CHEM 524-Course Outline(Sect.3-b-solid state lasers)-2013

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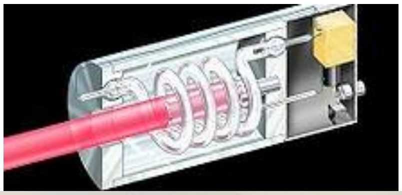


b.Solid state -- note 1st laser was "ruby" (Cr^{+3} in Al_2O_3)

by Ted Maiman, 1960, Hughes Lab.

-- red, 694.3 nm, pulsed, ~msec,

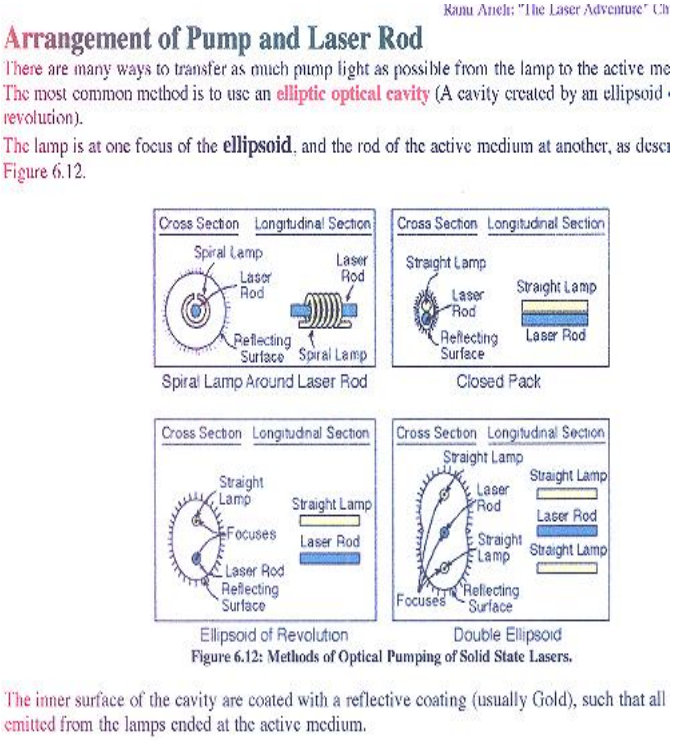
-- inefficient, three level system, self-absorbent rod

-- Xe flash lamp pump, original rod ends polish/silvered

- **Nd^{+3} 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



Rami Arieli: "The Laser Adventure" Ch

Arrangement of Pump and Laser Rod

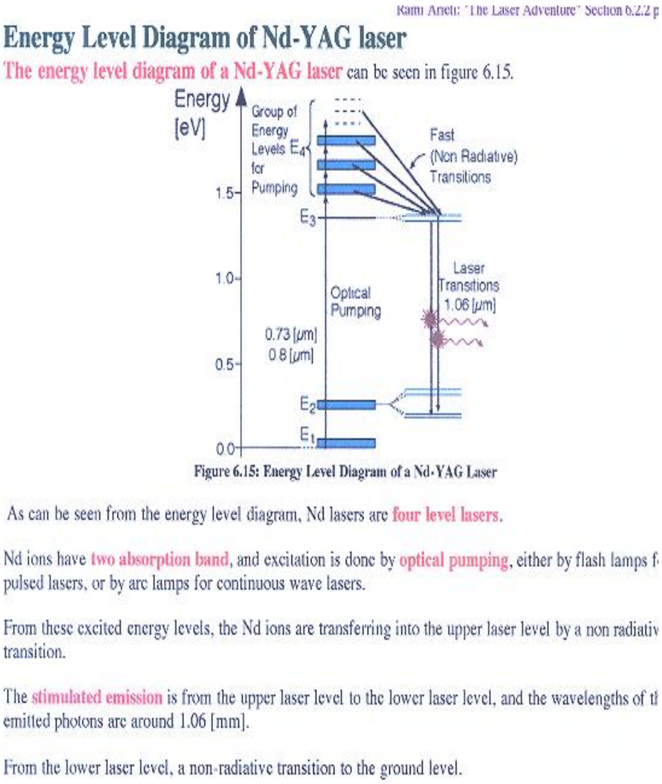
There are many ways to transfer as much pump light as possible from the lamp to the active me

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.



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.

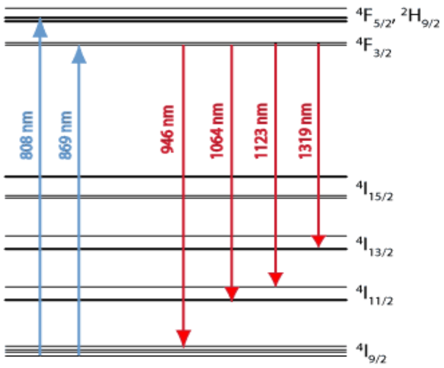
The stimulated emission is from the upper laser level to the lower laser level, and the wavelengths of th emitted photons are around 1.06 [mm].

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

Nd+3 (rare earth, 4f) transitions weak, narrow. Flash inefficient, diodes now popular pumps

also double to 532 nm, triple to 355 nm, quadruple to 266 nm

– green, near uv, deep uv

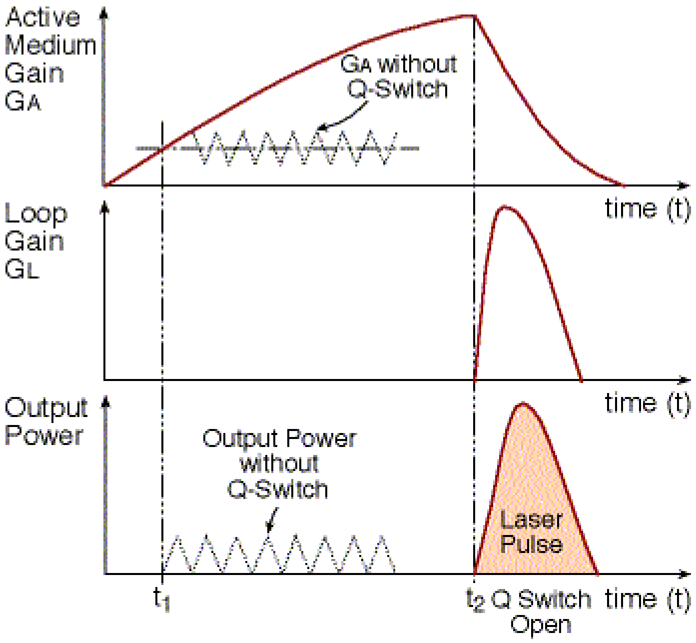


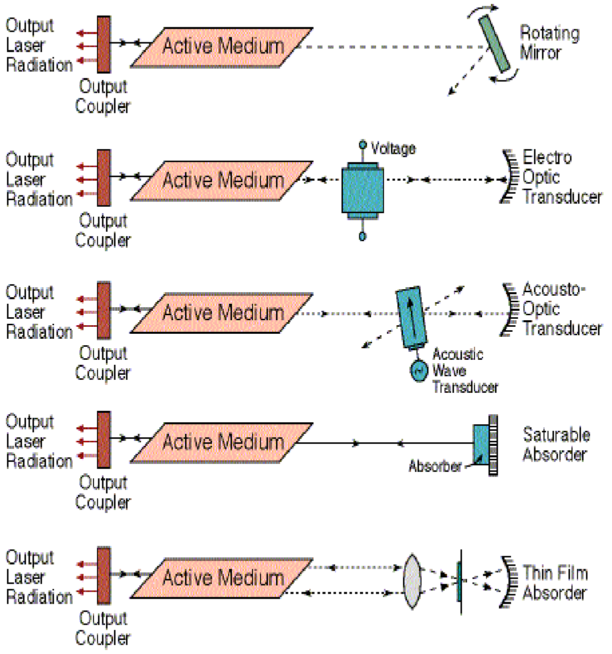
Originally -- flashlamp pumped
-- Xe discharge, broad pump, but absorb narrow
-- various cavity designs for transfer excite
Levels have slight variation
--different host matrices (xtal) can affect

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

Pulse operation -- need Q-switch to control pulse (8-12 ns, *dump excitation*), different types

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

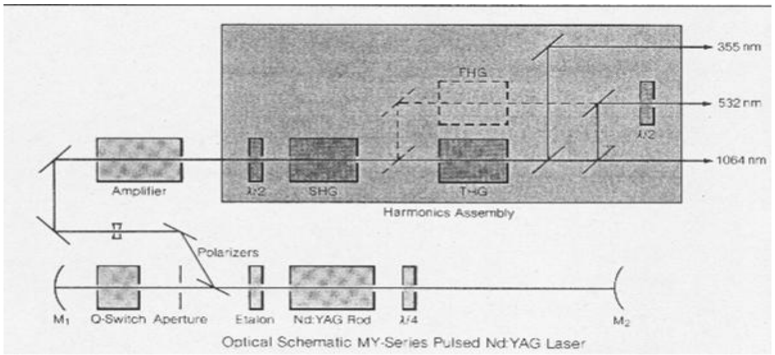




--power 100’s mJ/pulse, but with an amplifier get more,

non linear crystals— high efficiency frequency conversion (**Sect. c below**)

--double (532 nm), triple (355 nm = fundamental+doupled, 1064/3), or quadruple (266nm)



Optical Schematic MY-Series Pulsed Nd:YAG Laser

-- 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)

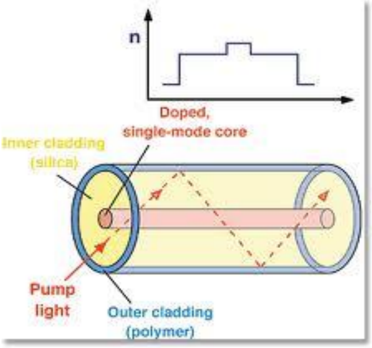
- Other host materials possible: YLF and YVO_4 other crystal hosts (*can shift frequency*)

  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

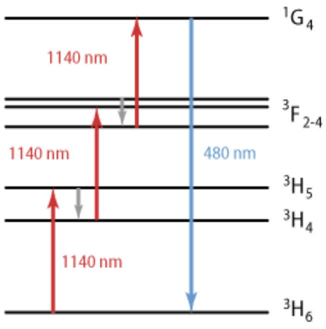
Solid-state lasers Main article: *Solid-state laser*

Laser gain medium and type	Operation wavelength(s)	Pump source	Applications and notes
Ruby laser	694.3 nm	Flashlamp	Holography, tattoo removal. The first visible light laser invented; 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 nanosec)
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.
Nd doped yttrium calcium oxoborate Nd:YCa$_4$O(BO$_3$)$_3$ or simply Nd:YCOB	~1.060 μm (~530 nm, 2nd 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 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 (Si-O glasses), ~1.054 μm (P-O 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:$_2$O$_3$ (glass or ceramics) laser	1.03 μm	Laser diode	ultrashort pulse research, [2]

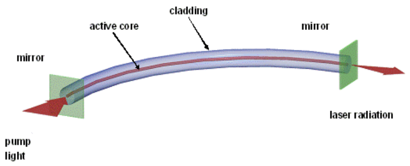
Ytterbium doped glass laser (rod, plate/chip, and fiber)	1. µm	Laser diode.	Fiber version is capable of producing several-kilowatt continuous power, having ~70-80% optical-to-optical and ~25% electrical-to-optical efficiency. Material processing: cutting, welding, marking; nonlinear fiber optics: broadband 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	UV laser pump, Nd: YAG -4th, excimer, Cu	Remote atmospheric sensing, LIDAR, optics research.
Promethium 147 doped phosphate glass (^{147}Pm^{+3}:Glass)	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	Tuned in the range of 700 to 820 nm	Flashlamp, laser diode, Hg arc (cw)	Dermatological uses, LIDAR, laser machining.
Erbium and Er:Yb 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	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 (act like dye laser, broad band emit, select λ with grating)



Fiber lasers – variant on Solid State, and pump optical fiber with diode, core is doped with r.e.
Cavity - can coat ends (below, lt), but better incorporate *grating in fiber*
Long length, big gain region, low loss, good cooling (surf/vol), self contained alignment, rugged, compact (coil), cw up to kW levels



Upconversion - NIR pump for blue emission, e.g. Tm^{+3} levels (*right*)



Can be Q-switched to get 10s ns pulses and mode lock for ps/fs

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

Concept is generally one of using the higher order susceptibility to get a new wave (E-M oscillation) from an original one.

Linear response: $\mathbf{P} = \varepsilon_0 \chi_e \mathbf{E}$, where ***E*** is applied filed, ***P*** is induced polarization

To account for nonlinear behavour, expand in Taylor series:

$$\boldsymbol{P} = \chi^{(1)}\boldsymbol{E} + \chi^{(2)}\boldsymbol{E}^2 + \chi^{(3)}\boldsymbol{E}^3 + \ldots \quad \text{(can also be tensorial representation)}$$

So field that develops according to $\chi^{(2)}$ has *different frequency components* due to mixing

e.g. Oscill. field: $P^{(2)} = \chi^{(2)}[Ee^{-i\omega t} + Ee^{i\omega t}]^2 = \chi^{(2)}[E^2(e^{-2i\omega t} + e^{2i\omega t}) + 2E^2]$ → double freq.

other combinations work, depending on input of different fields to mix (also $\chi^{(3)}$ triple in gases)

Materials: to have $\chi^{(2)}$ non zero, need to be birefringent crystal ($n_x \neq n_y$)

But need phase matching of two frequencies, so typically vary angle, temperature

Facilitated in crystal preparation by periodic poling (change sign of $\chi^{(2)}$ in ferroelectric)

Lithium niobate ($LiNbO_3$) and lithium tantalate ($LiTaO_3$) are materials with a relatively strong nonlinearity – can be periodically poled, high damage threshold, also electro-optic modulator

Potassium niobate ($KNbO_3$) has a high nonlinearity, frequency doubling to blue , piezoelectric

Potassium titanyl phosphate (KTP, $KTiOPO_4$) better for high powers, includes KTA ($KTiOAsO_4$), RTP ($RbTiOPO_4$) and RTA ($RbTiAsPO_4$). relatively high nonlinearities and suitable for periodic poling.

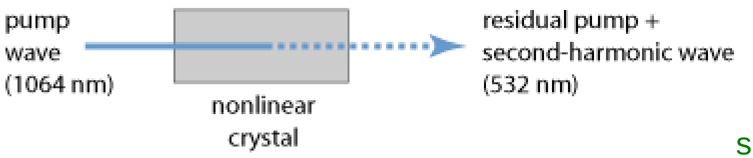
Potassium dihydrogen phosphate (KDP, KH_2PO_4) and potassium dideuterium phosphate (KD^*P or DKDP, KD_2PO_4, better NIR), larger sizes and cheaper – traditional crystals for E-O modulators. high damage threshold, but are hygroscopic and have low nonlinearity

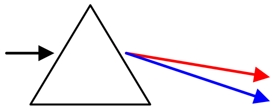
Borates, lithium triborate (LiB_3O_5 = LBO), cesium lithium borate (CLBO, $CsLiB_6O_{10}$*), β-barium borate (β-BaB_2O_4 = BBO,* strongly hygroscopic, often used in Pockels cells), bismuth triborate (BiB_3O_6 = BIBO), and cesium borate (CSB_3O_5 = CBO). LBO, BBO, CLBO, CBO and other borate crystals are suitable for short wavelength and UV generation , relatively resistant to UV light, and suitable phase-matching options. LBO and BBO also work well in broadly tunable optical parametric oscillators and optical parametric chirped-pulse amplification.

Mid IR requires transparency into infrared - zinc germanium diphosphide (ZGP, $ZnGeP_2$), silver gallium sulfide and selenide ($AgGaS_2$and $AgGaSe_2$), gallium selenide (GaSe), and cadmium selenide (CdSe).

UV/vis:

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





separate outputs with prism

Control function by which frequencies are phase matched (angle, temperature): $\mathbf{k}_s + \mathbf{k}_i = \mathbf{k}_p$

Frequency tripling is usually sequential, first frequency doubling the input beam and then sum frequency generation of both waves, both processes based on nonlinear crystal materials with $\chi^{(2)}$. (*See Previous YAG Laser setup example*)

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 (*isotropic*) with 3rd order susceptibility, $\chi^{(3)}$
  - --Typical use a very polarizable rare gas, e.g. Xe, Pb vapor (can do others)
  - Results in output at tripled frequency (non-linear): $\omega_0 = 3\omega_\iota$
- Raman shift-pass laser (ν_0) through gas cell, output contains frequencies shifted by Raman effect (Stokes, decrease ν, anti-Stokes, increase ν)

  $\boldsymbol{\omega_0 = \omega_\iota \pm n\omega_{vib}}$ -- often H_2 since ω_{vib} ~4000 cm^{-1} , alternate D_2 or CH_4 (less ~2800 cm^{-1})
  - setup,, multiple frequency shifts, Results, again,:
- Shift by multiple units of ν_{vib}, due to re-pump with ν_S or ν_AS

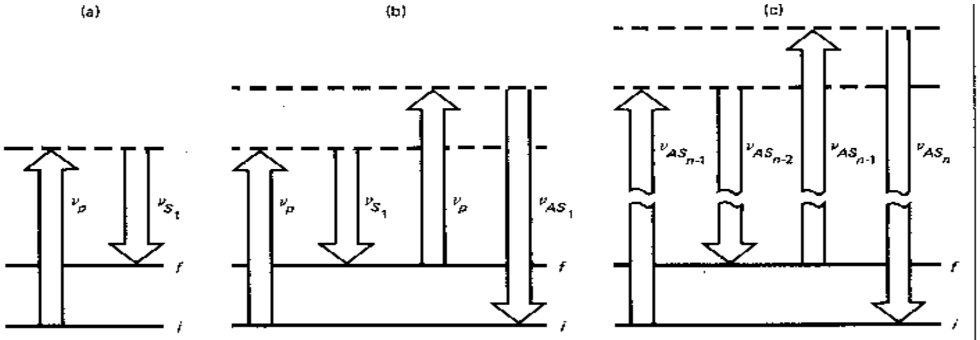
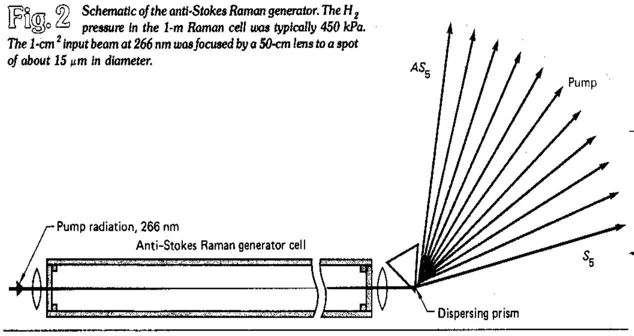
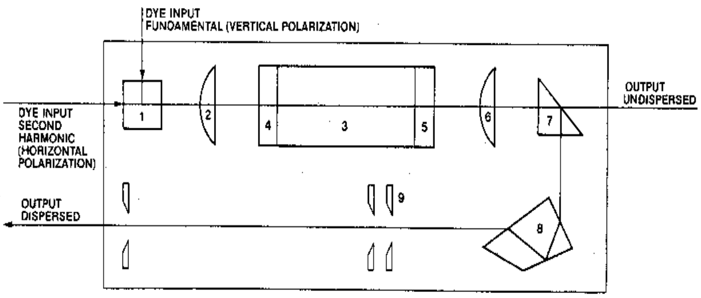


Fig. 1 *Simplified energy-level diagram depicting the energetics of the stimulated Raman scattering phenomena. (a) Stimulated Stokes scattering in which a pump photon at frequency ν_p is absorbed and a Stokes photon at frequency $\nu_{S_1} = \nu_p - \nu_R$ is emitted. Note that $\nu_R = \nu_f - \nu_i$. (b) Generation of first anti-Stokes radiation, AS_1, at frequency $\nu_{AS_1} = \nu_p + \nu_R$ by four-wave parametric mixing. (c) Parametric generation of the nth anti-Stokes Raman radiation (where n = 1,2,3,...). Here, AS_0 is just the pump laser.*

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-cm^2 input beam at 266 nm was focused by a 50-cm lens to a spot of about 15 µm in diameter.*





Alternate use crystals, Stimulated Raman shifting, no phase match, high conversion, easy handling - most efficient Raman crystals: **$Ba(NO_3)_2$ and $KGd(WO_4)_2$**, (KGW) plus - $BaWO_4$

Stokes generation in KGW crystal shift 901.5 cm^{-1} and $Ba(NO_3)_2$ shift 1048.6 cm^{-1}

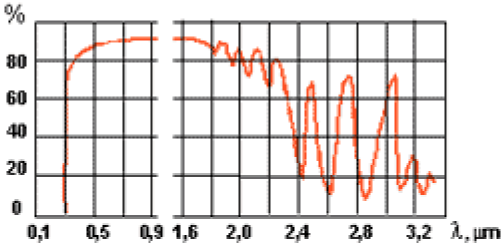


Fig.1 The dependence of transmission range τ from the wavelength λ

Fig.2 Sheme of the radiation conversion

Fig.3 Sheme of the radiation conversion

Fig.4 Sheme of the radiation conversion

Also exist at Raman Fiber lasers, where shift occurs in fiber, in SiO_2 shift ~450 cm^{-1}

IR:

- Optical parametric oscillator: --$LiNbO_3$ typical at YAG (1-4 μ) , can use BBO in vis

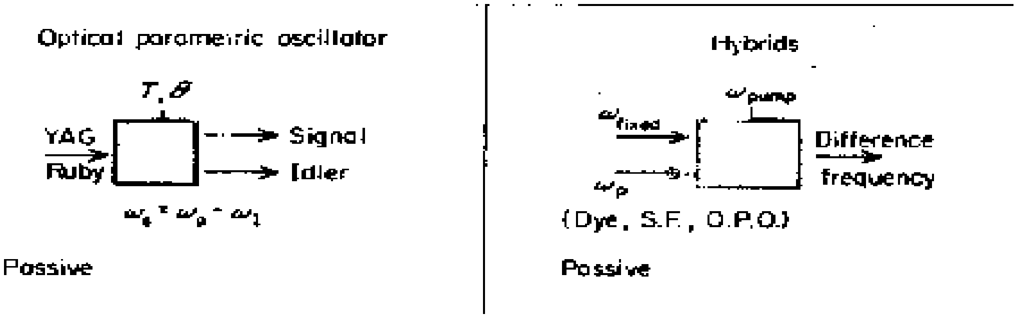


FIGURE 2. Principal mechanisms used for tunable infrared lasers since 1970.

OPO: $\omega_s + \omega_i = \omega_p$: *Input pump* ω_p *and out put signal* ω_s (higher freq.) *and idler* ω_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) from pump to desired outputs

Tune by changing phase matching— $\mathbf{k}_s + \mathbf{k}_i = \mathbf{k}_p$ --typically by angle, but also temperature

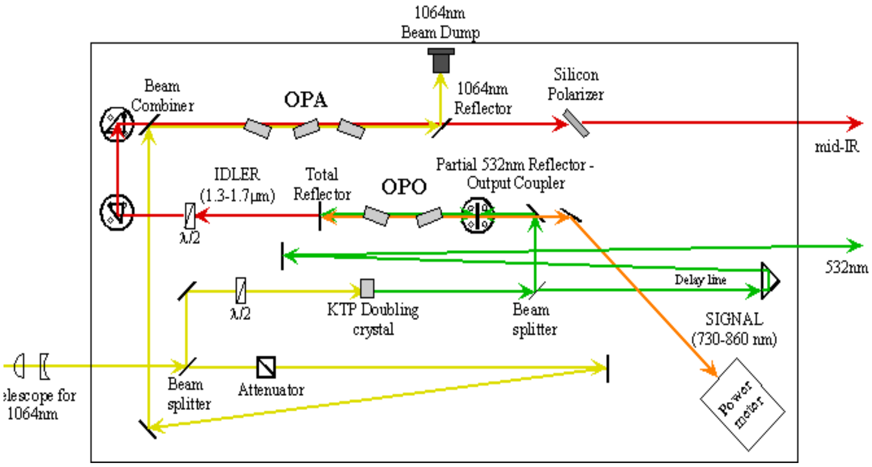
Mode hopping can be a problem for continuous tuning

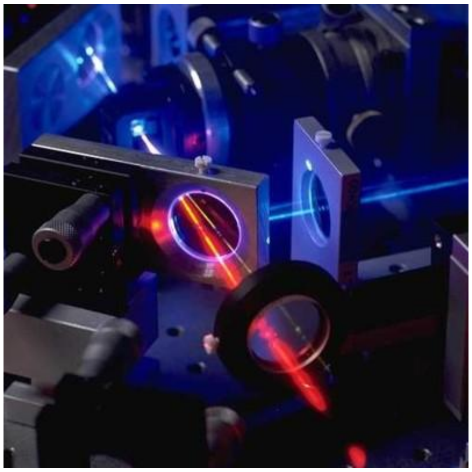
Optical Parametric Amplifiers – common commercial term, seems to operate essentially the same

Big deal is high power OK, since total conversion of one photon in → 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 ω_3 output by tune ω_2 vs. ω_1

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

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

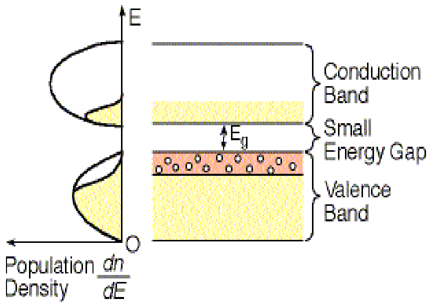
Diode: vis to IR, depends on composition (band gap) low power, tune each over narrow band by current and temperature variation, background: See Kansas State site: (and following sequential pages) and Florida State diode section:

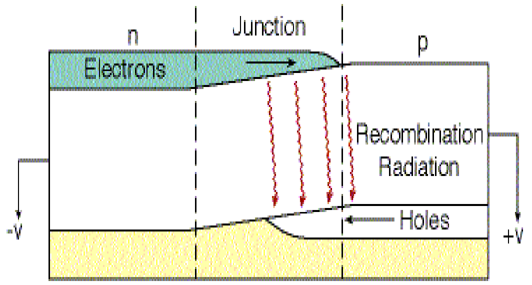
--this has been major growth area in lasers for past decade due to optoelectronics

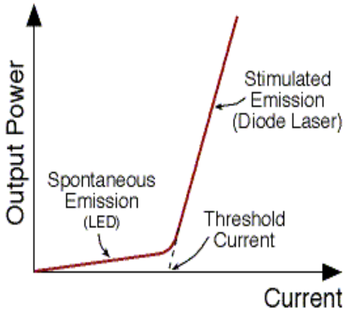
--Very efficient (~20%), high reliability, low power, long lived, cheap

semiconductor has energy gap, electrons change level can emit light,

p-n junction diode, if forward bias can create current flow and radiation

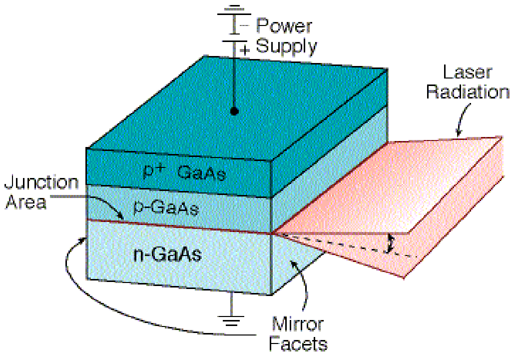


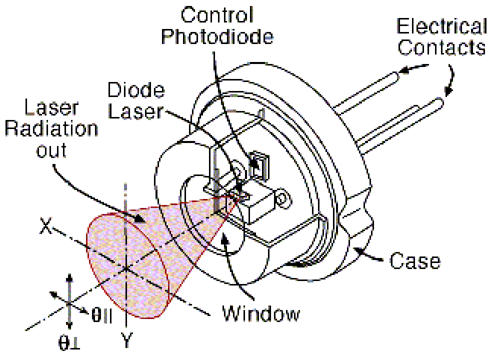




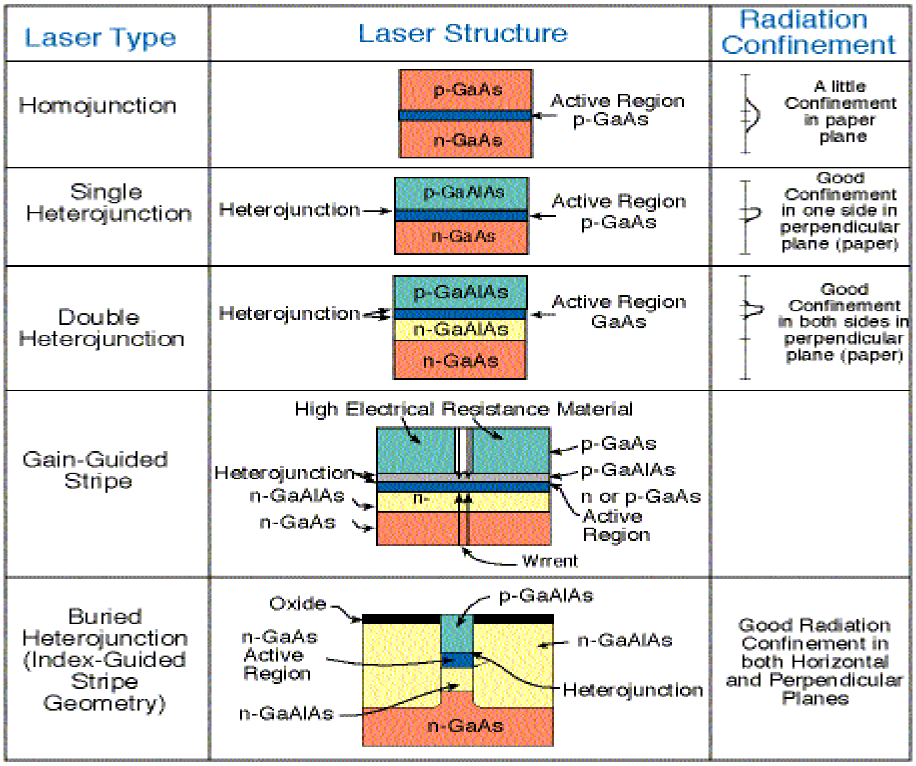
degree of bias means <u>spontaneous or stimulated</u> emission

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	p-GaAs n-GaAs Active Region p-GaAs	A little Confinement in paper plane
Single Heterojunction	Heterojunction p-GaAlAs n-GaAs Active Region p-GaAs	Good Confinement in one side in perpendicular plane (paper)
Double Heterojunction	Heterojunction p-GaAlAs n-GaAlAs n-GaAs Active Region GaAs	Good Confinement in both sides in perpendicular plane (paper)
Gain-Guided Stripe	High Electrical Resistance Material Heterojunction n-GaAlAs n-GaAs n- p-GaAs p-GaAlAs n or p-GaAs Active Region Wrrent	
Buried Heterojunction (Index-Guided Stripe Geometry)	Oxide p-GaAlAs n-GaAs Active Region n-GaAlAs n-GaAlAs Heterojunction n-GaAs	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 μ) power~1 mW (cw)

— high resolution IR absorption spectroscopy, remote sensing

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

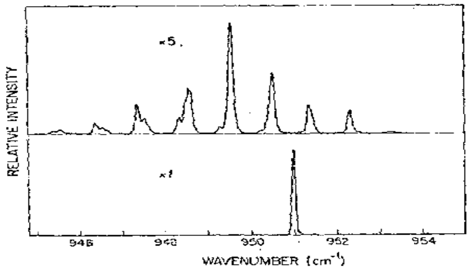


Fig. 4. Emission spectra of $Pb_{1-x}Sn_xTe$ diode laser with polished end faces operated near liquid He temperature. Top trace was taken with a dc current of 1 A before reflection coating, bottom trace

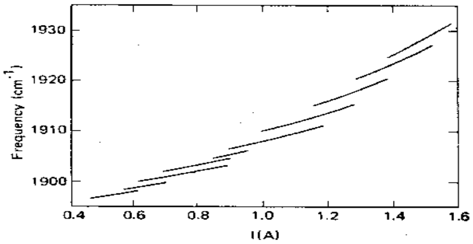


Fig. 1. Typical Current-Tuning Characteristics for a Model SDL Laser

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

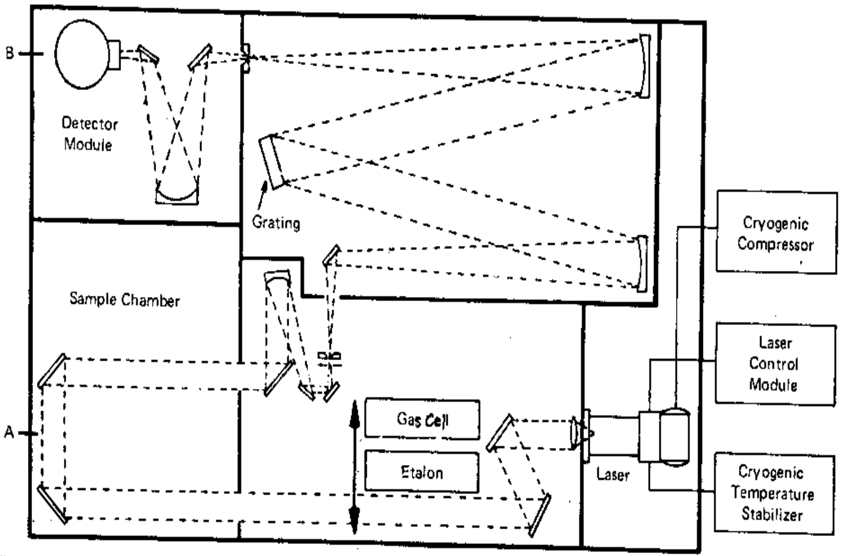
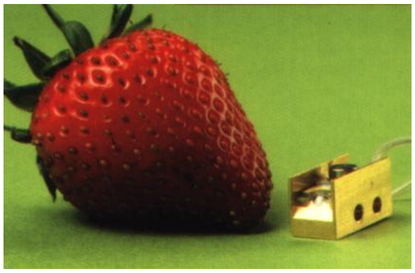
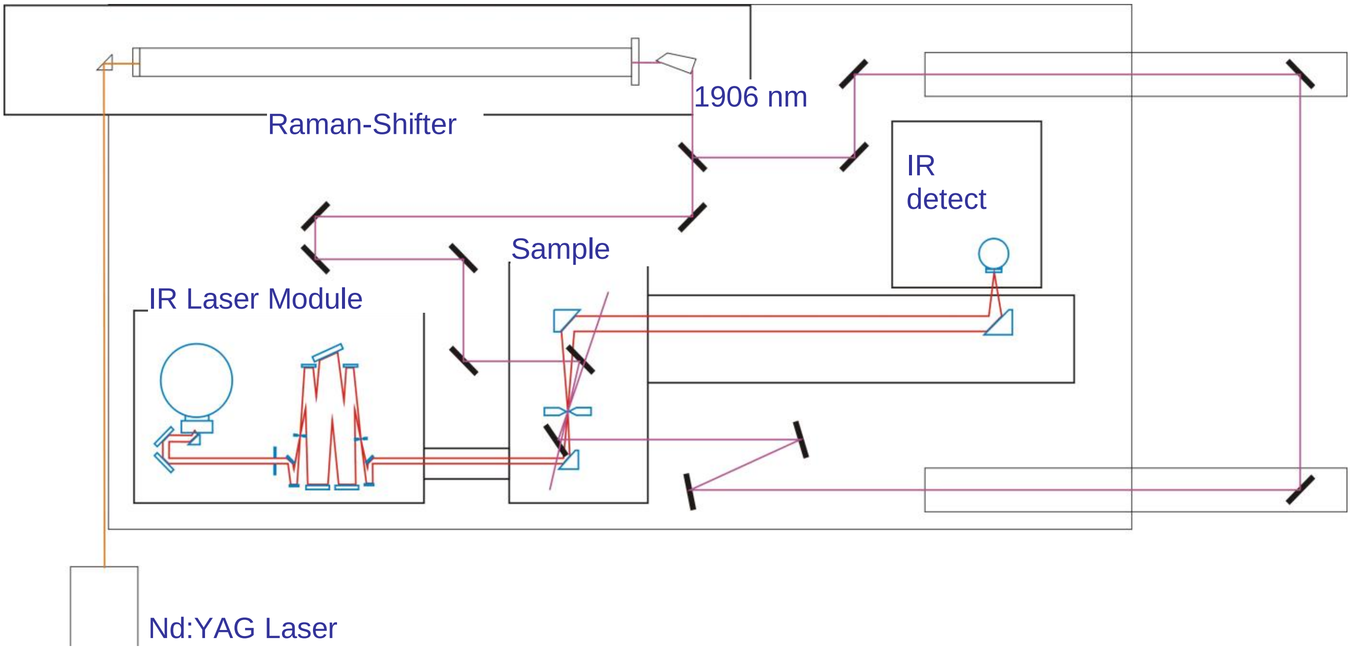


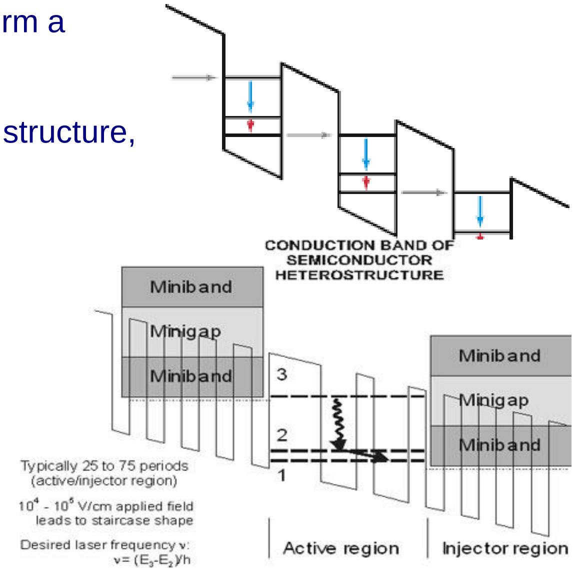
Fig. 2. Optical Schematic of Model LS-3 Laser Source Spectrometer.



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

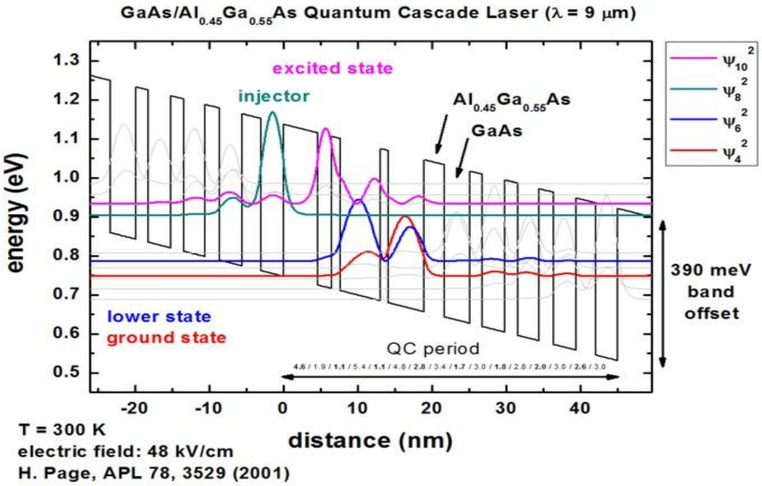
Schematic of a T-jump type spectrometer, probing ns conformational changes





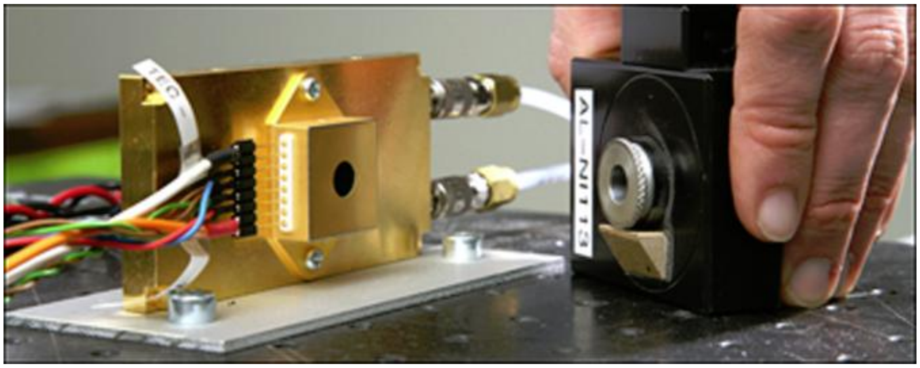
<u>Quantum Cascade lasers</u>, instead of single photon form a single gap in a semiconductor

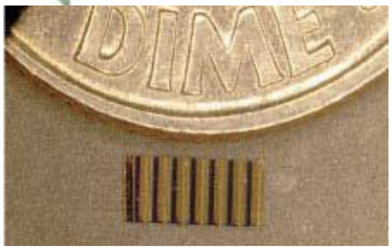
QCL has emission from subands in a multilayer structure, higher power and tunablity



H. Page, APL 78, 3529 (2001)

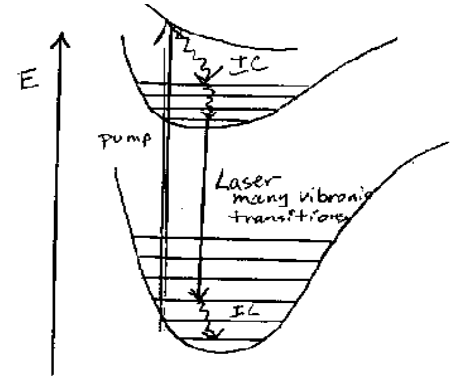
Can get 10s mW , tune >100 cm^{-1}, but also have “spectrometers” - 100s cm^{-1}



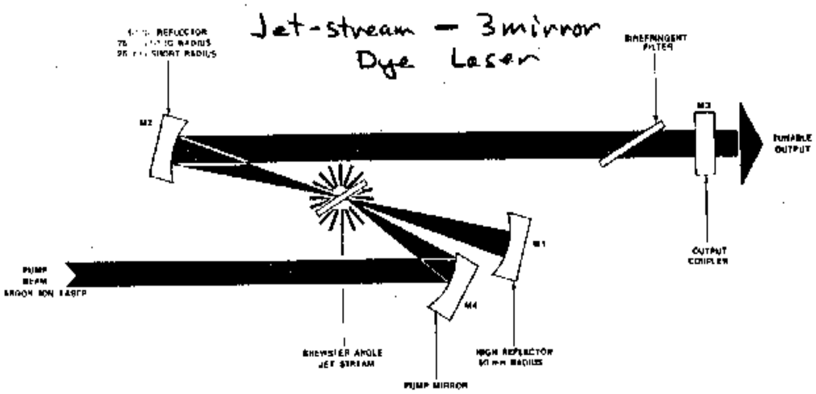


e. Tunable visible lasers/ vibronic lasers (include-- Ti:sapphire and F-center)

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



Dye laser energies



Timing-- mimic time character of pump:

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

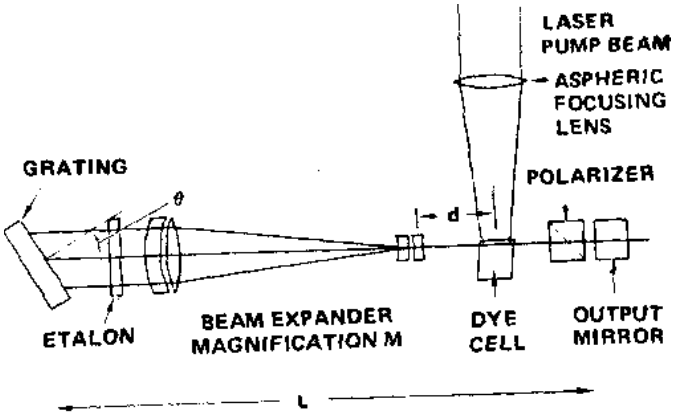
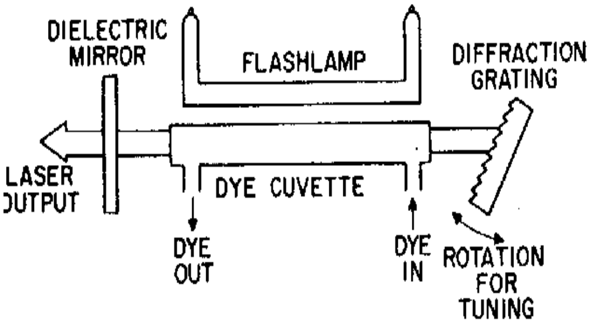
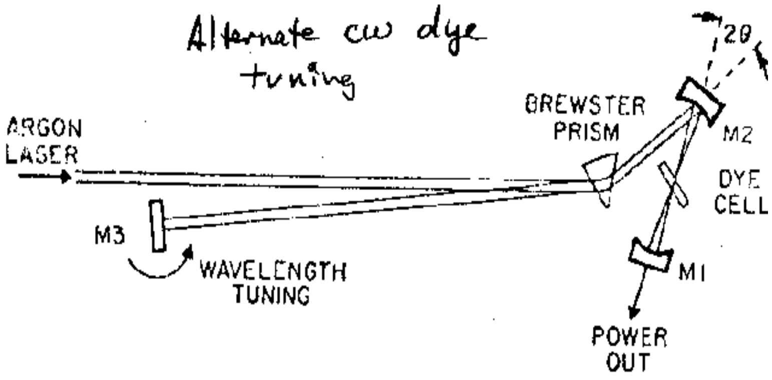


Figure 1. Schematic of Hänsch Oscillator with typical



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



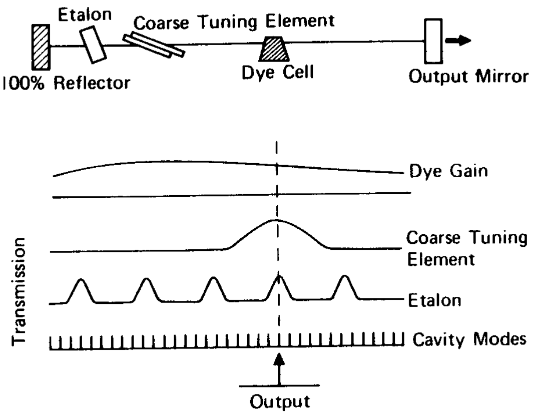
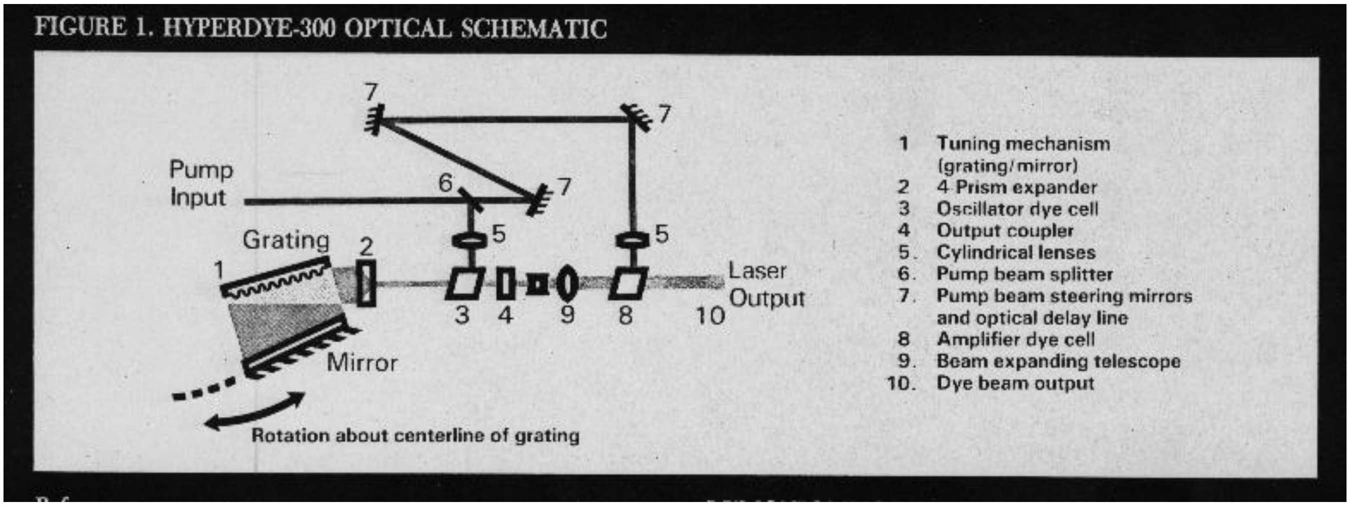


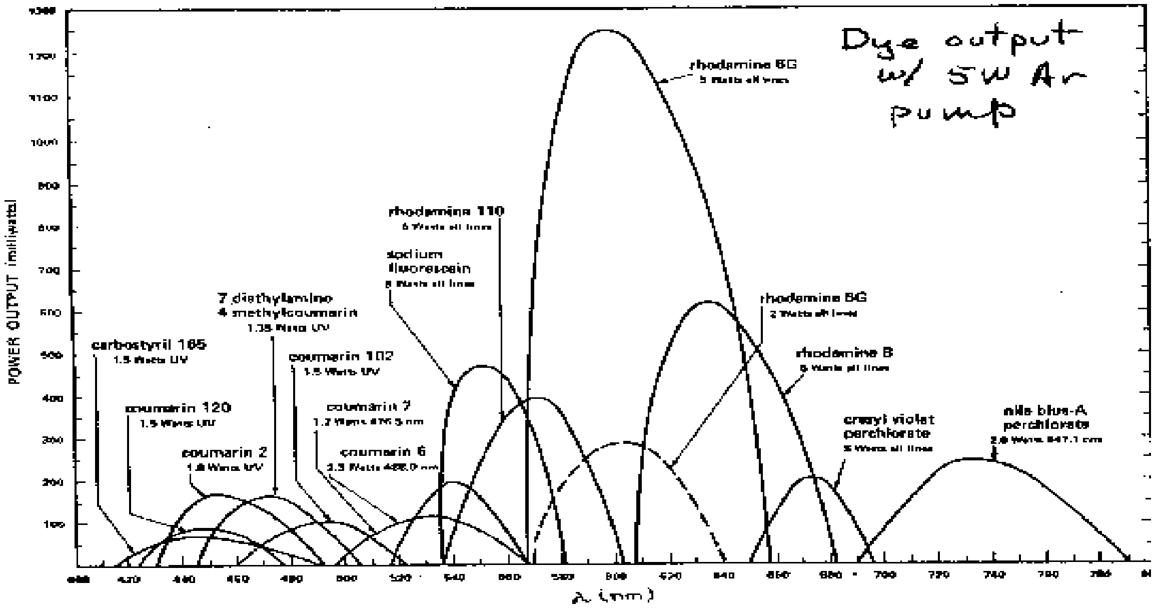
FIGURE 1. HYPERDYE-300 OPTICAL SCHEMATIC



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 interst

--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)

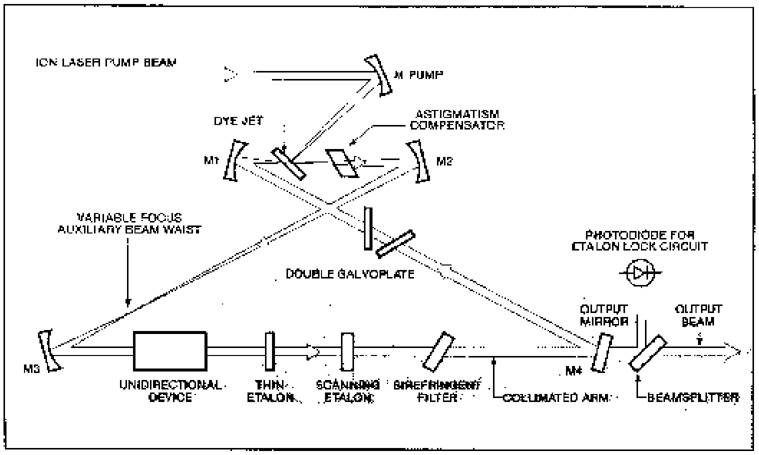


Figure 2. Schematic of Spectra Physics 380A Scanning Ring Dye Laser

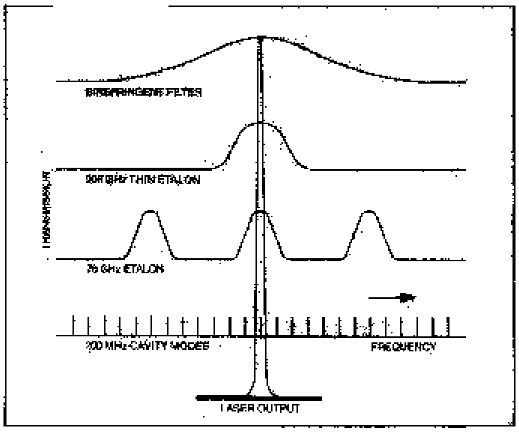
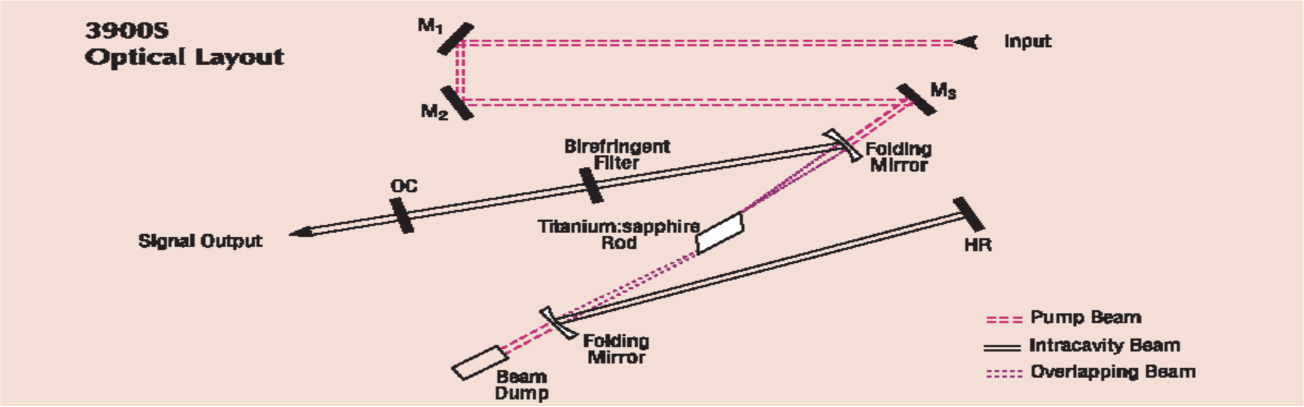


Figure 3. Bandpass of the Ring Laser tuning elements (Not to Scale)

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

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



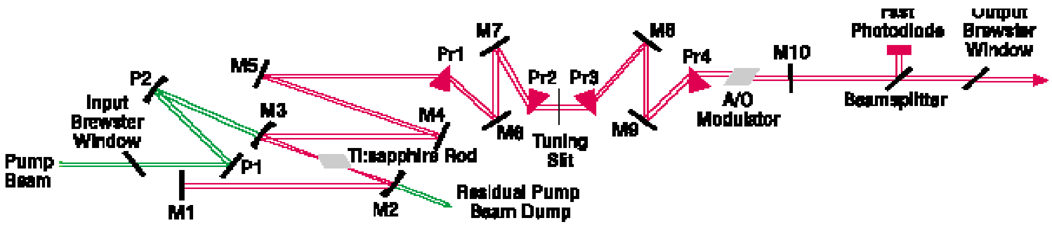
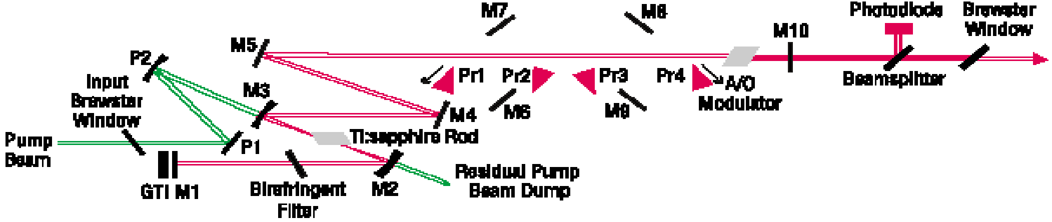
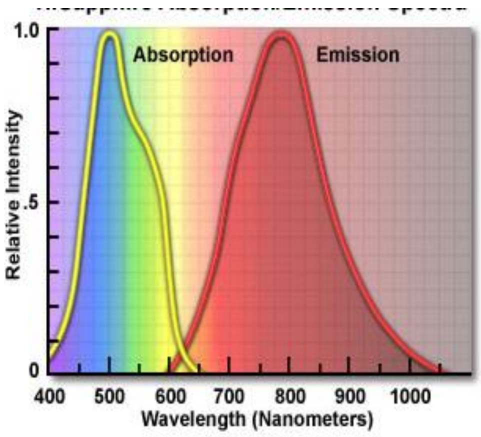
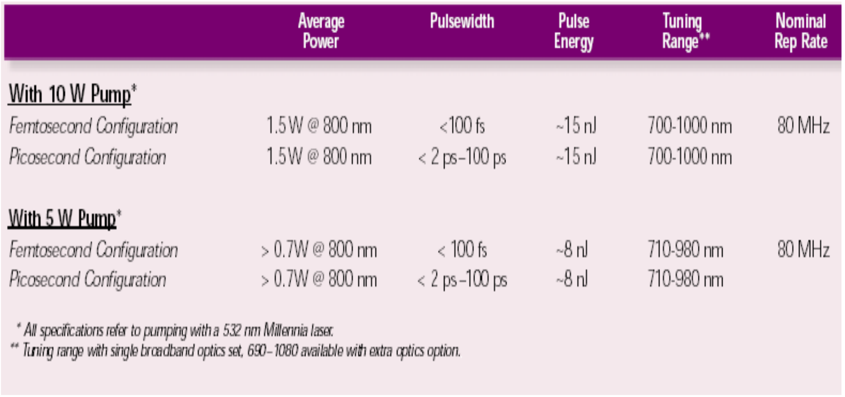


Figure B. Tsunami picosecond cavity layout (femtosecond optics also shown)



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





	Average Power	Pulsewidth	Pulse Energy	Tuning Range**	Nominal Rep Rate
With 10 W Pump*					
Femtosecond Configuration	1.5 W @ 800 nm	<100 fs	~15 nJ	700-1000 nm	80 MHz
Picosecond Configuration	1.5 W @ 800 nm	< 2 ps–100 ps	~15 nJ	700-1000 nm	
With 5 W Pump*					
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, 690–1080 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

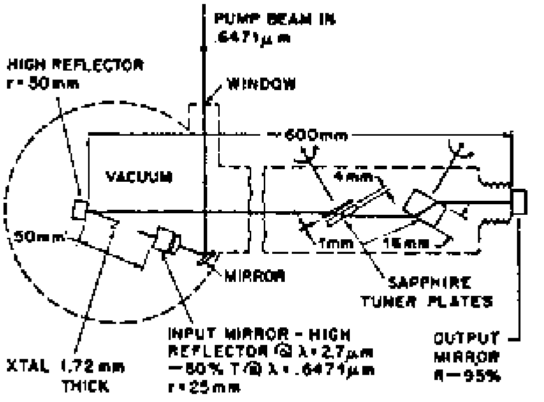


Figure 7 Laser Schematic

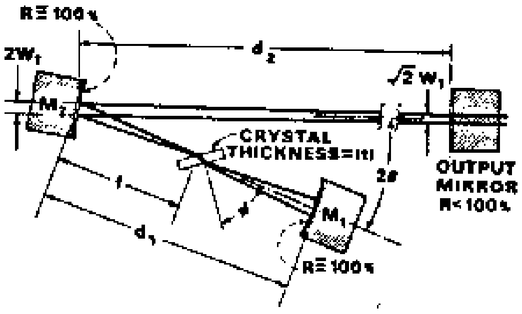


Figure 6 Basic Cavity Configuration

-- 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:

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:

a. Raman spectrometer, routine with microsocpe for materials

b. Resonance Raman spectrometer for small molecules
c. T-jump fluorimeter for biological systems, like proteins
d. 2D IR correlation IR of fs pulses,
e. Very high resolution IR of gases for polution detection
f. laser ablation/ pulsed beam measurements
g. MPI molecular beam studies of small molecules

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

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

1.4 If two levels at 300° 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 $\lambda_0 = 488$ 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
θ_d = divergence, λ = 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 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

RP laser Encyclopedia

Fiber lasers: http://www.rp-photonics.com/fiber_lasers.html

Nonlinear optics principles

http://scholar.lib.vt.edu/theses/available/etd-061899-103951/unrestricted/cain1.pdf