition (band gap) low power, tune each over narrow band by current and temperature variation, **background:** See [Kansas State site](#): (and following sequential pages) and [Florida State diode](#) section:

- this has been major growth area in lasers for past decade due to optoelectronics
- Very efficient (~20%), high reliability, low power, long lived, cheap
- semiconductor has [energy gap](#), electrons change level can emit light,
- [p-n junction diode](#), if [forward bias](#) can create current flow and [radiation](#)

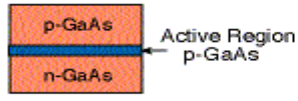
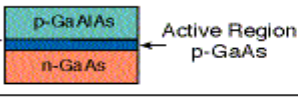

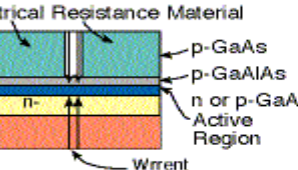
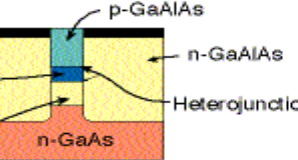


[degree of bias](#) means spontaneous or stimulated emission

emits form gap/junction so small volume, but can be spread on crystal



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

Laser Type	Laser Structure	Radiation Confinement
Homojunction		A little Confinement in paper plane
Single Heterojunction		Good Confinement in one side in perpendicular plane (paper)
Double Heterojunction		Good Confinement in both sides in perpendicular plane (paper)
Gain-Guided Stripe		
Buried Heterojunction (Index-Guided Stripe Geometry)		Good Radiation Confinement in both Horizontal and Perpendicular Planes

--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  $\mu$ ) power~1 mW (cw)  
— high resolution IR absorption spectroscopy, remote sensing

[Modes](#) — each very narrow, separated by few  $\text{cm}^{-1}$ , hop between  
oscillate on (5-10) at a time, add monochromator for single mode

--[change composition](#) for other regions

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

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

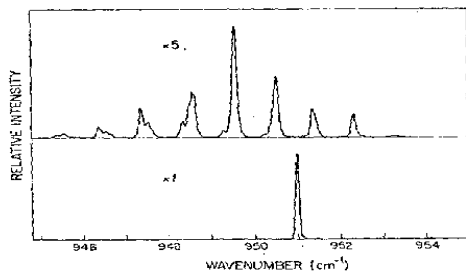


Fig. 4. Emission spectra of  $\text{Pb}_{1-x}\text{Sn}_x\text{Te}$  diode laser with polished end faces operated near liquid He temperature. Top trace was taken with a dc current of 1 A before reflection coating, bottom trace with a 0.9 A dc current after reflection coating.

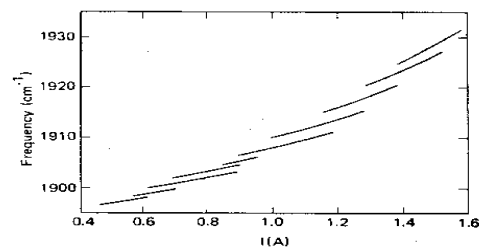


Fig. 1. Typical Current-Tuning Characteristics for a Model SDL Laser



Schematic of a diode based IR spectrometer for high resolution or single frequency IR probe

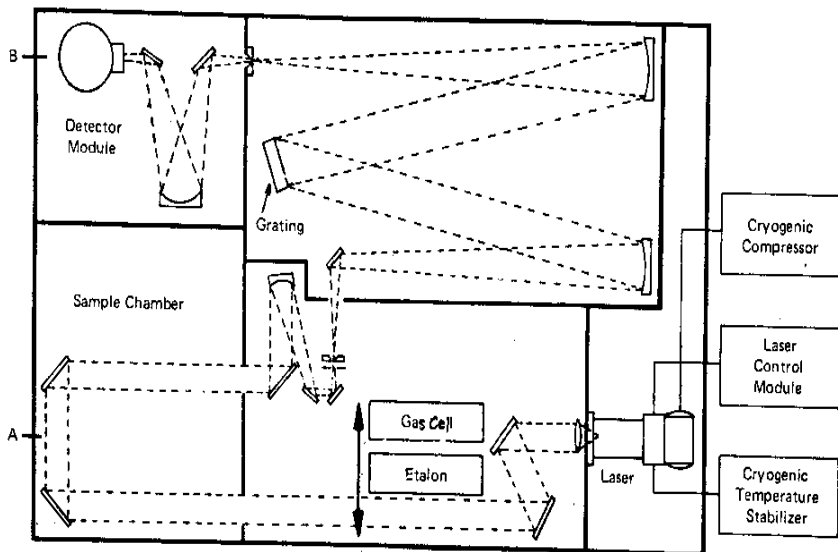
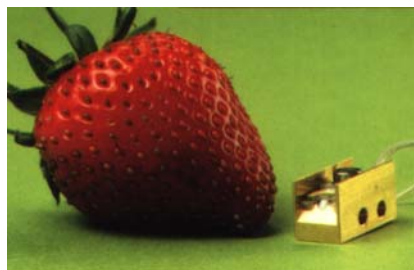
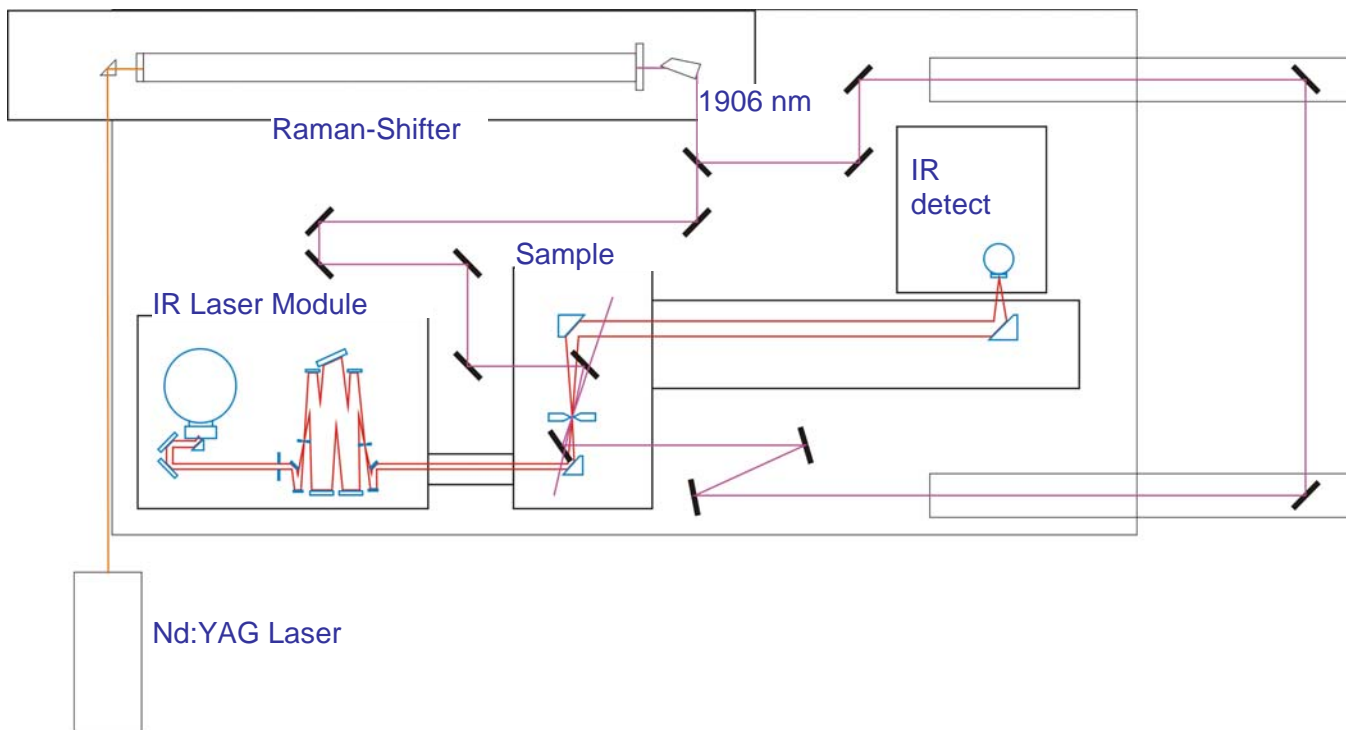


Fig. 2. Optical Schematic of Model LS-3 Laser Source Spectrometer.



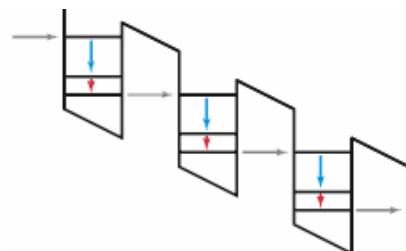
Small size, ~mW,  $\Delta\nu \sim 100 \text{ cm}^{-1}$

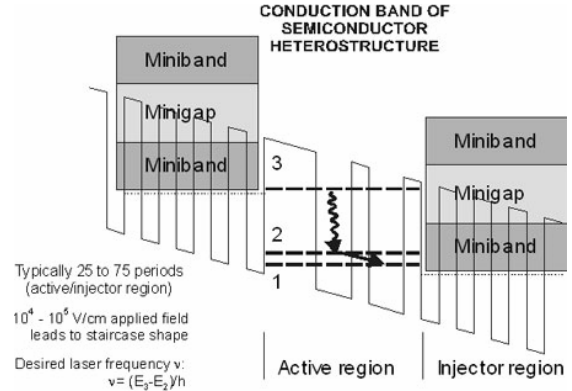
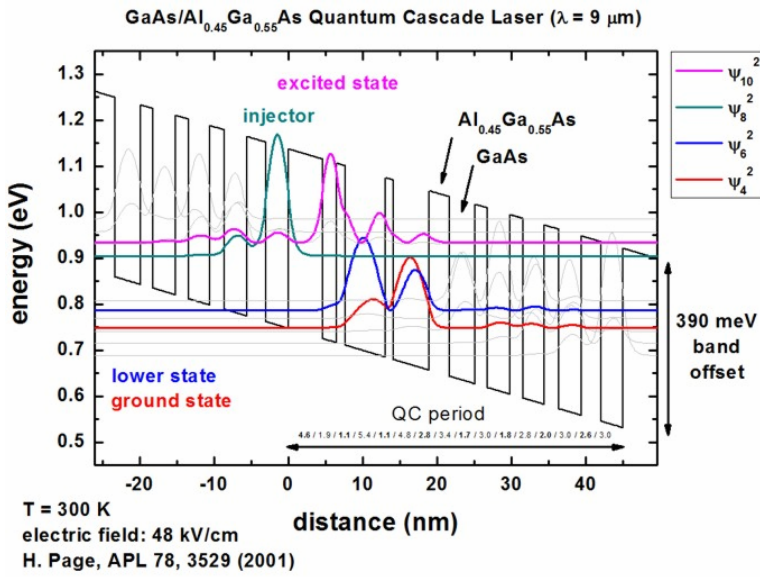
Schematic of a T-jump type spectrometer, probing ns conformational changes



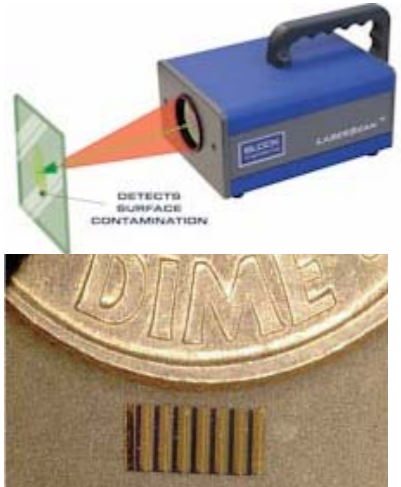
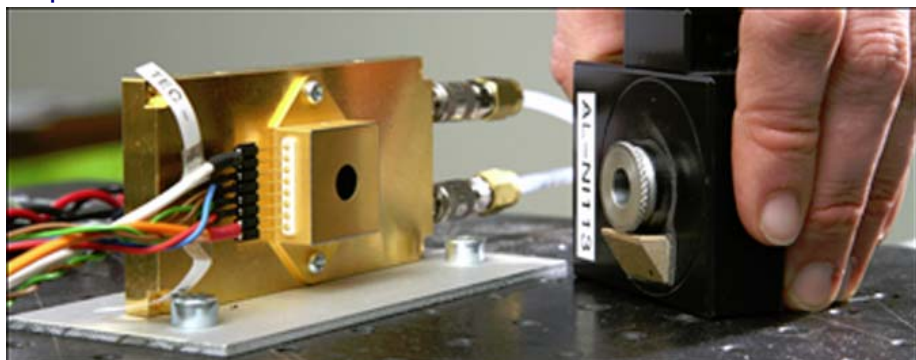
Quantum Cascade lasers, instead of single photon form a single gap in a semiconductor

QCL has emission from subbands in a multilayer structure, higher power and tunability



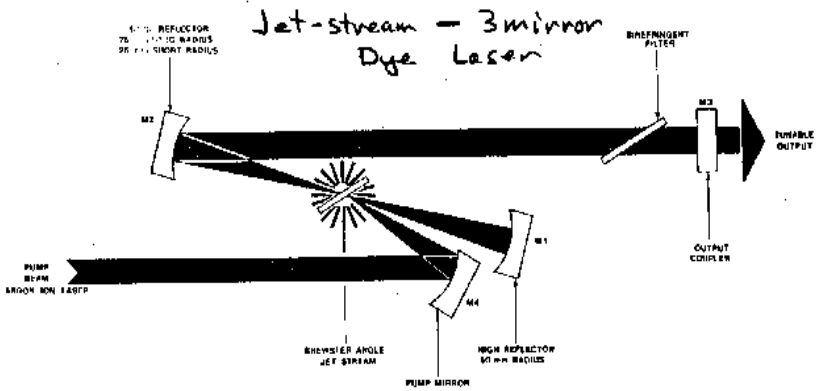
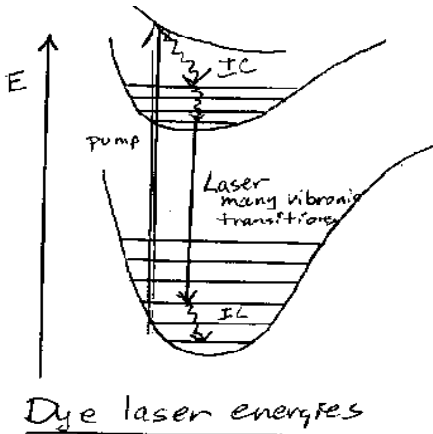


Can get 10s mW and tune  $>100 \text{ cm}^{-1}$ , but also have "spectrometers" -  $100\text{s cm}^{-1}$



**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](#)

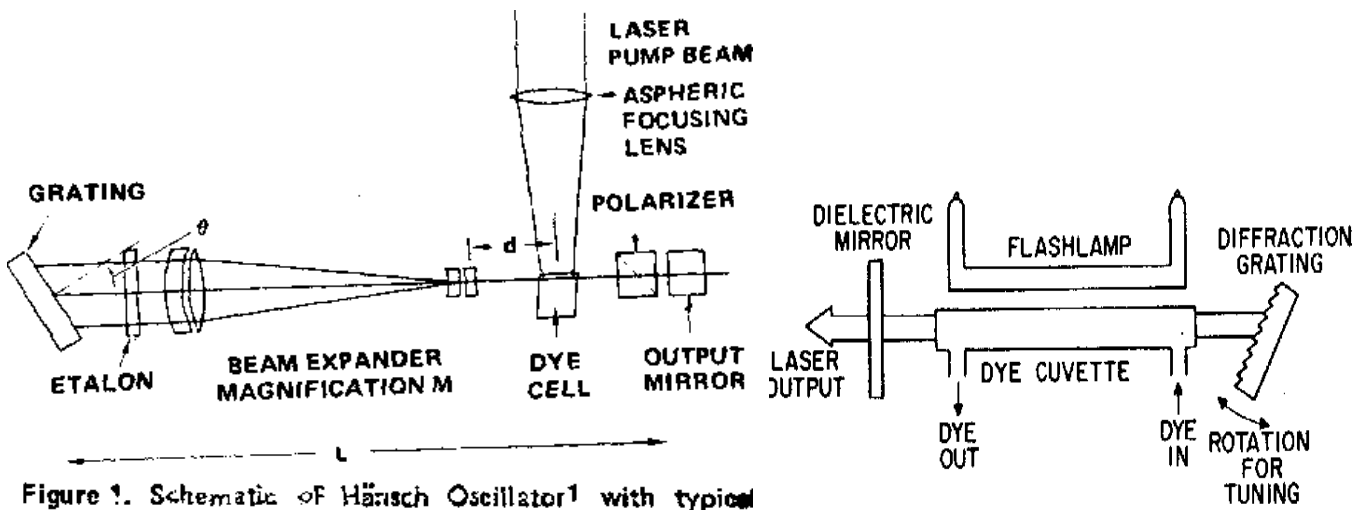


Figure 1. Schematic of Härsch Oscillator<sup>1</sup> with typical

--or **operate cw** (Ar<sup>+</sup>ion laser pump, or cw YAG doubled is typical)

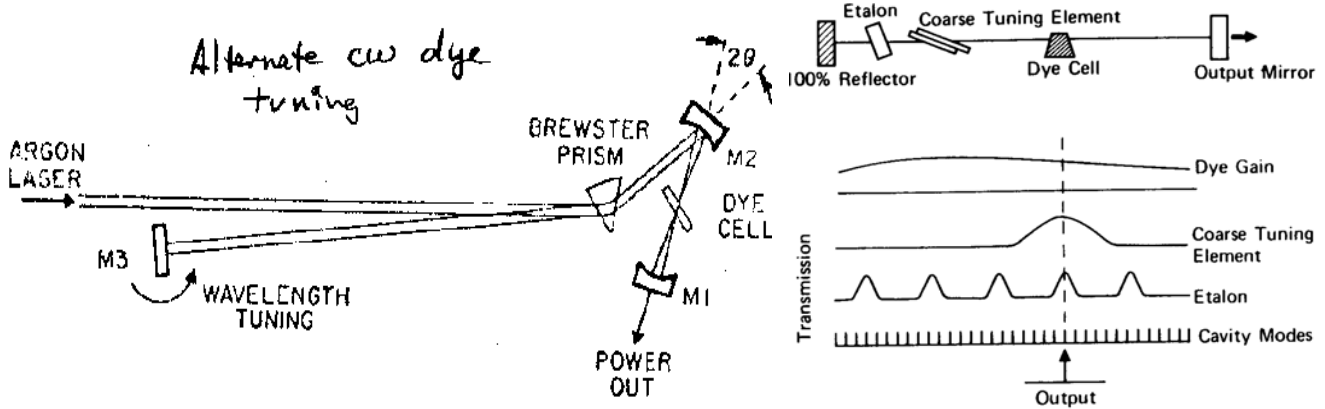
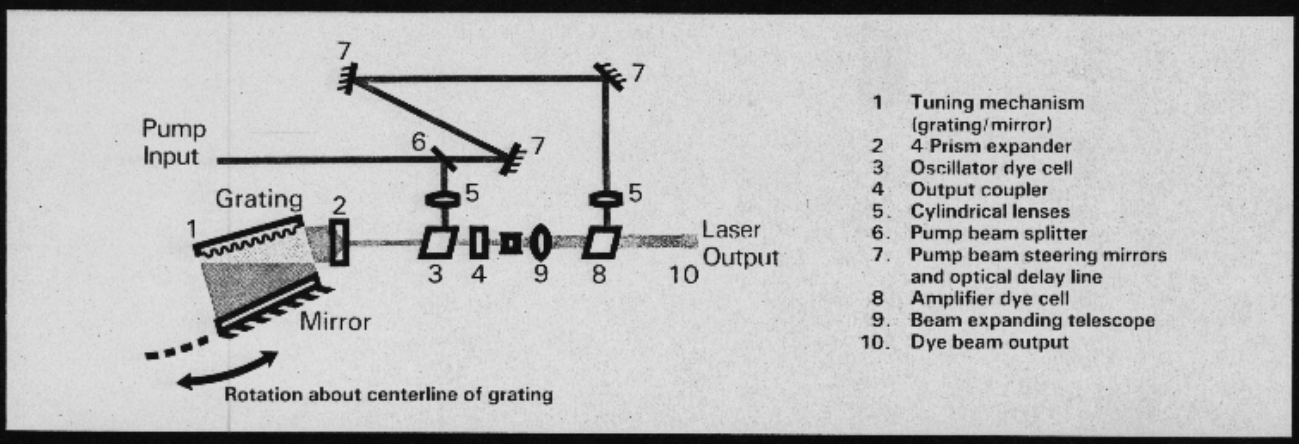


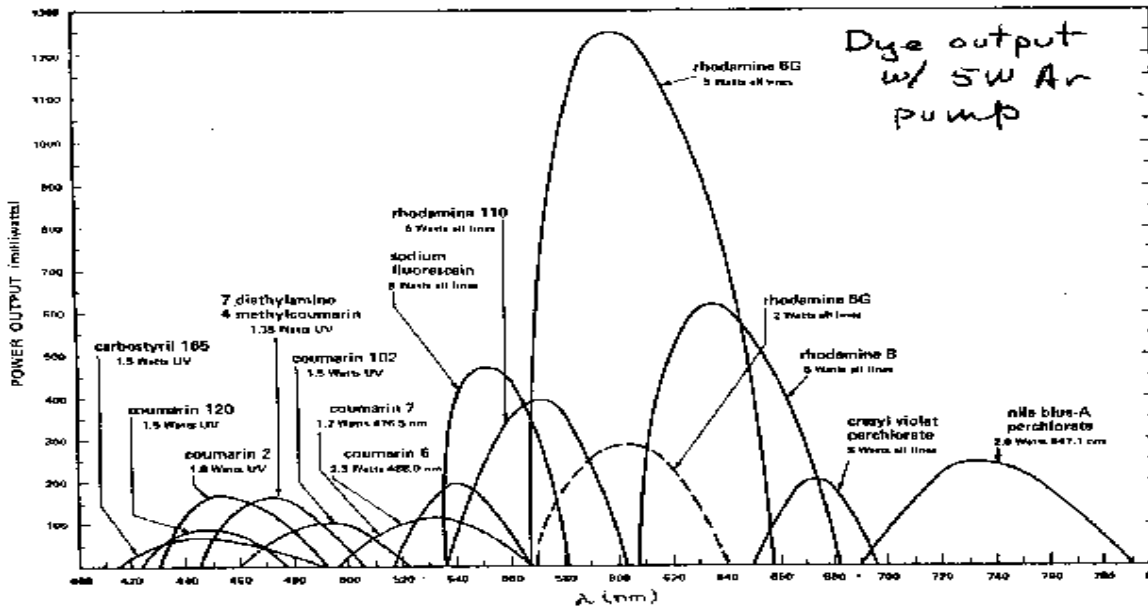
FIGURE 1. HYPERDYE-300 OPTICAL SCHEMATIC



Tune (with [grating/prism/etalon](#)) over fluorescence band — smooth, vary in intensity

tuning range depend on vibronic envelope, organic dye strong electron-vibrate coupling

--Big shifts – need to [change dye](#) (400-700 possible, near IR very unstable)



- Relatively high efficiency (~10% of pump power with rhodamine, less with others)
- Transverse or longitudinal pump – power depends on pump and volume (saturate)
- for very high powers need [amplifier](#) stage avoid saturation,
- Major resource for spectroscopy, resolution can be high, tune to transition of interest
- Can be operated at very high resolution with accessory tuning
- Designs: [jet \(cw, no cell\)](#), [ring \(traveling wave\)](#), [etalon tune modes](#), [transverse + amplifier](#) (see drawings above)

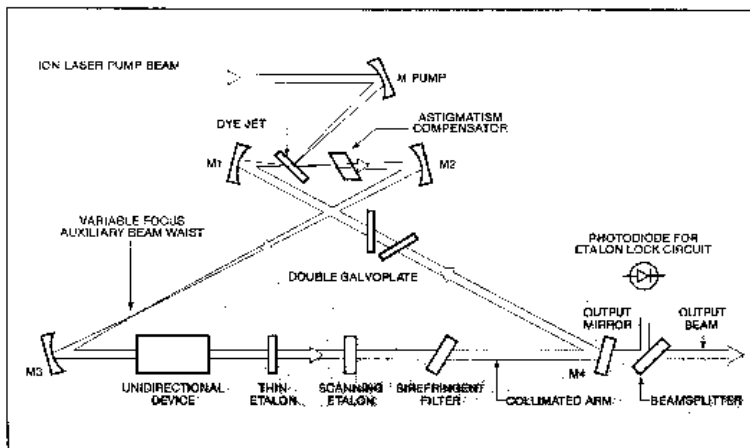


Figure 2. Schematic of Spectro Physics 6800 Scanning Ring Dye Laser

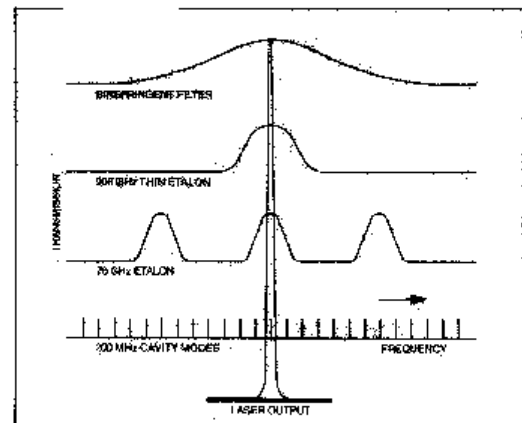


Figure 3. Spectra of the Ring Laser for frequency mode (100) in Scinty

Wavelength selection with etalons, means getting different free spectral range overlaps

- [Ti: Sapphire](#) -- solid state --dye-like laser, [capable of fsec operation](#)

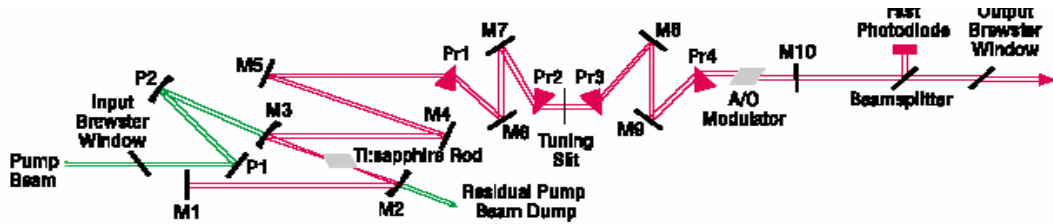
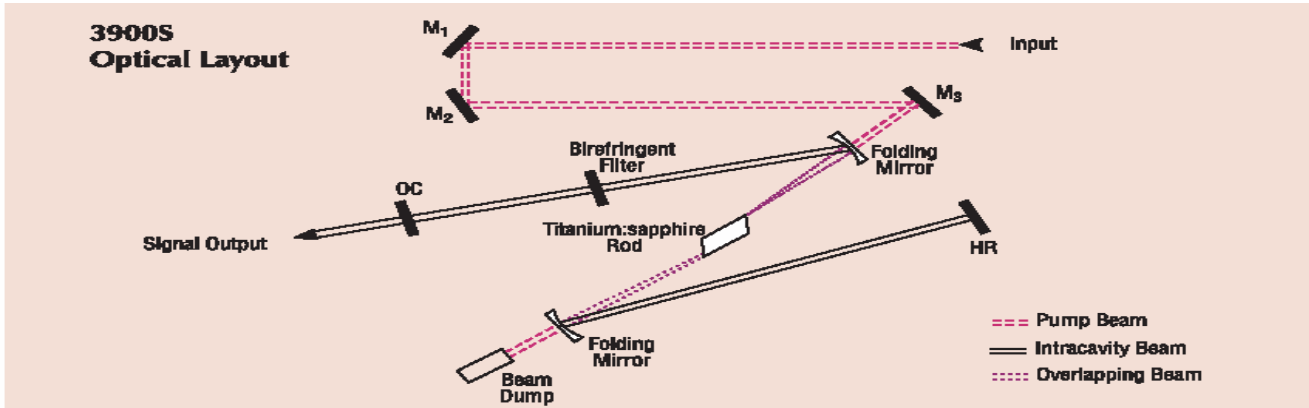
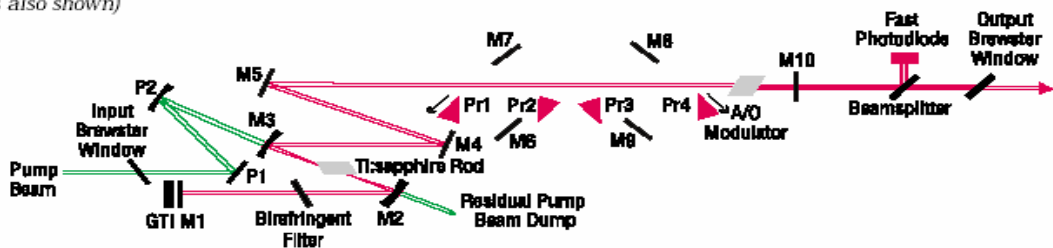
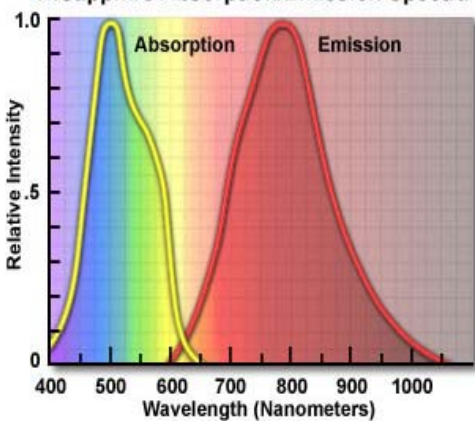


Figure B. Tsunami picosecond cavity layout (femtosecond optics also shown)



- [Absorb ~500 nm, emit in red](#) tunability into near [IR, specifications](#)



	Average Power	Pulsewidth	Pulse Energy	Tuning Range**	Nominal Rep Rate
<b>With 10 W Pump*</b>					
Femtosecond Configuration	1.5W @ 800 nm	< 100 fs	~15 nJ	700-1000 nm	80 MHz
Picosecond Configuration	1.5W @ 800 nm	< 2 ps-100 ps	~15 nJ	700-1000 nm	
<b>With 5 W Pump*</b>					
Femtosecond Configuration	> 0.7W @ 800 nm	< 100 fs	~8 nJ	710-980 nm	80 MHz
Picosecond Configuration	> 0.7W @ 800 nm	< 2 ps-100 ps	~8 nJ	710-980 nm	

\* All specifications refer to pumping with a 532 nm Millennia laser.  
\*\* Tuning range with single broadband optics set, 600-1080 available with extra optics option.

- 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

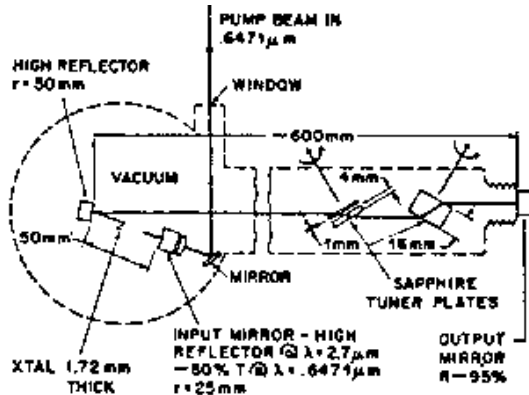


Figure 7 Laser Schematic

- excite with laser, operate like dye laser, tune w/grating— limited ( $\sim 100 \text{ cm}^{-1}$ )
- change xtal for bigger shift, F-center:  $M^+X^-$  xtal  $e^-$  trap

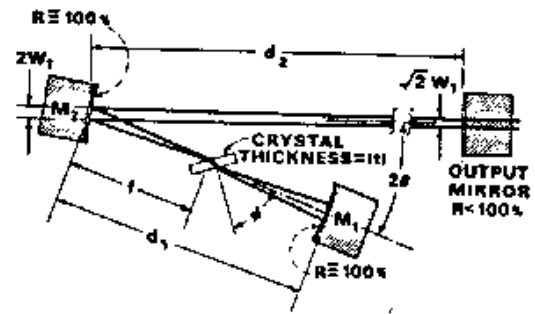


Figure 6 Basic Cavity Configuration

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

#### 3. Laser light sources:

Text reading this section covers: **Chapter 4-3**

Also review [Kansas State web pages](#) provided in links, plus handouts

**For discussion only:** Chap. 4 #2, 18 and

Consider best choice laser sources for the following, rationalize your selection:

- Raman spectrometer, routine with microscope for materials
- Resonance Raman spectrometer for small molecules
- T-jump fluorimeter for biological systems, like proteins
- 2D IR correlation IR of fs pulses,
- Very high resolution IR of gases for pollution detection
- laser ablation/ pulsed beam measurements
- MPI molecular beam studies of small molecules

**To hand in eventually:** Ch. 4 - # 2,14 and a and b below:

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

1.4 If two levels at  $300^\circ \text{ K}$  are in thermal equilibrium with  $n_2/n_1 = 0.2$ , calculate the frequency of the transition from  $1 \rightarrow 2$ . In what part of the spectrum does this occur? Change this to 0.005 and recalculate.

2.0 Calculate the number of longitudinal modes that occur in  $\Delta\nu = 1 \text{ cm}^{-1}$  at  $\lambda_0 = 488 \text{ nm}$  for a 0.7 m long laser cavity.

- 1.6. Ultimate limit of divergence of a laser is diffraction  $\theta_d = \beta\lambda/D$  where  
 $\theta_d$  = divergence,  $\lambda$  = wavelength,  $\beta \sim 1$  optimal design,  $D$  = diameter  
If a YAG:Nd laser beam ( $\lambda = 1.06 \mu$ ) is sent to the moon (384,000 km) from an oscillator of  
 $D = 1 \text{ mm}$ , calculate its diameter on arrival.

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

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 separation  $\Delta\lambda$  of adjacent modes when the cavity is shortened to half its length.

## WebLinks,

[laser companies](#), leads to details, drawings, explanations—good source of what is available

But I did not update from 2005, may have been bought/sold—name changes

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>