Laser Basics

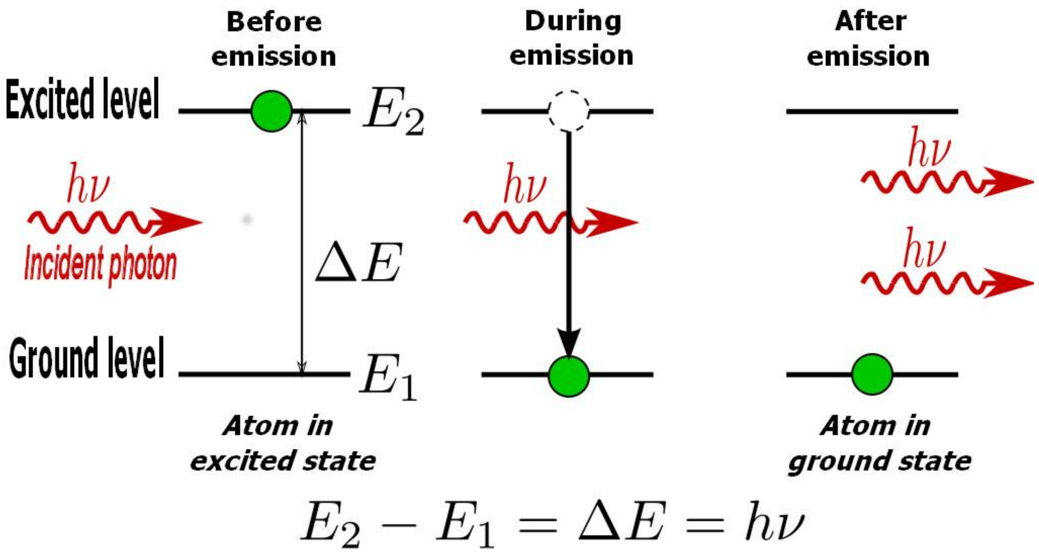
- What is a Laser?
  - Stimulated Emission, Population Inversion, Cavities
  - Some examples
  - Coherent sources in general

- Overview of Laser Applications in Accelerator Physics

- Some important Laser Configurations for AP
  - Ti:Sapphire lasers
  - Chirped Pulse Amplification
  - Nonlinear frequency synthesis
  - Fiber Lasers

What is a Laser?

Definition: *Light Amplification by Stimulated Emission*



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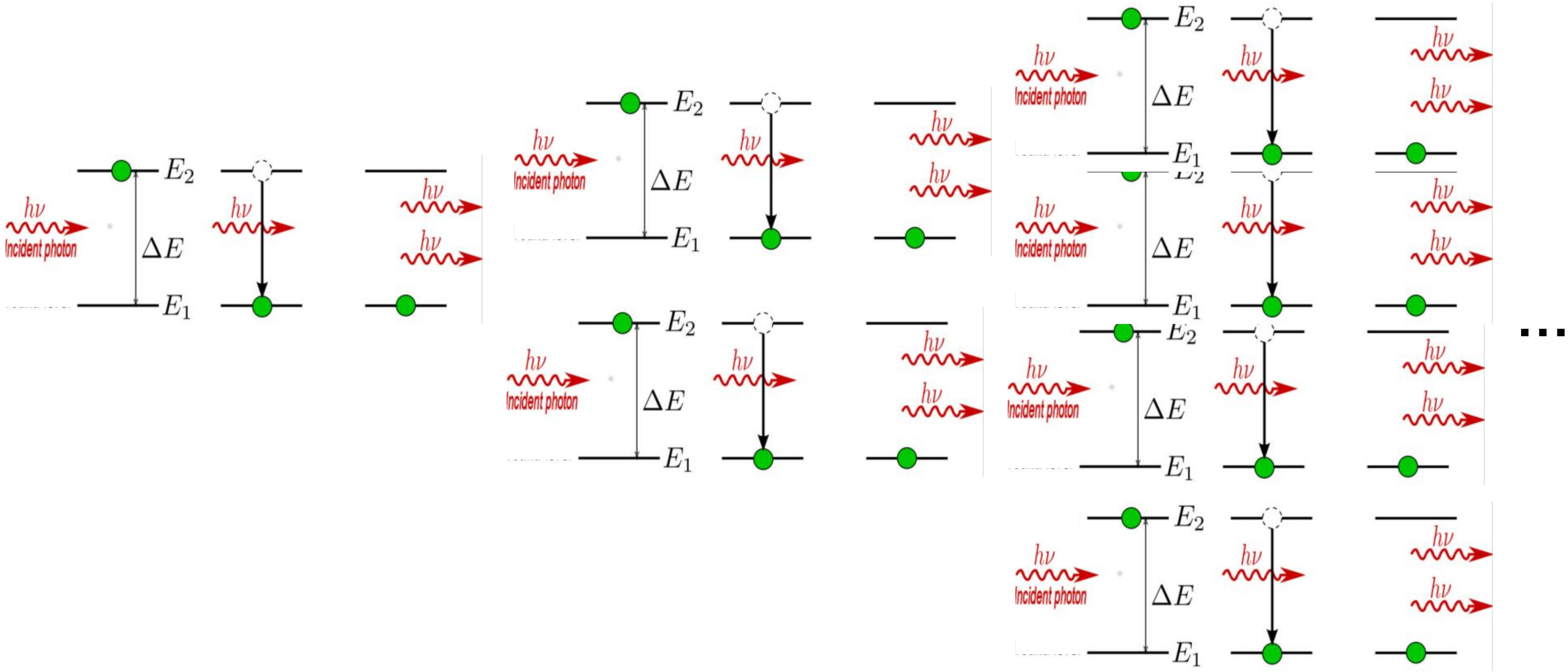
In principle, the only necessary and sufficient condition to call something a laser is that the gain mechanism be stimulated emission: the fact that the transition amplitude for emission into a field mode is linear in the field strength.

- an obvious instability similar to a nuclear fission chain reaction (but coherent)
- requires a "population inversion"



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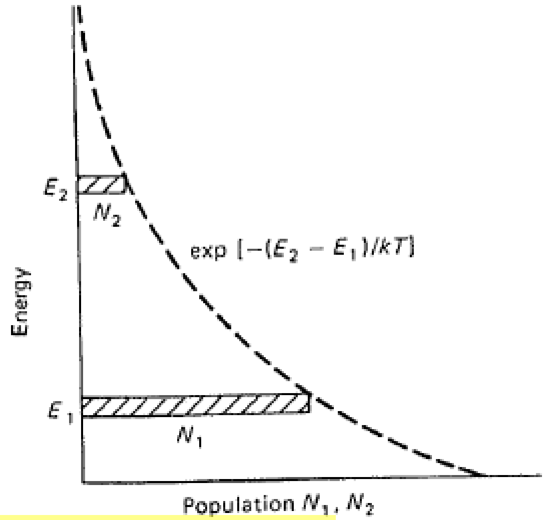
Population inversion



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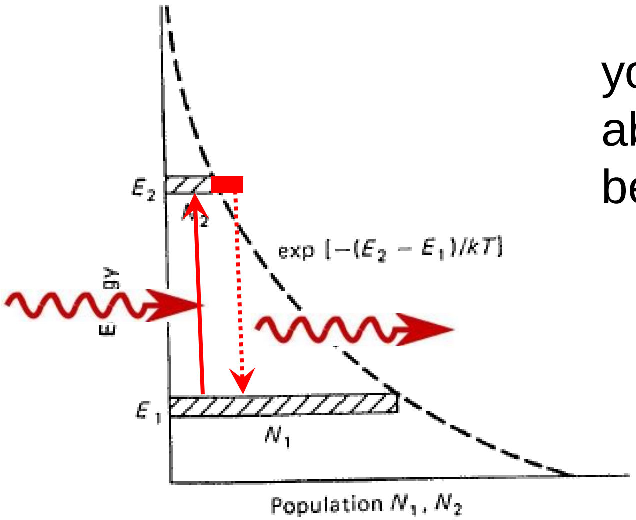
In thermal equilibrium, the relative populations N1, N2 of two energy levels are given by the Boltzmann distribution

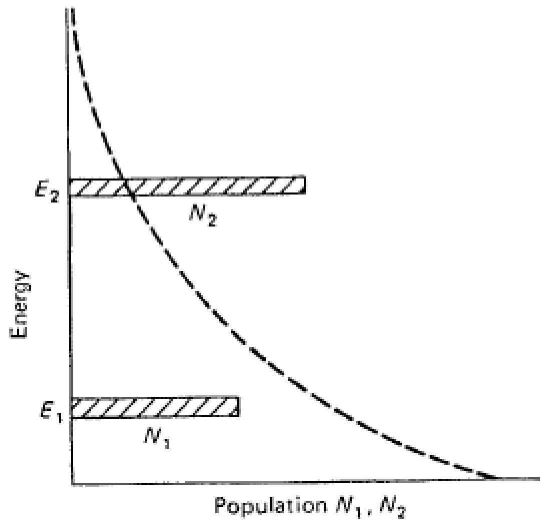
- in visible & near-ir ($\lambda < 1\ \mu$m) Boltzmann factor is <exp(-45), so upper state population is essentially zero



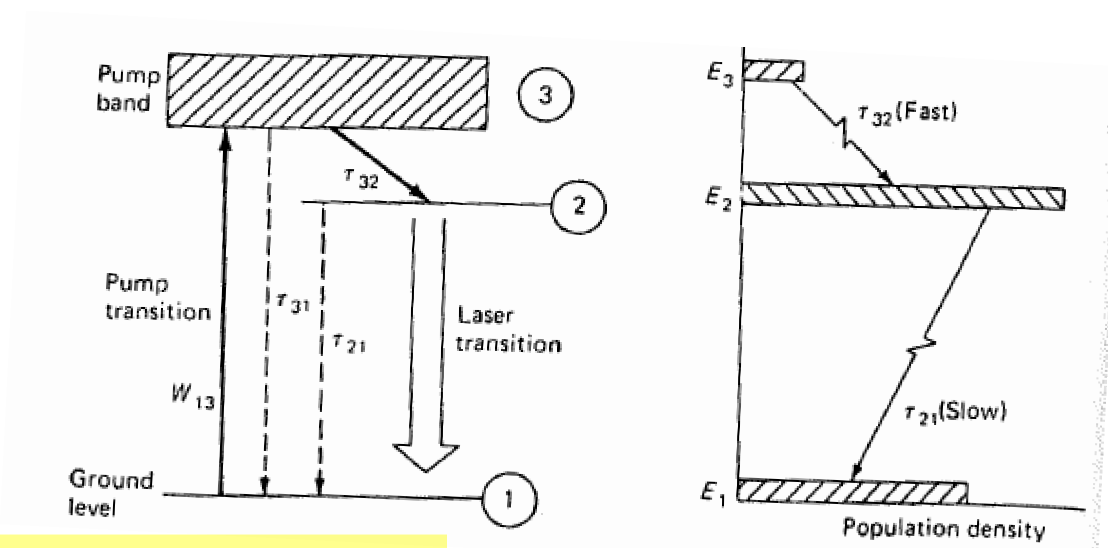
you can increase the excited state population with absorption, but in a 2-level system, you can never get beyond 50%

- $B_{12}=B_{21}$, the cross-sections for stimulated emission and absorption are the same
- no net gain

Population Inversion: 3-level system



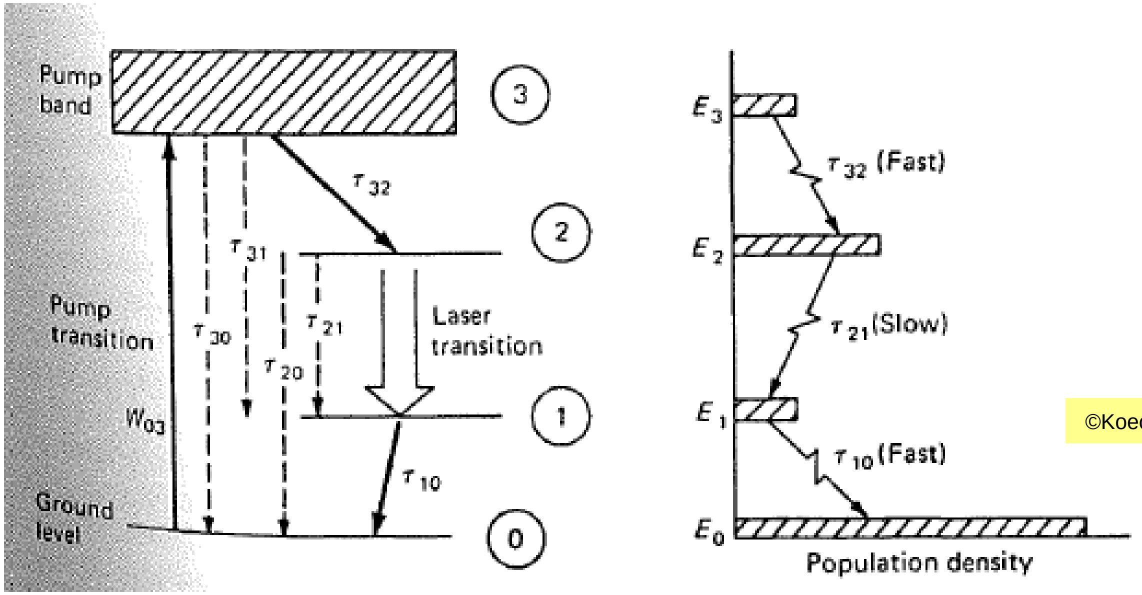
In order to achieve $N_2>N_1$, we need to fill the upper state indirectly (not using the signal field), and fill it faster than spontaneous emission depletes it.



In a 3-level system, you couple the ground state 1 to an intermediate state 3, which relaxes back to state 2; the laser transition is 2→1

- requires $\tau_{32}<\tau_{21}$

Population Inversion: 4-level system



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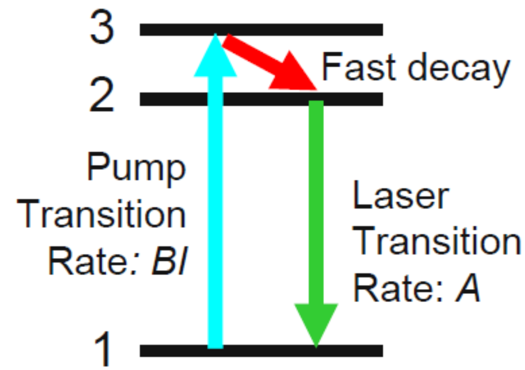
• state 1 starts out virtually empty, so any population driven into 2 creates an inversion
• again access 2 indirectly through a fast decay from 3
• can crudely think of it as a 3-level 'improved' by inserting an empty target state

A 3-level system



Assume we pump to a state 3 that rapidly decays to level 2.

Spontaneous emission

$$\frac{dN_2}{dt} = BIN_1 - AN_2$$

Absorption

$$\frac{dN_1}{dt} = -BIN_1 + AN_2$$

The total number of molecules is N:

$$N \equiv N_1 + N_2$$

$$\Delta N \equiv N_1 - N_2$$

Level 3 decays fast and so is zero.

$$\frac{d\Delta N}{dt} = -2BIN_1 + 2AN_2$$

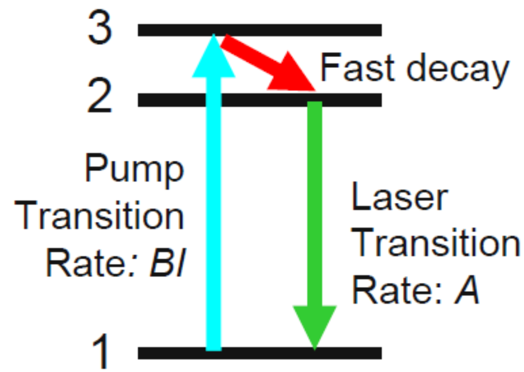
$$2N_2 = N - \Delta N$$

$$2N_1 = N + \Delta N$$

$$\Rightarrow \frac{d\Delta N}{dt} = -BIN - BI\Delta N + AN - A\Delta N$$

Credit: R. Trebino

Population inversion, 3 level system



$$\frac{d\Delta N}{dt} = -BIN - BI\Delta N + AN - A\Delta N$$

In steady-state: $0 = -BIN - BI\Delta N + AN - A\Delta N$

$$\Rightarrow (A + BI)\Delta N = (A - BI)N$$

$$\Rightarrow \Delta N = N(A - BI)/(A + BI)$$

$$\Rightarrow \boxed{\Delta N = N\frac{1 - I/I_{sat}}{1 + I/I_{sat}}}$$

where: $I_{sat} = A/B$

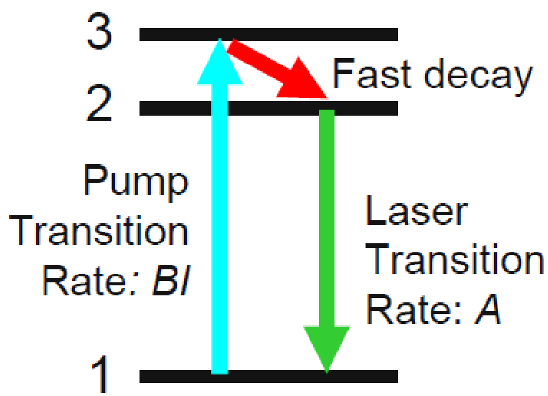
I_{sat} is the **saturation intensity**.

Now if $I > I_{sat}$, ΔN is negative!

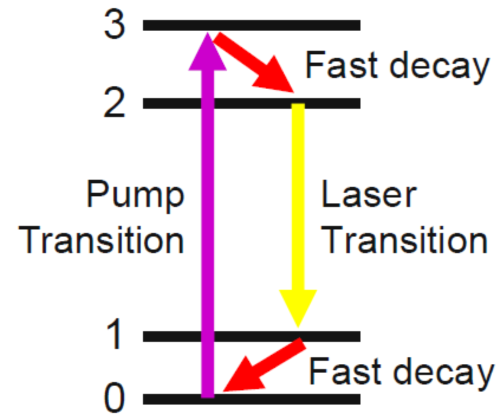
Gain: $g \propto -\sigma\Delta N$

Credit: R. Trebino

3-level vs 4-level



$$\Delta N = N\,\frac{1 - I/I_{sat}}{1 + I/I_{sat}}$$



$$\Delta N = -N\,\frac{I/I_{sat}}{1 + I/I_{sat}}$$

- Homework: derive ΔN for the 4-level system, using the infinitely fast decay assumption that we used in the 3-level case (τ=0 for all of the red lines)
  - if you want to cheat you can look at 2008 USPAS notes, but try it yourself first.
- Why does this make 4-level systems advantageous over 3-level?

What we have so far

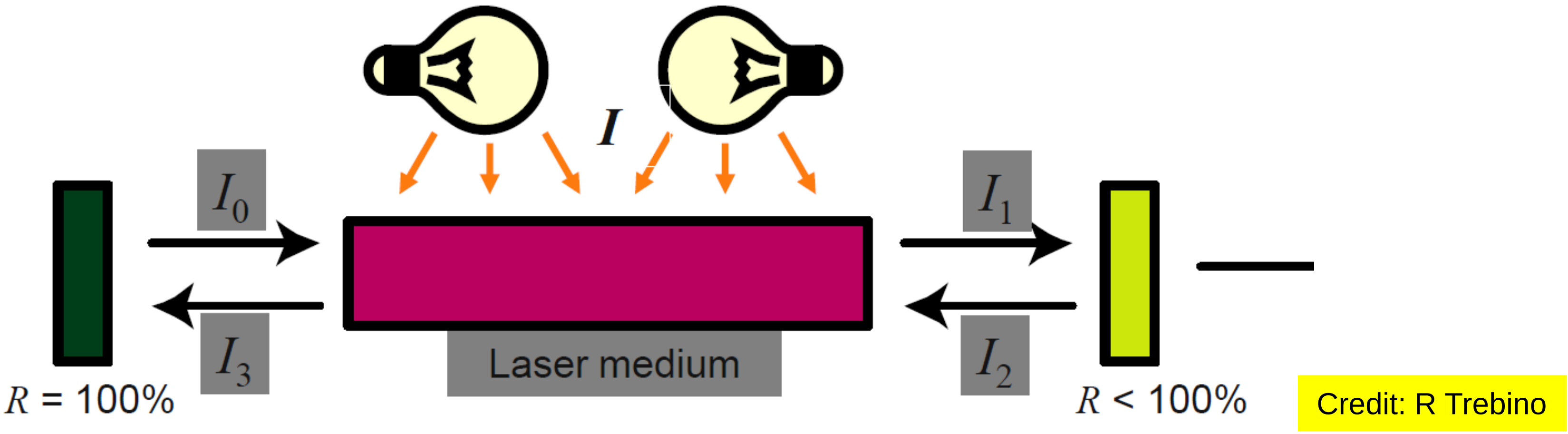
Lasers exploit stimulated emission to provide gain for coherent signals

- Where to get the signal to begin with?
  - cavities, amplifiers vs oscillators

- So far we are pretty constrained by Nature's whims
  - Available, gain, wavelength, bandwidth (pulse width), pump requirements all depend on finding quantum systems in Nature that 'fit'

- How to reach wavelengths where Nature is less generous?

Cavities



- Place lasing medium in an optical resonator

- Exponential growth
  - can start from spontaneous emission ‘noise’

- Can gate in a weak signal from another source
  - regenerative amplification

Cavities: Longitudinal modes (plane wave approximation)

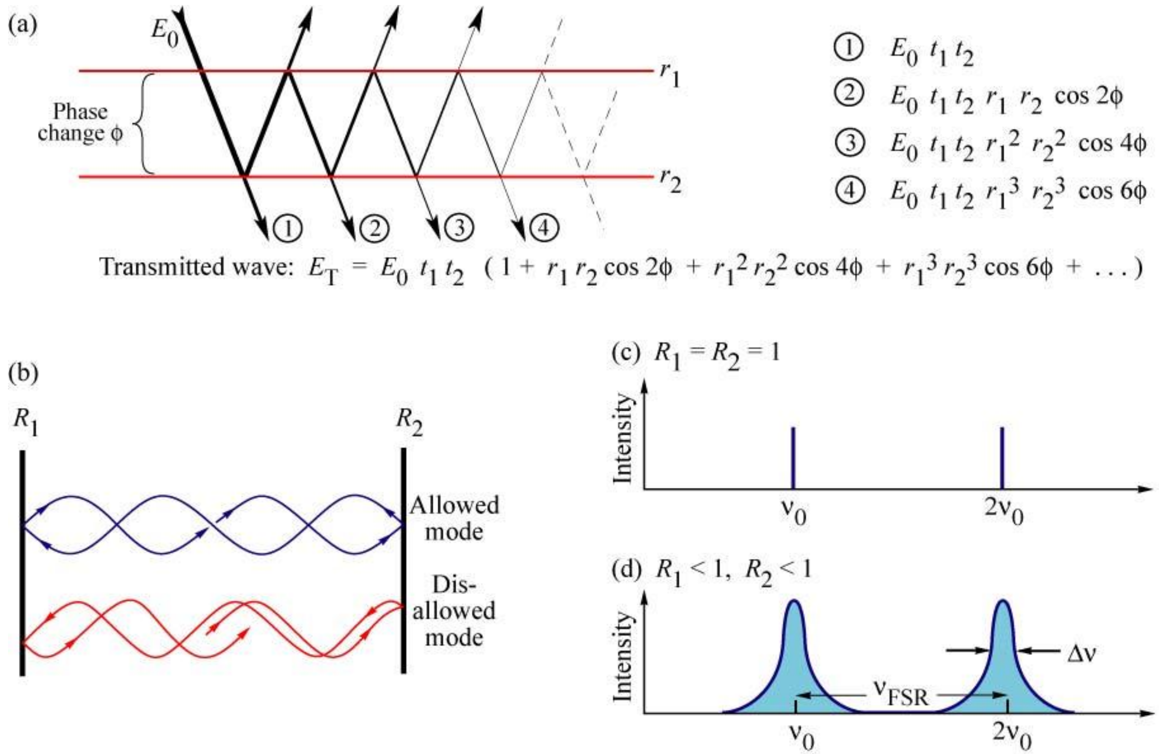


Fig. 14.1. (a) Transmission of a light wave with electric field ampltitude E_0 through a Fabry–Perot resonator. (b) Schematic illustration of allowed and disallowed optical modes in a Fabry–Perot cavity consisting of two coplanar reflectors. Optical mode density for a resonator with (c) no mirror losses ($R_1 = R_2 = 100$ %) and (d) mirror losses.

E. F. Schubert
Light-Emitting Diodes (Cambridge Univ. Press)
www.LightEmittingDiodes.org

$$n\lambda = 2L \rightarrow \lambda_n = \frac{2L}{n}$$

$$\lambda_n - \lambda_{n+1} = \frac{2L}{n} - \frac{2L}{n+1} = \frac{\lambda_n}{n+1}$$

- for 1-100 cm cavities, at optical wavelengths, n~10^4-10^6
  - mode spacing less than width
    - continuous tuning
  - can have many within the gain bandwidth
    - mode-locked laser
- for small cavities, e.g. diode lasers, n is smaller
  - can see ‘mode hops’ when there is no feedback.

Cavities: including transverse modes

- *Nothing goes on forever*: plane waves don't exist
- Round-trip phase change is in general a function of the transverse field distribution
- Resonator modes must reproduce shape at each point on each pass, and round-trip phase shift must be a multiple of 2π
- Solutions to the wave equation that are self-consistent can be expanded in Hermite-Gaussian modes

$$E(x,y,z) = E_0 \frac{w_0^2}{w^2(z)} H_n\left(\frac{\sqrt{2}x}{w(z)}\right) H_m\left(\frac{\sqrt{2}y}{w(z)}\right) e^{-\frac{x^2+y^2}{w^2(z)}} e^{-i\left[k\frac{x^2+y^2}{2R(z)}-(1+n+m)\eta(z)\right]}$$

$$H_0(x) = 1$$
$$H_1(x) = 2x$$
$$H_2(x) = 4x^2 - 2$$
$$H_3(x) = 8x^3 - 12x$$

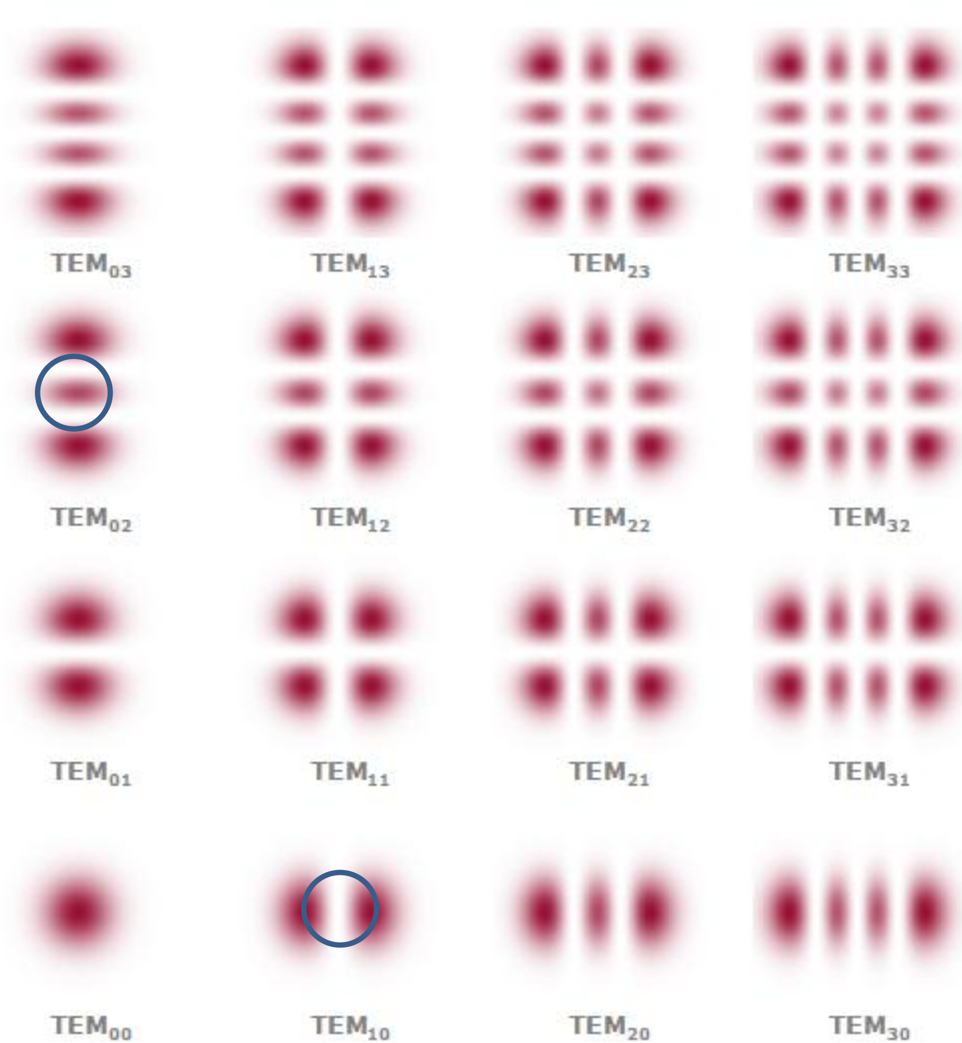
$$z_0 = \frac{\pi w_0^2}{\lambda} \quad w(z) = w_0\left(1+\frac{z^2}{z_0^2}\right)^{1/2} \quad R(z) = z\left(1+\frac{z_0^2}{z^2}\right) \quad \eta = \tan^{-1}\frac{z}{z_0}$$

NB, for *n=m=0*, we have a very simple Gaussian beam :

$$E(r,z) = E_0 \frac{w_0}{w(z)} \exp\left(-\frac{r^2}{w^2(z)}\right) \exp\left[-i\left(\frac{kr^2}{2R(z)} - \eta(z)\right)\right]$$

phase term

Intensity profiles for the first 16 Hermite-Gaussian modes

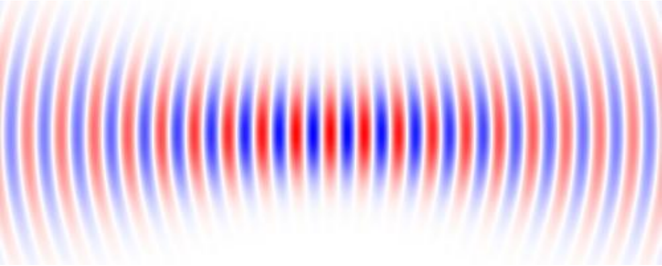


For the most part we will be concerned with the lowest order mode

$$E(r,z) = E_0 \frac{w_0}{w(z)} \exp\left(-\frac{r^2}{w^2(z)} \right)$$

- curvature infinite at waist
- can discriminate against HOMs with an aperture

- very slow divergence
  - eg z_0=5.9 m for w_0=1mm, λ=532 nm; ~0.3mrad

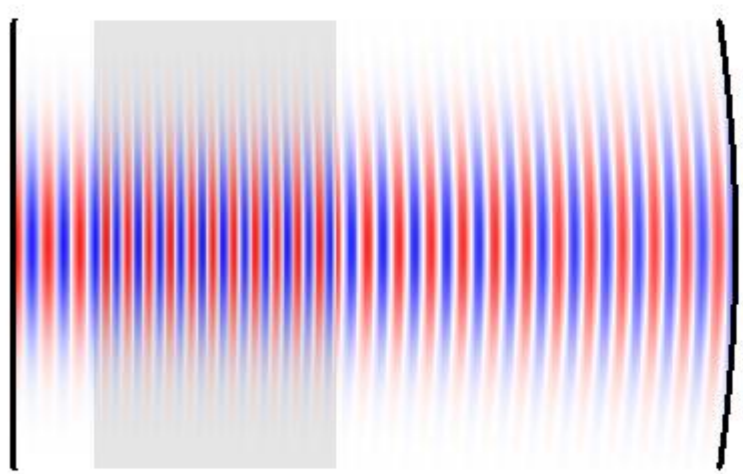


Gaussian mode near a very hard focus

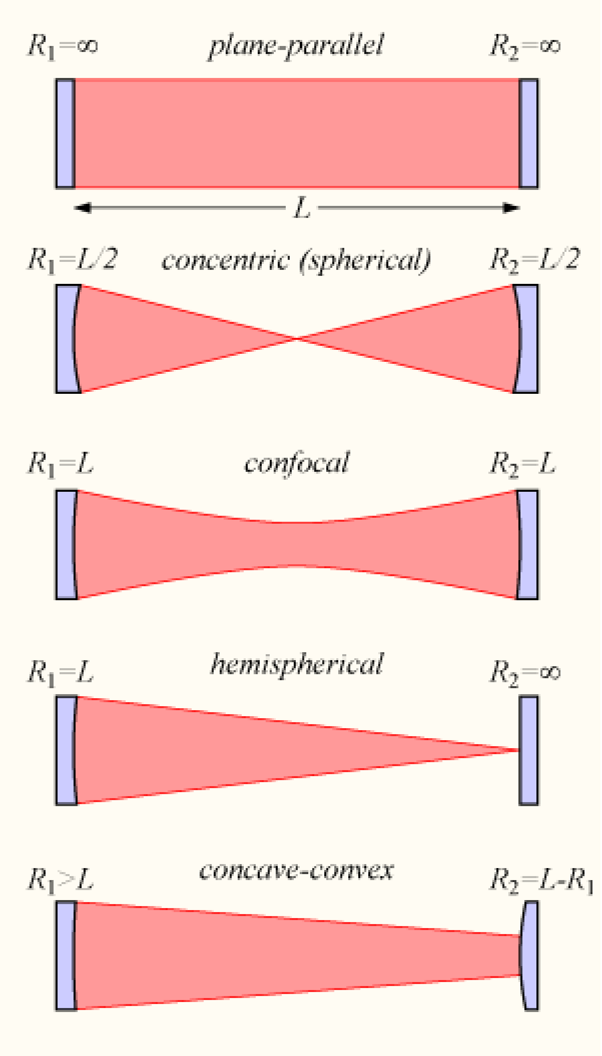
$$\left(w_0 \approx \lambda\right)$$

pics from Ency of Laser Physics & Technology, RP Photonics
http://www.rp-photonics.com/gaussian_beams.html

2-mirror cavities



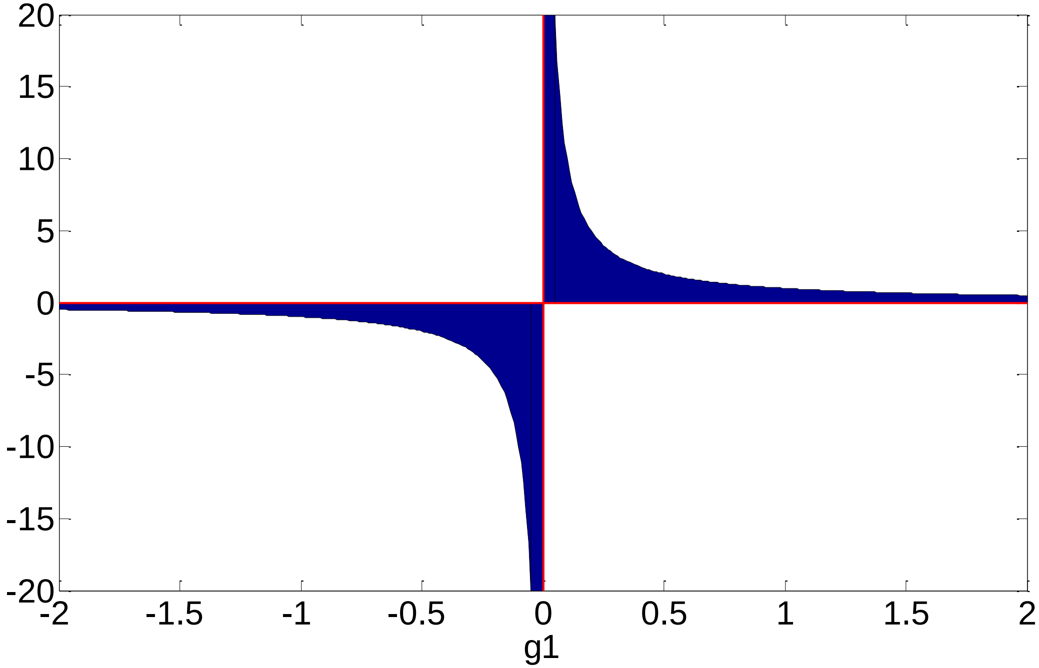
Ency of Laser Physics & Technology, RP Photonics



- Create a stable cavity by putting a flat mirror at the waist, and another mirror matching the curvature away from the waist

- Lots of other configurations →

Stability Criterion



In general:

$$g_1 \equiv 1 - \frac{L}{R_1}$$

$$g_2 \equiv 1 - \frac{L}{R_2}$$

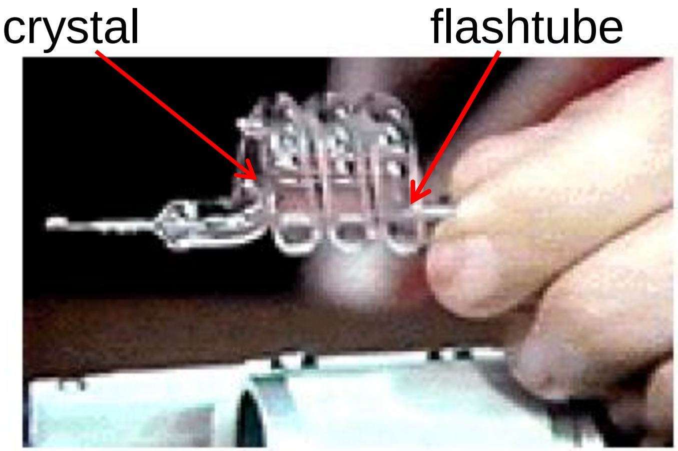
$$0 \le g_1 g_2 \le 1$$

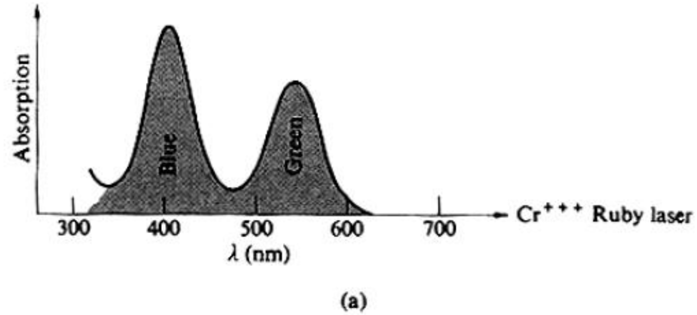
stability condition

Homework: verify the stability of the 5 cavity types on the previous slide

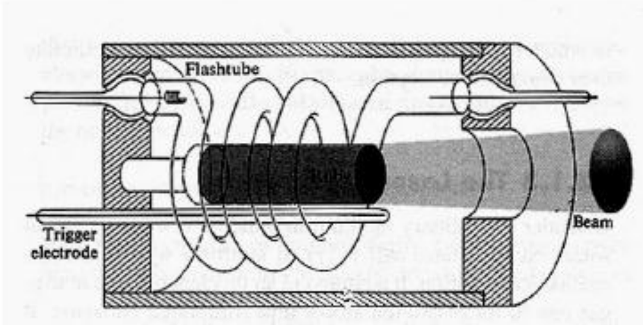
Extra Credit Project: use ABCD matrices to derive the stability condition & present to the class

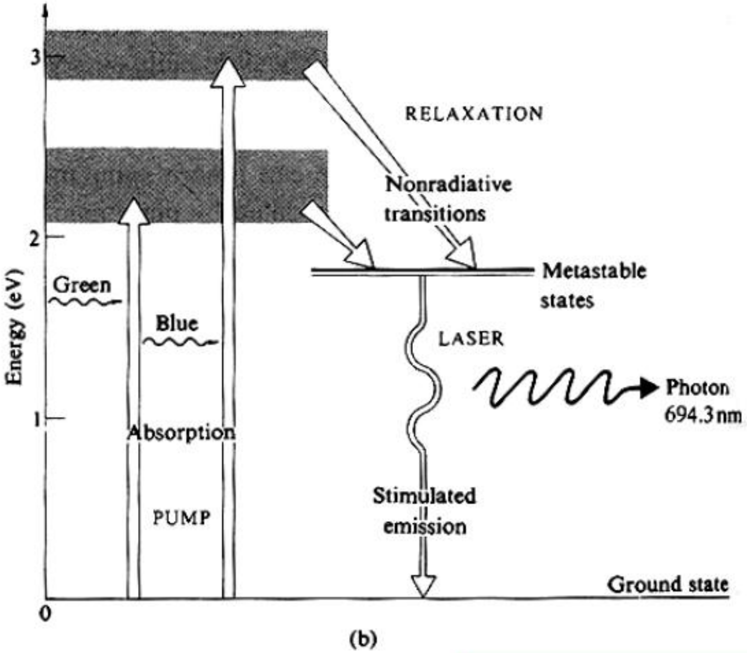
You never forget your first: the ruby laser





- 3-level system, Cr^{3+} in Al_2O_3 host
  - absorption bands in green & blue
  - lasing in red (694 nm)
- invented in 1960 by Ted Maiman





Credit: R. Trebino

HeNe laser

4-level system

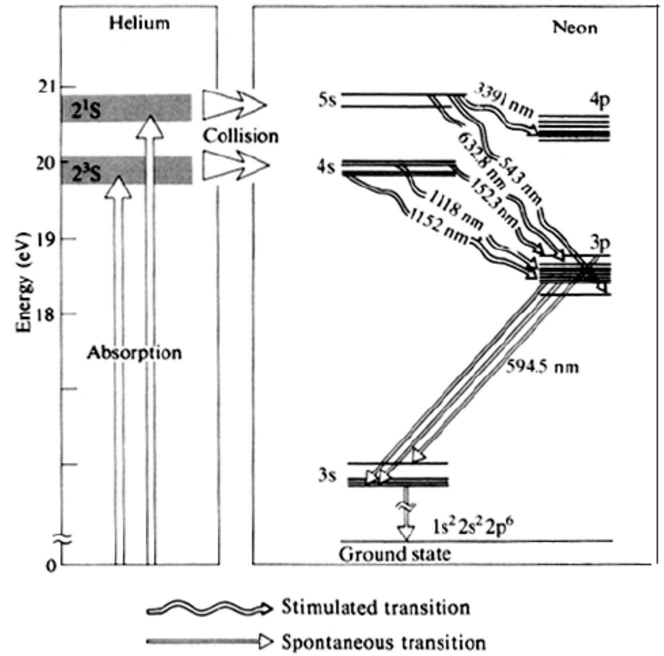
- e^- - He collisions in discharge excite He atoms

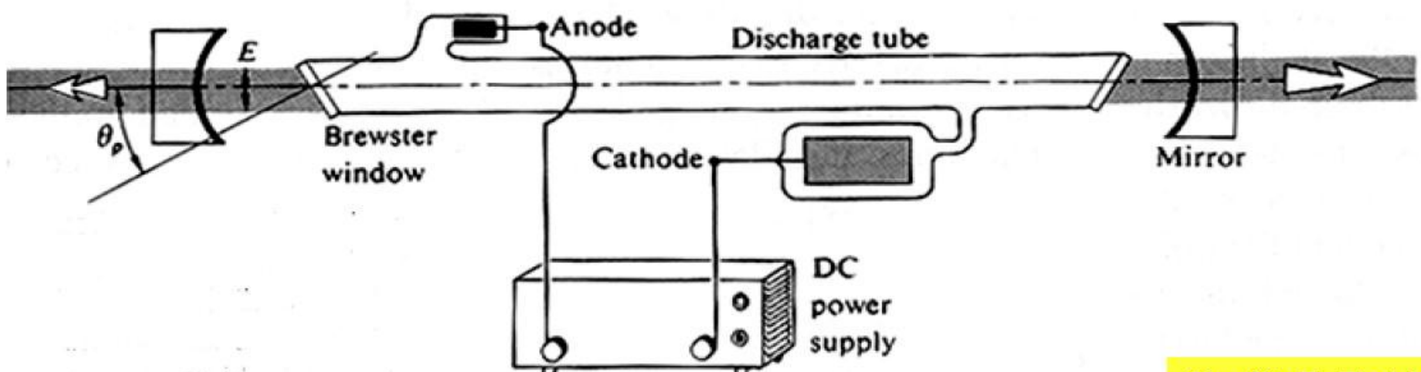
- excited He collide with Ne and excite Ne into 4s and 5s manifolds

- lasing transitions to 3p and 4p

- fast radiative transitions to metastable 3s

- decay to ground state by collisions with walls





Credit: R. Trebino

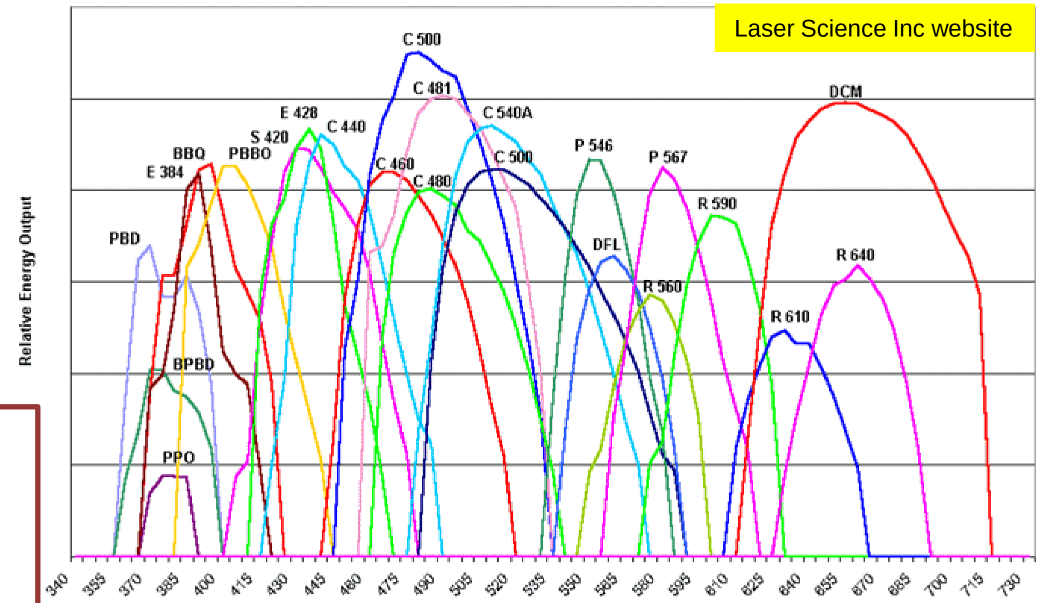
Dye Lasers

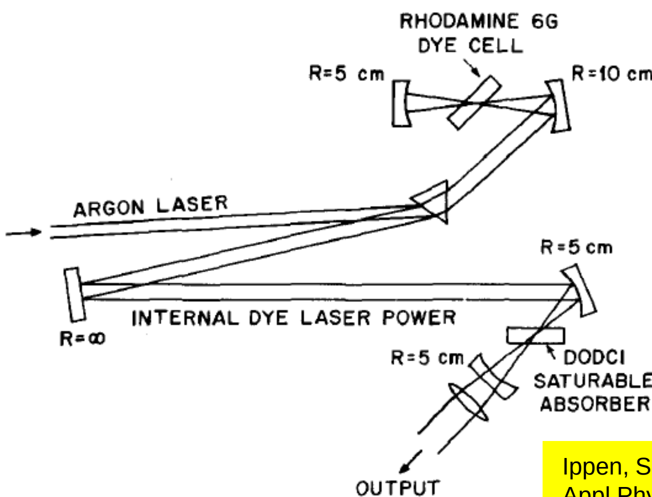
- Typically big organic molecules in organic solvents
  - dense manifold of states offers tunability, and bandwidth
- broad wavelength coverage over many dyes

Pro's:
- tunability & coverage: great for spectroscopy
- bandwidth: short pulses possible

Con's:
- toxicity: carcinogens, difficult to handle
- decay of the dye
- low peak power

Dye Tuning Curves

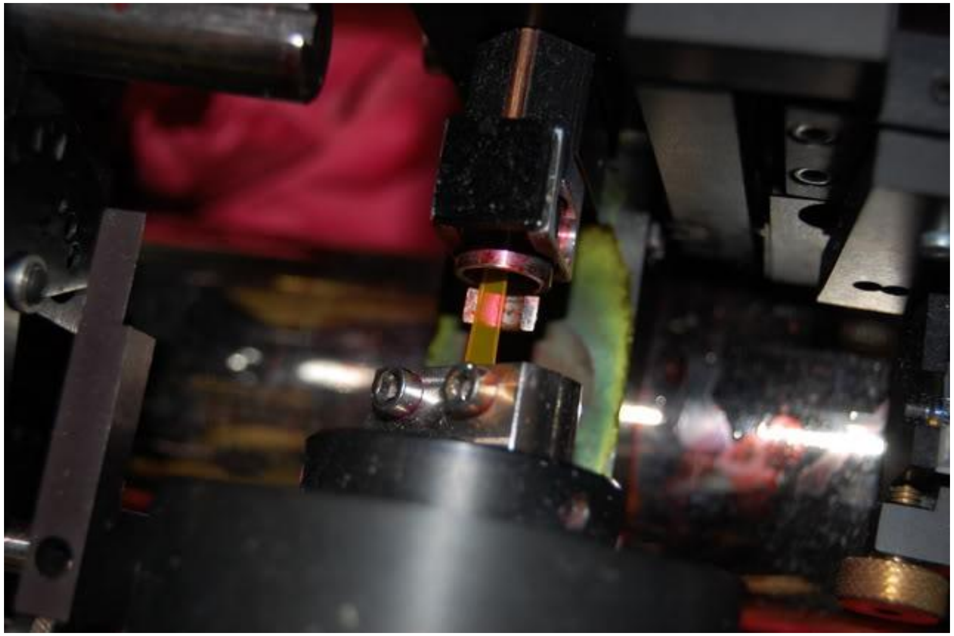




First passively mode-locked dye laser, 1972.
- 1.5 psec

Ippen, Shank & Dienes
Appl Phys Lett 21, 348 (1972)

A glimpse of the dark side of dye lasers

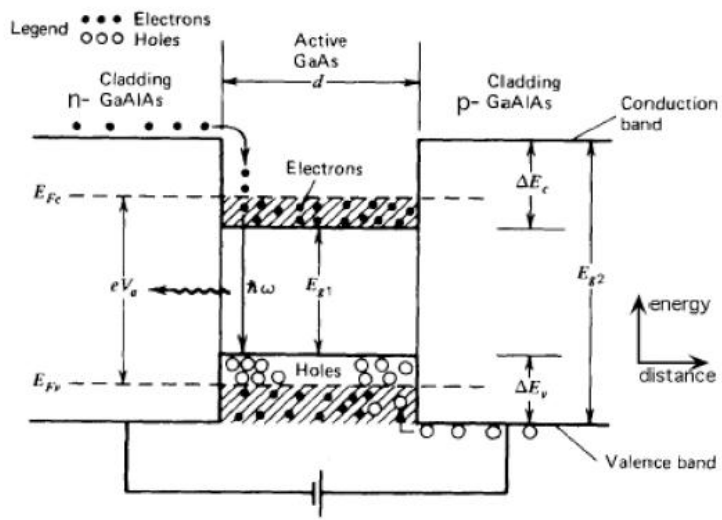


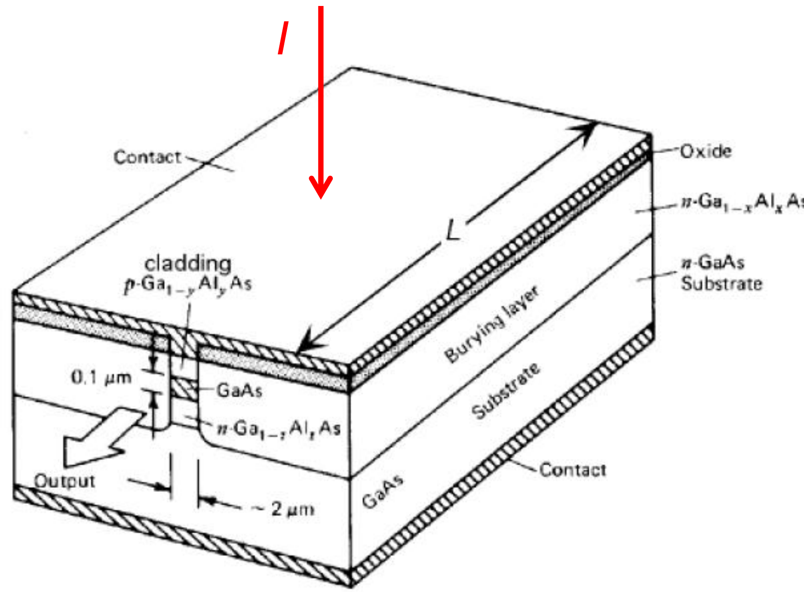
Dye jet surrounded by dye mess

every laser lab in the 80s

pics from http://www.dailykos.com/story/2008/05/20/518722/-Big-Scary-Laser-Part-I-w-photos-and-video

Engineer the quantum states: Diode & Quantum Cascade Lasers

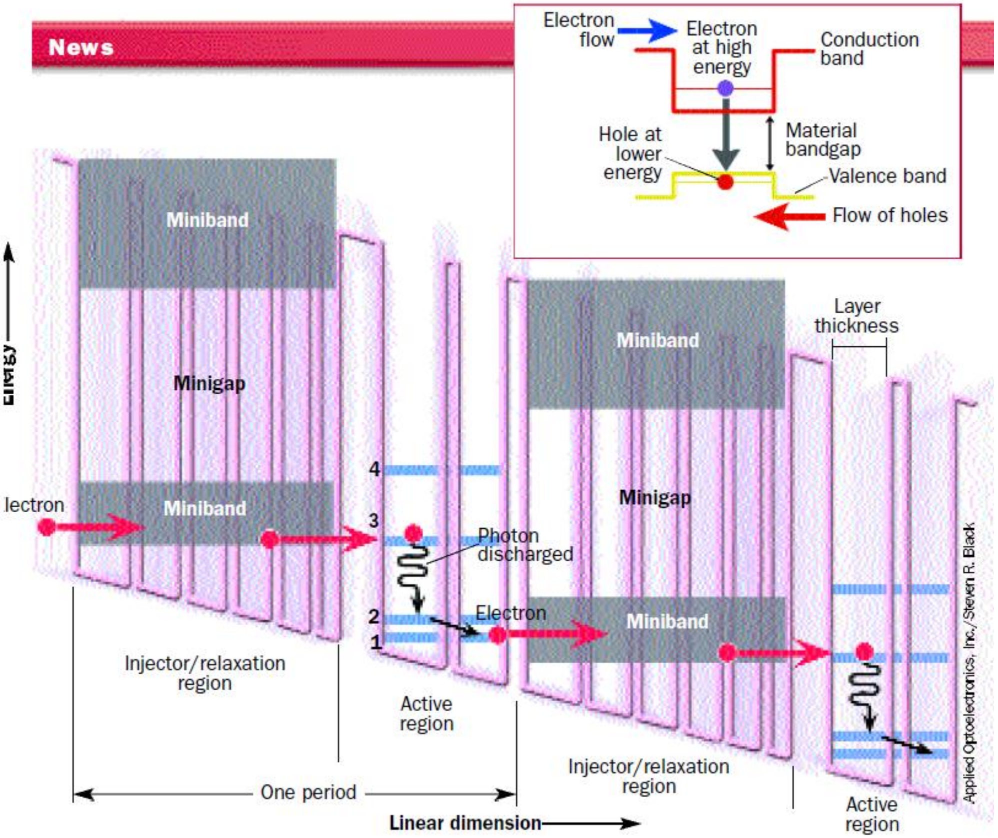




credit: Yariv, *Quantum Electronics*

- Optical pumping replaced by carrier injection current
- Cladding layers form waveguide and with cleaved end facets form cavity
- Lasing transition energy tuned by material choice/doping
- Fine Tuning by current, temperature, optical feedback
- Limitations: peak power, pulse width, wavelength

Quantum Cascade Lasers



credit: Industrial Physicist/Applied Optoelectronics

- Unipolar: electrons, no holes
- intersubband transitions: discrete structure imposed within conduction band by quantum confinement
- operate in infrared
- structure repeats across a potential gradient, electron tunnels between structures
    - multiple lasing transitions per electron
    - Quantum Efficiency > 1!

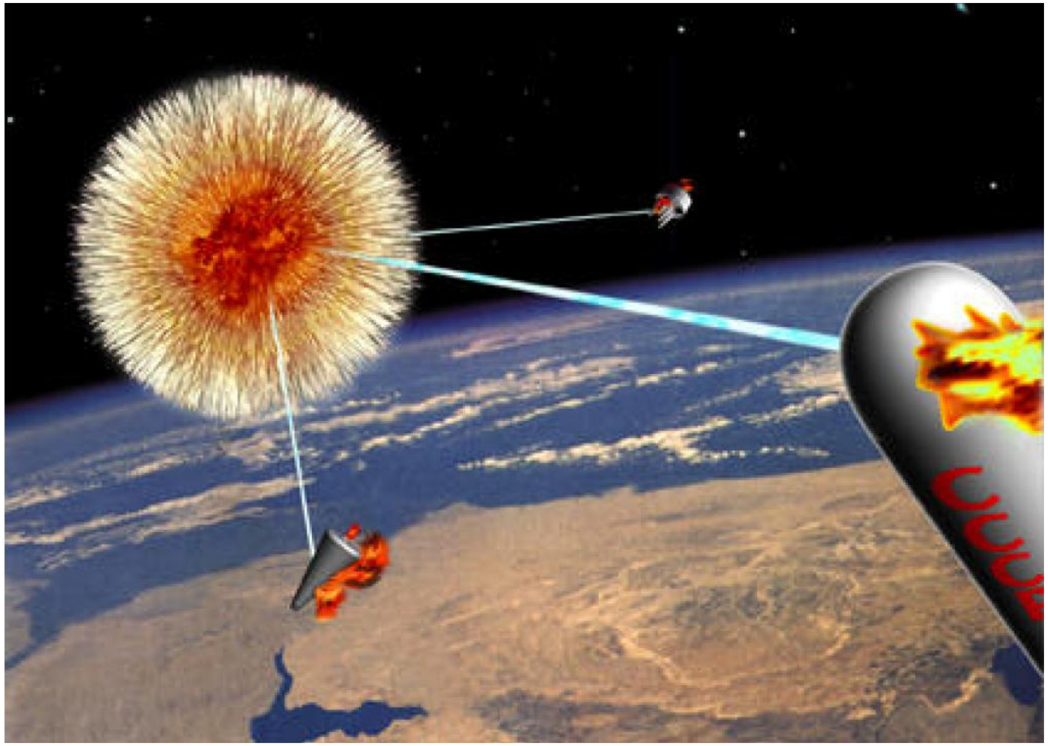
Lanthanide Lasers

Ion	Common host media	Important emission wavelengths
neodymium (Nd^{3+})	YAG, YVO_4, YLF, silica	1.03–1.1 µm, 0.9–0.95 µm, 1.32–1.35 µm
ytterbium (Yb^{3+})	YAG, tungstates, silica	1.0–1.1 µm
erbium (Er^{3+})	YAG, silica	1.5–1.6 µm, 2.7 µm, 0.55 µm
thulium (Tm^{3+})	YAG, silica, fluoride glasses	1.7–2.1 µm, 1.45–1.53 µm, 0.48 µm, 0.8 µm
holmium (Ho^{3+})	YAG, YLF, silica	2.1 µm, 2.8–2.9 µm
praseodymium (Pr^{3+})	silica, fluoride glasses	1.3 µm, 0.635 µm, 0.6 µm, 0.52 µm, 0.49 µm
cerium (Ce^{3+})	YLF, LiCAF, LiLuF, LiSAF, and similar fluorides	0.28–0.33 µm

credit: Ency of Laser Physics & Technology, RP Photonics
http://www.rp-photonics.com/rare_earth_doped_gain_media.html

- Trivalent Lanthanides in robust crystal or glass hosts
    - Fiber lasers
- Inner shell optical activity relatively unperturbed by host environment
- Long (eg Nd:YAG 230 usec) upper state lifetime
    - store energy from low intensity pump (diode, lamp)
    - Q-switch to make intense pulses
- Great systems, but still a finite set of wavelengths
    - Workhorses: used to pump frequency conversion and other lasers
        - Ti:Sapphire lasers

Star Wars Laser



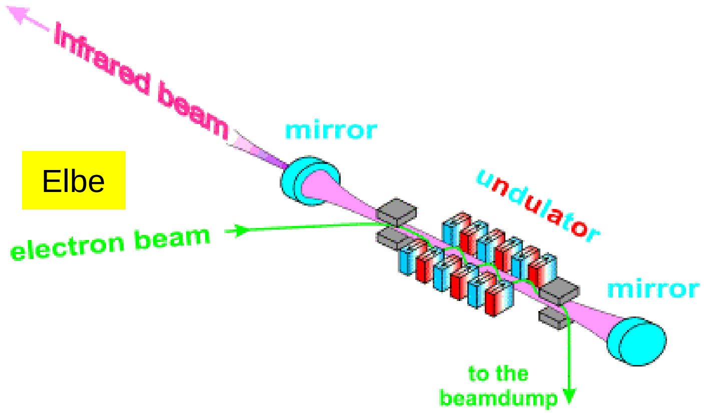
- Kilotons-yield nuclear bomb produces intense burst of black-body radiation
- Rods of Zn arrayed around the source are ionized and excited
- Superradiant X-ray beams strike and disable missiles in the boost phase.
  - right in their axis of evil !
- Don’t tell anyone.

FEL a laser?

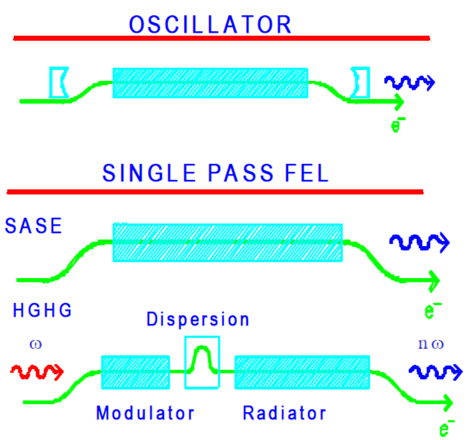
The laser nearest and dearest to most accelerator physicists' hearts – the free electron laser (FEL), turns out not to be a laser at all according to our definition, but a purely classical device.

• No stimulated emission, but a similar instability with coherent coupling between the field and the emitters, and exponential growth

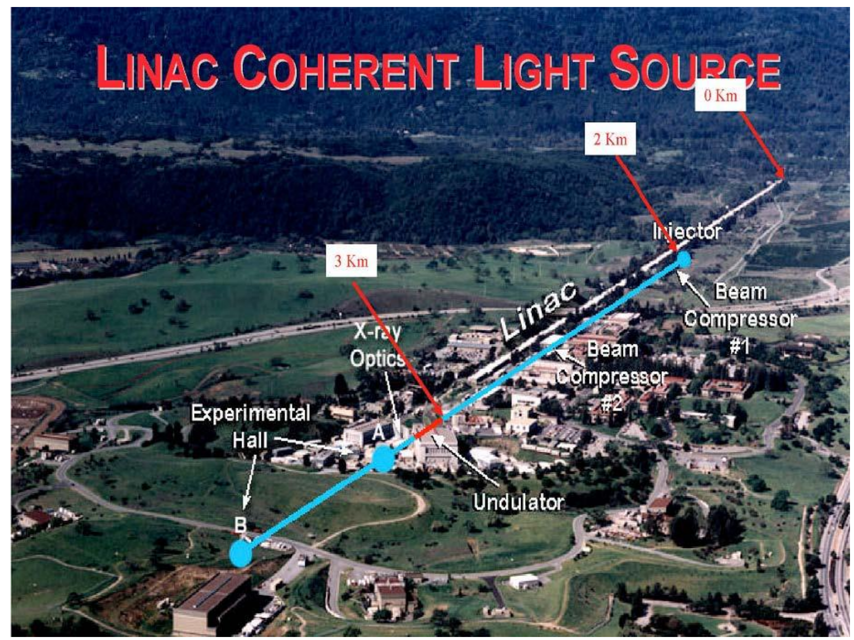
• possible in oscillator, ASE, and seeded configurations



Elbe



Sam Krinsky



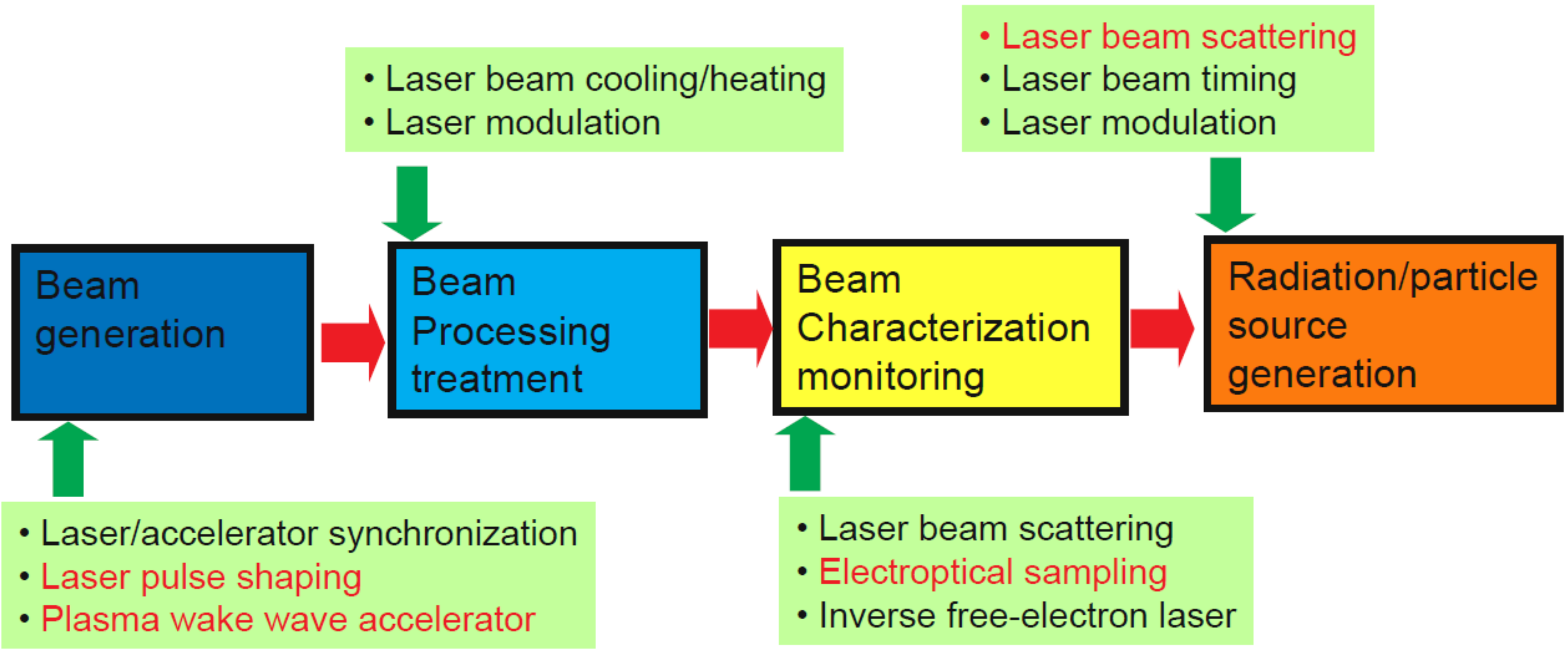
What is a laser?

The motivation for lasers has always been the development of coherent sources. Lasers as traditionally defined (gain from stimulated emission with enhancement in a cavity) turn out to be more of the starting point, and much of the field of laser physics is concerned with manipulating and transforming laser sources and exploiting their coherent properties.

A few examples (not exhaustive)

- *Nonlinear frequency synthesis: SFG, DFG, OPAs, HHG*
- *Attosecond pulses*
- *Optical frequency combs*
- *Coherent diagnostics (FROG, SPIDER, electro-optic beam detection)*
- *Pulse shaping*

A Map of laser applications/issues in acclerator physics



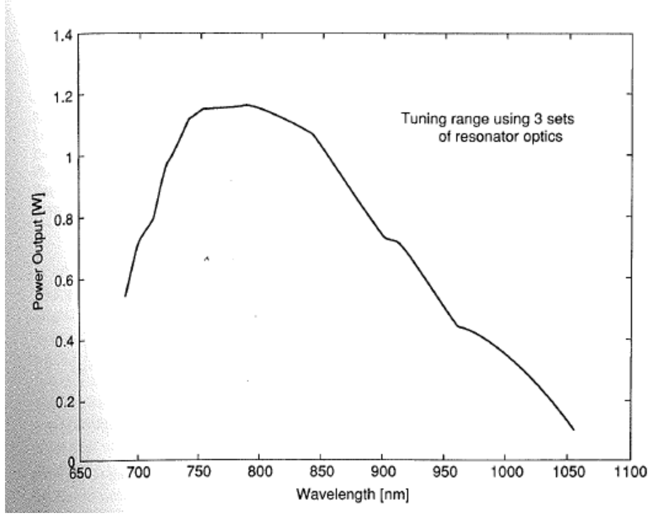
credit Yuelin Li

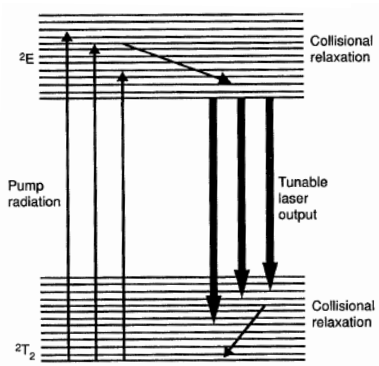
Ti:Sapphire lasers

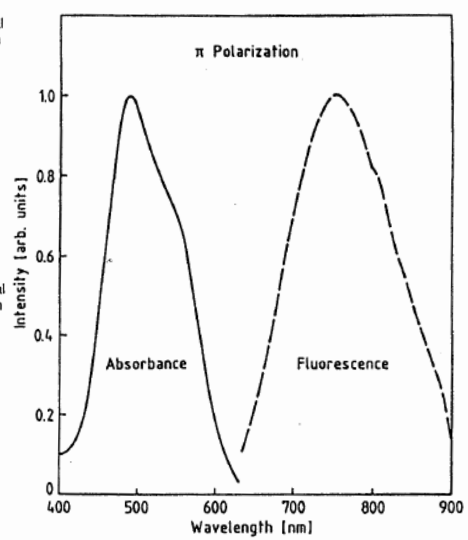
Table 2.10. Laser parameters of $Ti:Al_2O_3$

Index of refraction	1.76
Fluorescent lifetime	3.2 μs
Fluorescent linewidth (FWHM)	230 nm
Peak emission wavelength	780 nm
Peak stimulated emission cross section	
parallel to *c*-axis	$\sigma_{\parallel} \sim 4.1 \times 10^{-19}$ cm^2
perpendicular to *c*-axis	$\sigma_{\perp} \sim 2.0 \times 10^{-19}$ cm^2
Stimulated emission cross section at 0.795 μm	$\sigma_{\parallel} = 2.8 \times 10^{-19}$ cm^2
Quantum efficiency of converting a 0.53 μm photon into an inverted site	$n_Q \approx 1$
Saturation fluence at 0.795 μm	$E_s = 0.9$ J/cm^2

data from Koechner: *Solid-State Laser Engineering*

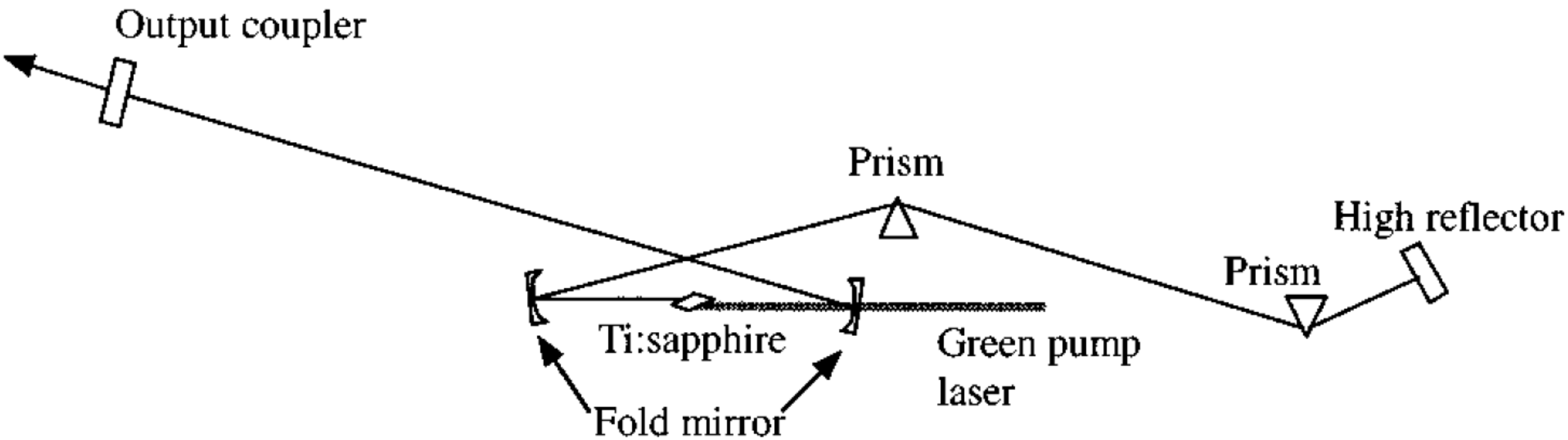






- Broad fluorescence linewidth
  - shortest pulses
  - broad tunability
- High saturation fluence
- efficiently pumped at 532 nm
- large stored energy density
- good thermal properties
- short fluorescence lifetime
  - laser pumping almost a must

Basic Mode Locked Ti:Sapph oscillator



What are the prisms for?

A Diversion on Dispersion

Consider the Taylor expansion of the spectral phase of a pulse transiting an optical system

$$\phi(\omega)=\phi(\omega_0)+\phi'(\omega_0)(\omega-\omega_0)+\frac{1}{2}\phi''(\omega_0)(\omega-\omega_0)^2+\frac{1}{6}\phi'''(\omega_0)(\omega-\omega_0)^3+\ldots\ldots.$$

The group delay is

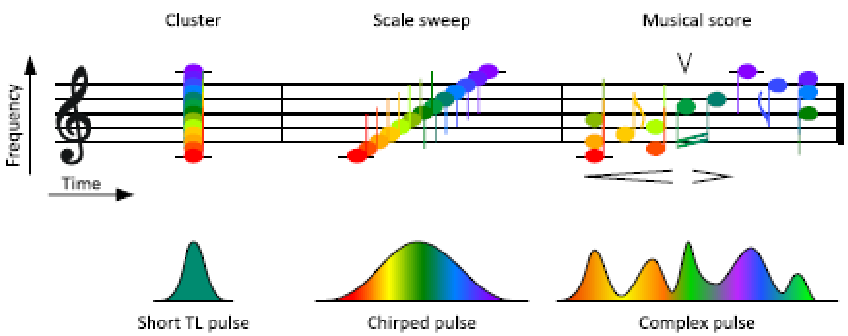
$$T(\omega)=\frac{\partial\varphi(\omega)}{\partial\omega}=\phi'(\omega_0)+\phi''(\omega_0)(\omega-\omega_0)+\tfrac{1}{2}\phi'''(\omega_0)(\omega-\omega_0)^2+\ldots.$$

The first term is a global delay. If all derivatives of order 2 or higher = 0, the pulse propagates undistorted

$$\text{if there is 2nd order dispersion, } \phi''\neq 0\text{, there is a linear chirp}$$

$$(\phi''>0 \; \textit{normal dispersion}, \; \phi''<0 \; \textit{anomalous dispersion})$$

$$\text{if there is 3rd order dispersion, } \phi'''\neq 0\text{, there is a quadratic chirp...etc}$$



Daan Sprunken U of Twente
Master's Thesis 2008

S Backus et al, Rev Sci. Inst. 69, 1207 (1998)

Dispersion cont.

Most general treatment of pulse shape change from dispersion:

take your initial pulse

$$E(t) = \xi(t) e^{i[\omega_0 t + \varphi(t)]}$$

transform to frequency domain

$$G(\omega) = \int_{-\infty}^{\infty} E(t) e^{-i\omega t} dt = g(\omega) e^{i\eta(\omega)}$$

System transfer function includes attenuation in *s*(w) and dispersion in σ(w)

$$G'(\omega) = G(\omega) S(\omega) = g(\omega) s(\omega) e^{i[\eta(\omega) + \sigma(\omega)]}$$

transform back into the time domain

$$E'(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} G'(\omega) e^{i\omega t} d\omega$$

But usually the lowest order terms dominate, you start with a transform limited pulse, and you want to cancel them…

S Backus et al, Rev Sci. Inst. 69, 1207 (1998)

Dispersion cont.

TABLE I. Expressions for the linear, quadratic, and cubic phase introduced by grating stretchers; compressors, prism pairs, and materials found in a typical amplifier.

Order	Material	Grating pair compressor/stretcher	Prism pair
GVD	$\frac{d^2\phi_m(\omega)}{d\omega^2}=\frac{\lambda^3 L_m}{2\pi c^2}\frac{d^2n(\lambda)}{d\lambda^2}$	$\frac{d^2\phi_c(\omega)}{d\omega^2}=\frac{\lambda^3 L_g}{\pi c^2 d^2}\left[1-\left(\frac{\lambda}{d}-\sin\gamma\right)^2\right]^{-3/2}$	$\frac{d^2\phi_p(\omega)}{d\omega^2}=\frac{\lambda^3}{2\pi c^2}\frac{d^2P}{d\lambda^2}$
TOD	$\frac{d^3\phi_m(\omega)}{d\omega^3}=-\frac{\lambda^4 L_m}{4\pi^2 c^3}\left(3\frac{d^2n(\lambda)}{d\lambda^2}+\frac{\lambda d^3n(\lambda)}{d\lambda^3}\right)$	$\frac{d^3\phi_c(\omega)}{d\omega^3}=-\frac{6\pi\lambda}{c}\frac{d^2\phi_c(\omega)}{d\omega^2}\left(\frac{1+\frac{\lambda}{d}\sin\gamma-\sin^2\gamma}{\left[1-\left(\frac{\lambda}{d}-\sin\gamma\right)^2\right]}\right)$	$\frac{d^3\phi_p(\omega)}{d\omega^3}=\frac{-\lambda^4}{4\pi^2 c^3}\left(3\frac{d^2P}{d\lambda^2}+\lambda\frac{d^3P}{d\lambda^3}\right)$
FOD	$\frac{d^4\phi_m(\omega)}{d\omega^4}=\frac{\lambda^5 L_m}{8\pi^3 c^4}\left(12\frac{d^2n(\lambda)}{d\lambda^2}+8\lambda\frac{d^3n(\lambda)}{d\lambda^3}+\lambda^2\frac{d^4n(\lambda)}{d\lambda^4}\right)$	$\frac{d^4\phi_c(\omega)}{d\omega^4}=\frac{6d^2}{c^2}\frac{d^2\phi_c(\omega)}{d\omega^2}\left(\frac{80\frac{\lambda^2}{d^2}+20-48\frac{\lambda^2}{d^2}\cos\gamma+16\cos 2\gamma-4\cos 4\gamma+\frac{32\lambda}{d}\sin\gamma+\frac{32\lambda}{d}\sin 3\gamma}{\left(-8\frac{\lambda}{d}+\frac{4d}{\lambda}+\frac{4d}{\lambda}\cos 2\gamma+32\sin\gamma\right)^2}\right)-\frac{d^3\phi_c(\omega)}{d\omega^3}\frac{6\pi\lambda}{c}\left(\frac{1+\lambda/d\sin\gamma-\sin^2\gamma}{(1-(\lambda/d-\sin\gamma)^2)}\right)$	$\frac{d^4\phi_p(\omega)}{d\omega^4}=\frac{\lambda^5}{8\pi^3 c^4}\left(12\frac{d^2P}{d\lambda^2}+8\lambda\frac{d^3P}{d\lambda^3}+\lambda^2\frac{d^4P}{d\lambda^4}\right)$
			$P(\lambda)=L_p\cos\beta(\lambda)$ $\beta(\lambda)=-\arcsin(n_p(\lambda)\sin\alpha(\lambda))$ $+\arcsin[n_p(\lambda_r)\sin\alpha(\lambda_r)]$ $\alpha(\lambda)=\xi$ $-\arcsin[\sin\theta_b(\lambda)]/n_p(\lambda)$ $\theta_b(\lambda)=\arctan[n_p(\lambda)]$

S Backus et al, Rev Sci. Inst. 69, 1207 (1998)

Dispersion cont.

TABLE II. Sample values of dispersion for material (1 cm), grating pairs, and prism pairs at 800 nm wavelength.

Optical element	GVD $d^2\varphi/d\omega^2$ (fs^2)	TOD $d^3\varphi/d\omega^3$ (fs^3)	FOD $d^4\varphi/d\omega^4$ (fs^4)
Fused silica	361.626	274.979	−114.35
BK7	445.484	323.554	−98.718
SF18	1543.45	984.277	210.133
KD*P	290.22	443.342	−376.178
Calcite	780.96	541.697	−118.24
Sapphire	581.179	421.756	−155.594
Sapphire at the Brewster angle	455.383	331.579	−114.912
Air	0.0217	0.0092	2.3×10^{-11}
Compressor: 600 ℓ/mm, $L=1$ cm, 13.89°	−3567.68	5101.21	−10226
Prism pair: SF18	−45.567	−181.516	−331.184

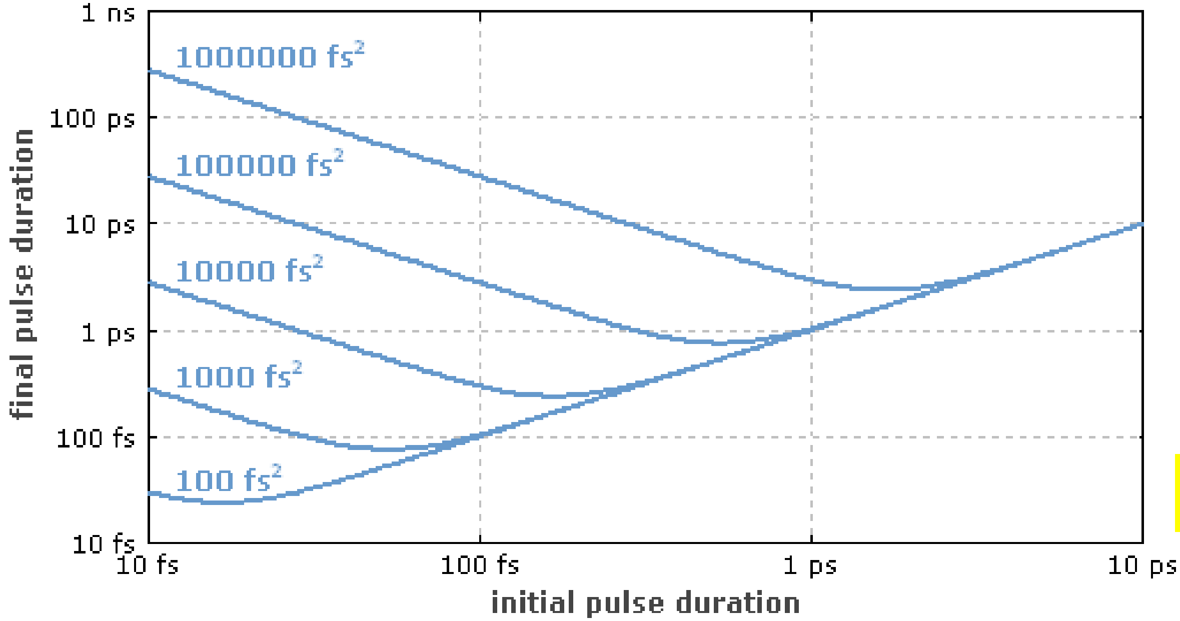
S Backus et al, Rev Sci. Inst. 69, 1207 (1998)

Dispersion cont.

If you start with a transform-limited Gaussian pulse of width τ_0, and have only second-order dispersion ϕ'', then the resulting pulse will be a Gaussian of width:

$$\tau_f = \tau_0 \sqrt{1 + \left(4\ln(2) \frac{\phi''}{\tau_0^2} \right)^2}$$

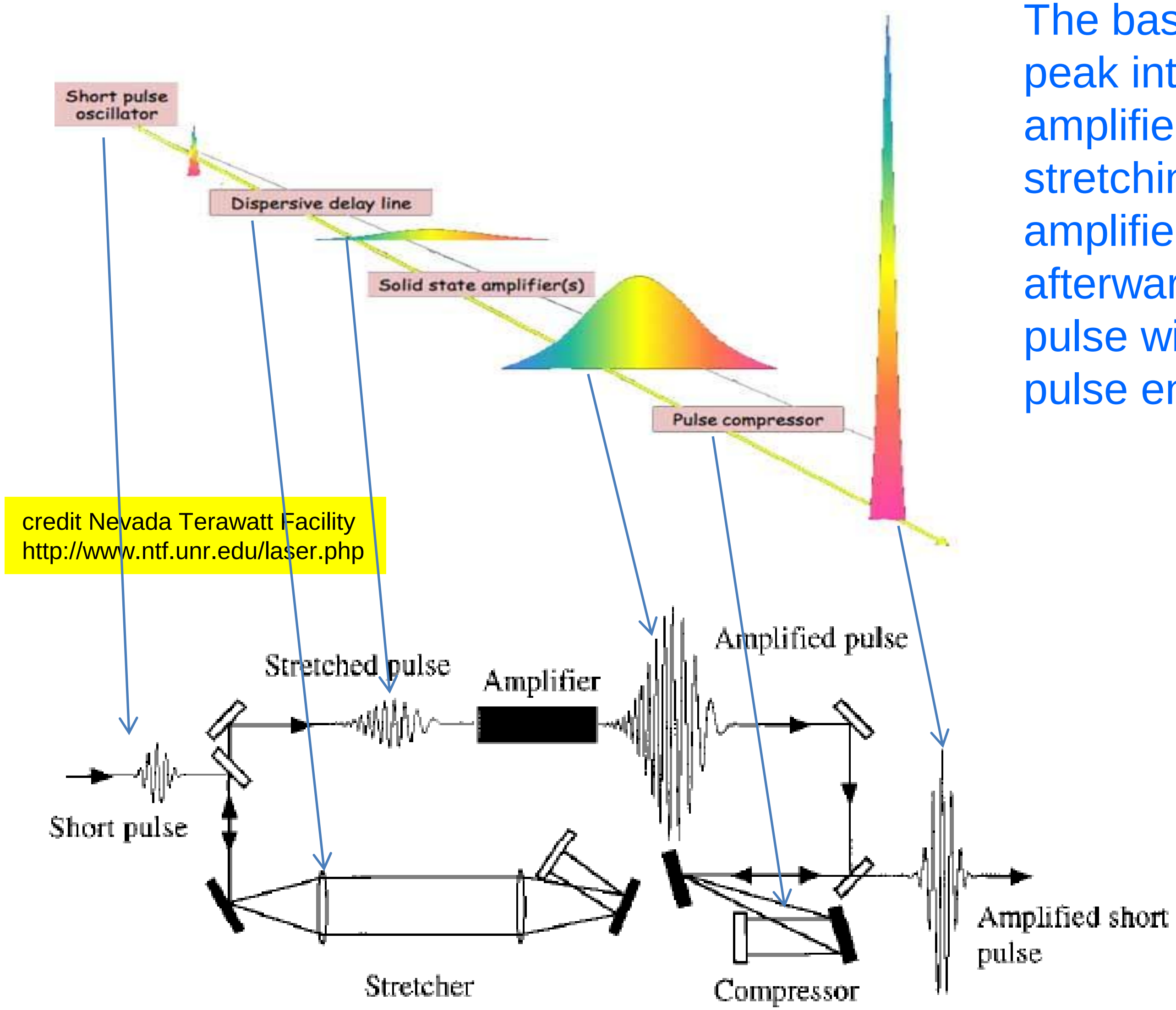
Homework: show this



credit: Ency of Laser Physics & Technology, RP Photonics

so a 100 fsec transform-limited pulse could pass through a 3 cm piece of fused silica (~1100 fs^2) and still be about 100 fsec, but a 10 fsec transform-limited pulse would come out longer than the 100 fsec pulse. In simple physical terms, why?

Chirped Pulse Amplification (CPA)

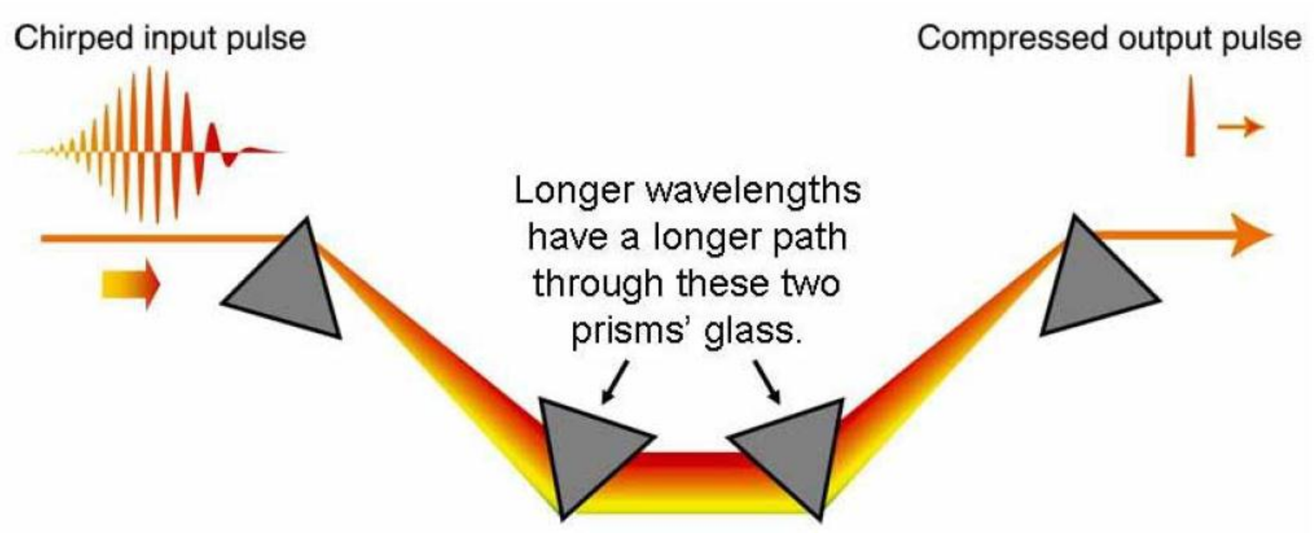


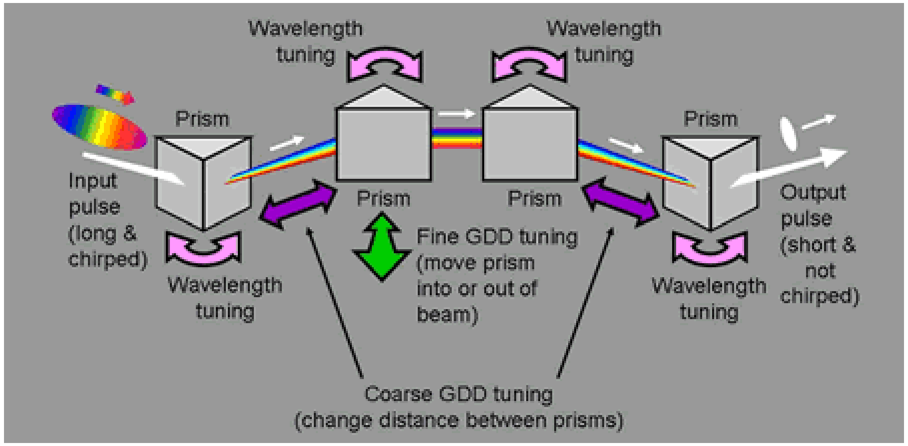
The basic idea is to keep the peak intensity low in the amplifier, by coherently stretching the pulse before the amplifier, then recompressing it afterwards to obtain the original pulse width with much higher pulse energy

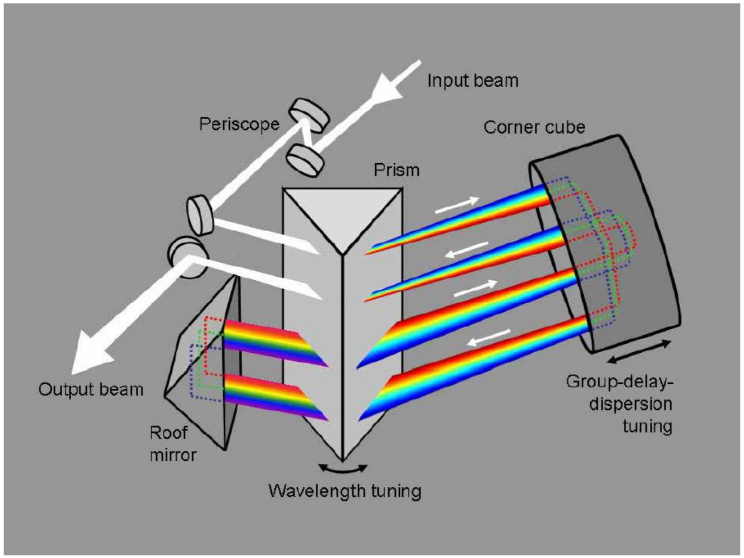
S Backus et al, Rev Sci. Inst. 69, 1207 (1998)

Prism Compressor

dispersive elements like prisms and gratings can be used to generate *negative* GDD and compensate material dispersion.

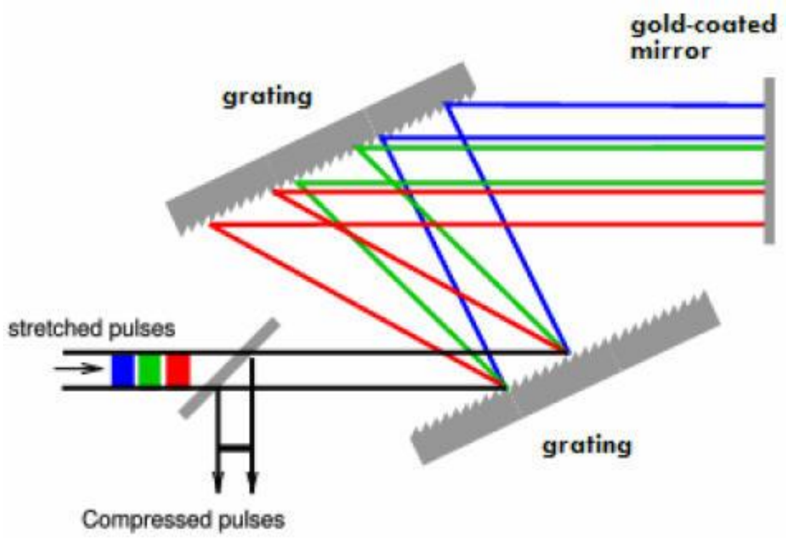






R. Trebino. swampoptics.com & Opt Exp 14, 10108 (2006)

Grating compressors



a much larger negative GDD can be achieved using gratings in the same length

red path length > *blue path length*

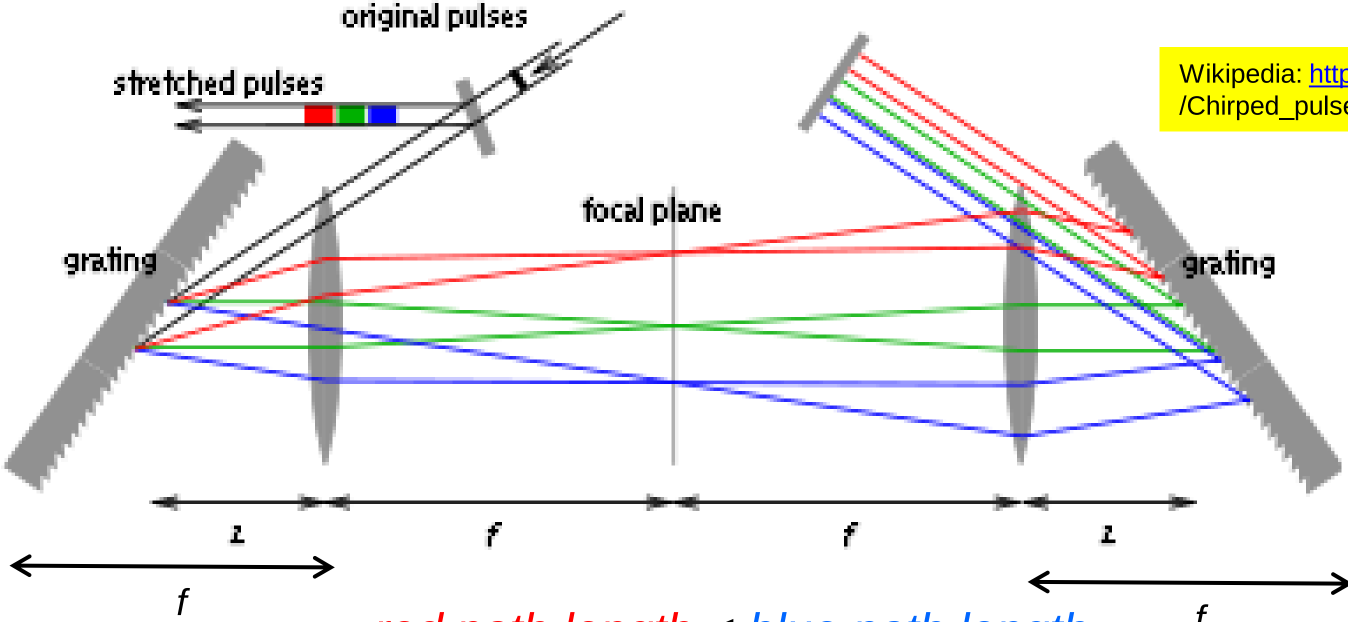
For CPA, we need to be able to generate large amounts of both positive and negative GDD, in order to stretch and recompress

We could stretch the pulse by using material dispersion, but then one also accumulates a lot of higher order dispersion. Absorption and distortion would also be issues.

Ruhman group.
http://chem.ch.huji.ac.il/sandy/Laser/Laser1.htm

Grating Stretcher

Wikipedia: http://en.wikipedia.org/wiki/Chirped_pulse_amplification

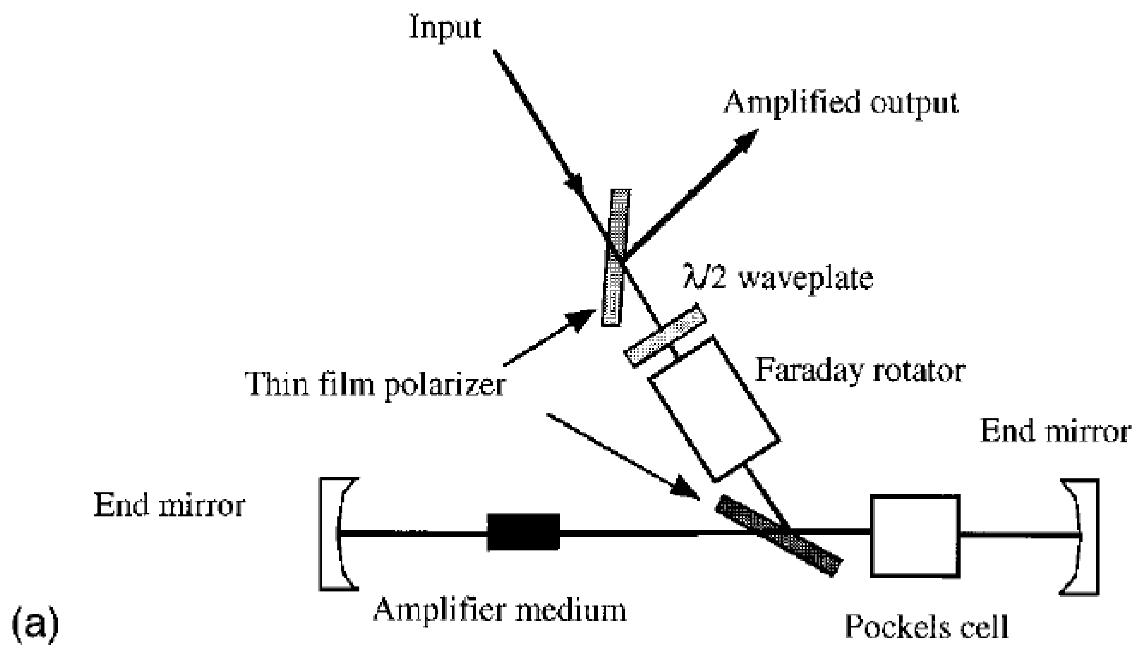


red path length < blue path length

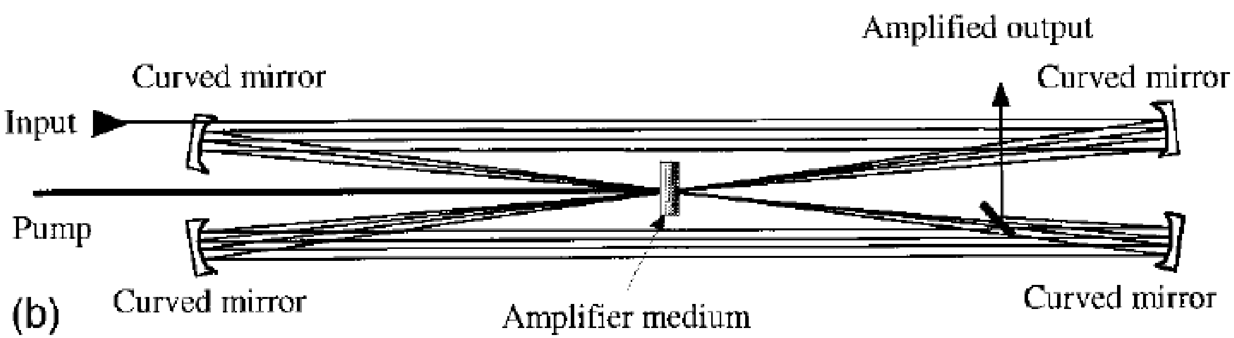
Imaging with a unity magnification telescope, with the gratings located within the focal planes, the effective length of the the compressor negative, and the dispersion is positive. $L_g=(2L-2f)<0$

NB the number of elements in both stretcher & compressor can be reduced by reflection at the mid-plane

Regenerative and multipass amplification



Regen
- single stage
- simpler alignment
- but more passes and more material in each pass
  - gain/output tradeofff



Multipass
- more stages
  - optimize each stage
- more complex alignment

S Backus et al, Rev Sci. Inst. 69, 1207 (1998)

A full Ti:Sapph CPA system

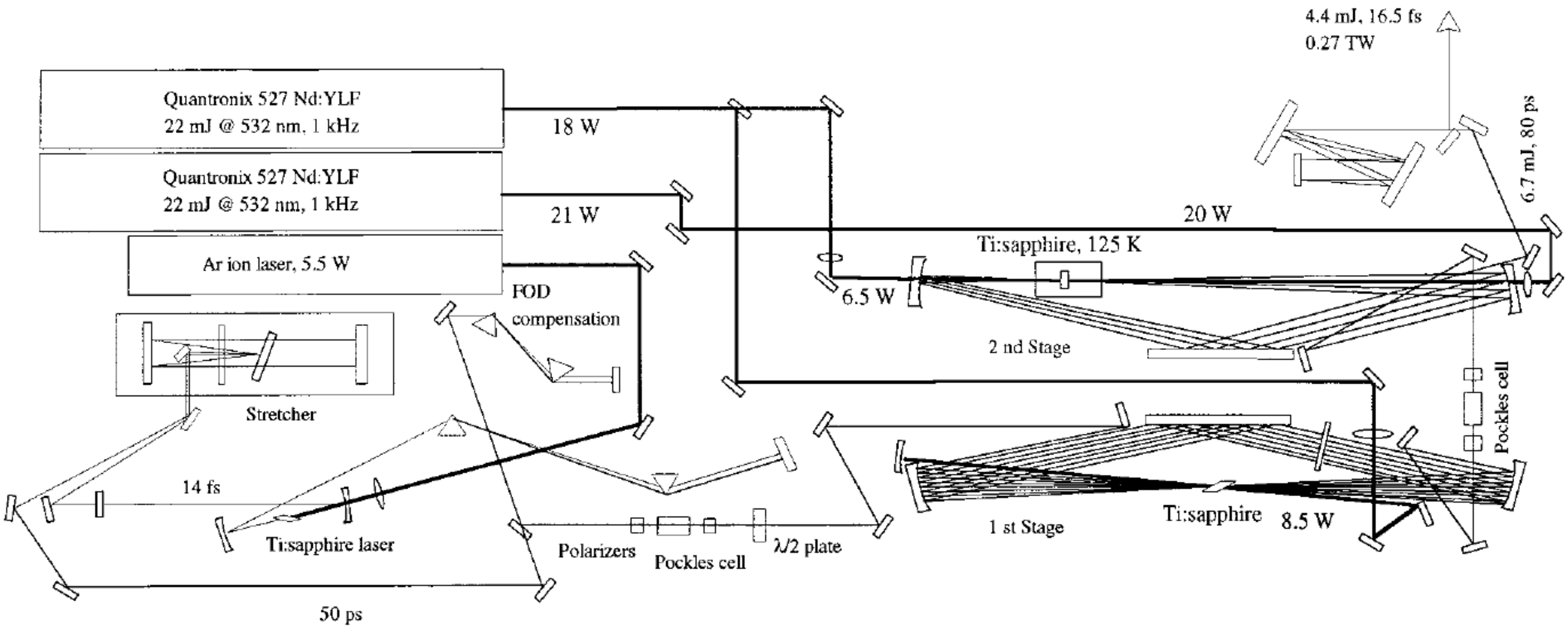


FIG. 7. Schematic diagram of a kHz repetition rate, 0.2 TW Ti:sapphire CPA system.

S Backus et al, Rev Sci. Inst. 69, 1207 (1998)

Extra Credit Project (2 people)

Do a study of a regenerative amplifier Ti:Sapph CPA system. Assume that the initial pulsewidth is 50 fsec, and that it makes 18 round-trips in the cavity. Choose a grating and optics that makes a reasonably-sized stretcher and compressor. Make reasonable estimates for the material dispersion encountered (Ti:Sapph crystal, Pockels Cell Crystal, Faraday Isolator…) and be sure to compensate (to second order) in the compressor. Present results to the class

Nonlinear Frequency Conversion

Start with the inhomogeneous wave equation

$$\frac{\partial^2 \mathscr{E}}{\partial z^2} - \frac{1}{c^2}\frac{\partial^2 \mathscr{E}}{\partial t^2} = \mu_0 \frac{\partial^2 \mathscr{P}}{\partial t^2}$$

The polarization term may be written:

$$\mathscr{P} = \varepsilon_0 \left[\chi^{(1)} \mathscr{E} + \chi^{(2)} \mathscr{E}^2 + \chi^{(3)} \mathscr{E}^3 + \ldots \right]$$

- At low intensities, the response is linear, and only the first term is important.
- Physically, the higher order terms arise from the anharmonicity of the electronic response in the crystal
- the χ^i are tensors: when you push an electron in the crystal lattice in the x-direction, it might induce a force in the y- or z-direction, with a frequency -dependent response

Trebino Ultrafast Optics Textbook & NLO Talk
http://frog.gatech.edu/prose.html

NLO cont.

Consider the second order term, with a single frequency

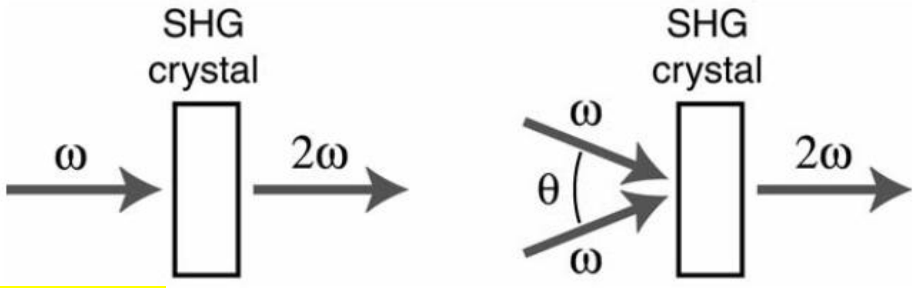
$$\mathscr{E}^2(t) = \tfrac{1}{4}E^2(t)\exp(2i\omega_1 t) + \tfrac{1}{2}E_1(t)E_1^*(t) + \tfrac{1}{4}E_1^{*2}\exp(-2i\omega_1 t)$$

so if χ^2 is nonzero, you will have fields at:

2ω: Second Harmonic Generation (SHG)

DC: Optical Rectification

Up to now, we have suppressed the spatial dependence, but both energy and momentum must be conserved



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NLO cont.

Consider two fields, including spatial phase:

$$\mathscr{E}(\vec{r},t) = \tfrac{1}{2}E_1(\vec{r},t)\,\exp[i(\omega_1 t - \vec{k}_1\cdot\vec{r})] + \tfrac{1}{2}E_2(\vec{r},t)\,\exp[i(\omega_2 t - \vec{k}_2\cdot\vec{r})] + \text{c.c.}$$

$$\mathscr{E}^2(\vec{r},t) = \tfrac{1}{4}E_1^2\exp[2i(\omega_1 t - \vec{k}_1\cdot\vec{r})]$$ Second Harmonic Generation (SHG)

$$+\ \tfrac{1}{2}E_1E_1^* + \tfrac{1}{4}E_1^{*2}\exp[-2i(\omega_1 t - \vec{k}_1\cdot\vec{r})]$$

$$+\ \tfrac{1}{4}E_2^2\exp[2i(\omega_2 t - \vec{k}_2\cdot\vec{r})] + \tfrac{1}{2}E_2E_2^*$$ Optical Rectification

$$+\ \tfrac{1}{4}E_2^{*2}\exp[-2i(\omega_2 t - \vec{k}_2\cdot\vec{r})]$$

$$+\ \tfrac{1}{2}E_1E_2\exp\{i[(\omega_1+\omega_2)t - (\vec{k}_1+\vec{k}_2)\cdot\vec{r}]\}$$ Sum Frequency Generation (SFG)

$$+\ \tfrac{1}{2}E_1^*E_2^*\exp\{-i[(\omega_1+\omega_2)t - (\vec{k}_1+\vec{k}_2)\cdot\vec{r}]\}$$

$$+\ \tfrac{1}{2}E_1E_2^*\exp\{i[(\omega_1-\omega_2)t - (\vec{k}_1-\vec{k}_2)\cdot\vec{r}]\}$$ Difference Freq Generation (DFG)

$$+\ \tfrac{1}{2}E_1^*E_2\exp\{-i[(\omega_1-\omega_2)t - (\vec{k}_1-\vec{k}_2)\cdot\vec{r}]\}$$

there are fields at every combination of ω_1 and ω_2: SFG, DFG, SHG, & Optical Rectification. But remember, this is the polarization wave, light at any of these frequencies will only see gain if it stays in phase with the polarization.

Trebino Ultrafast Optics Textbook & NLOTalk
http://frog.gatech.edu/prose.html

Phase matching, general case

Energy conservation requires:

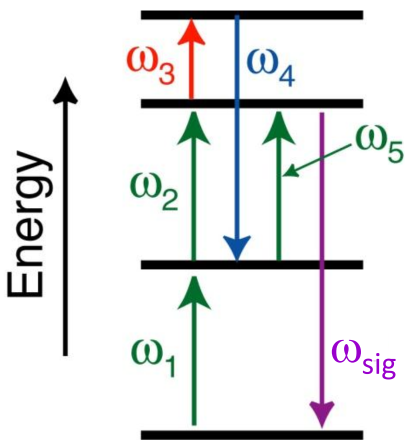
$$\omega_{sig} = \omega_1 + \omega_2 + \omega_3 - \omega_4 + \omega_5$$

so the wavevector for this light is

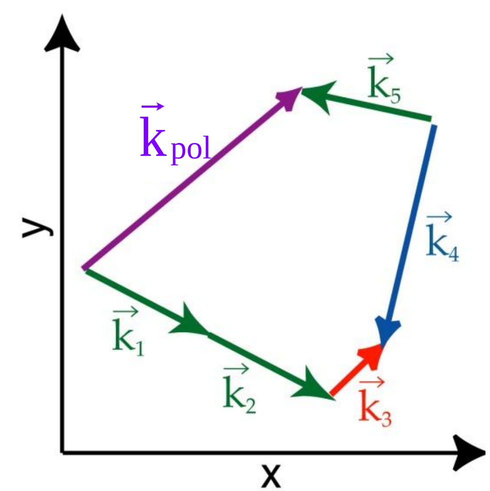
$$k_{sig} = \omega_{sig} / c = \omega_{sig} \, n(\omega_{sig}) / c_0$$

But the wavevector of the polarization is the vector sum of the wavevectors contributing to the process, and the two are not in general equal

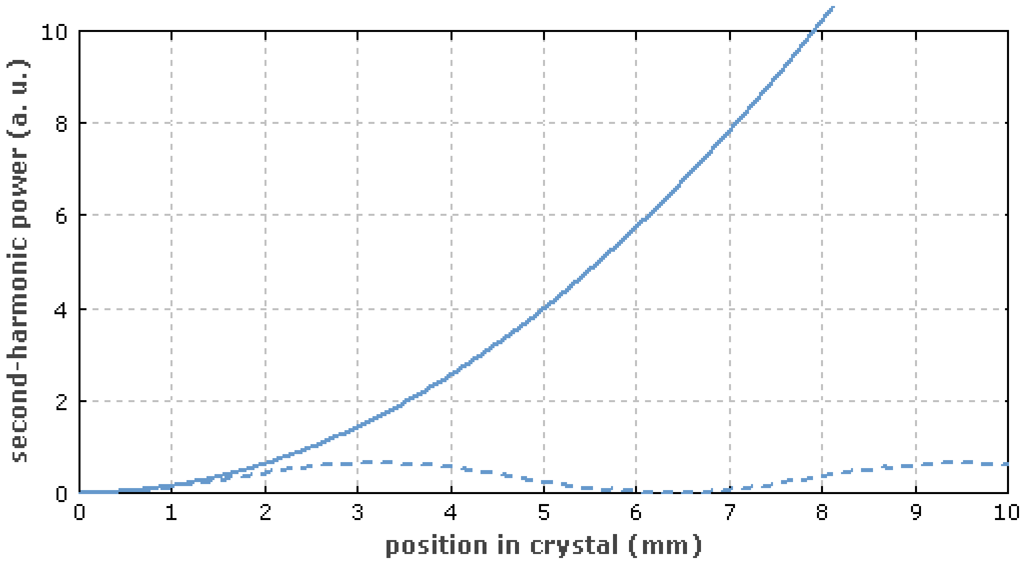
$$\vec{k}_{pol} = \vec{k}_1 + \vec{k}_2 + \vec{k}_3 - \vec{k}_4 + \vec{k}_5$$



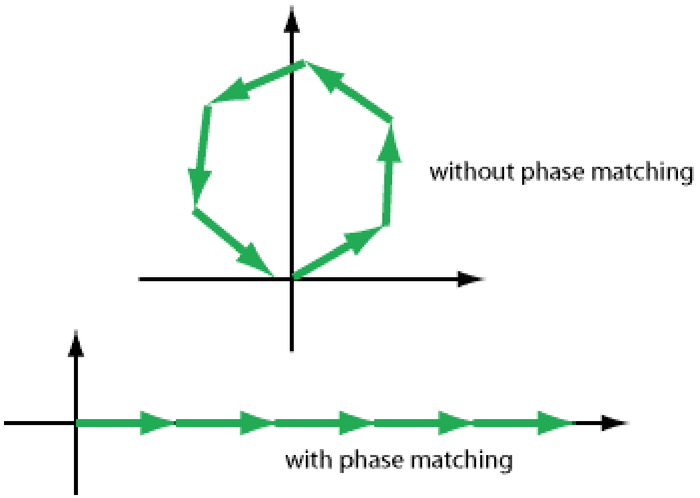
phase matching is requiring conservation of momentum as well as energy



Phase matching cont.



frequency doubling in LBO, phase-matched(solid) and non-phase-matched (dotted)

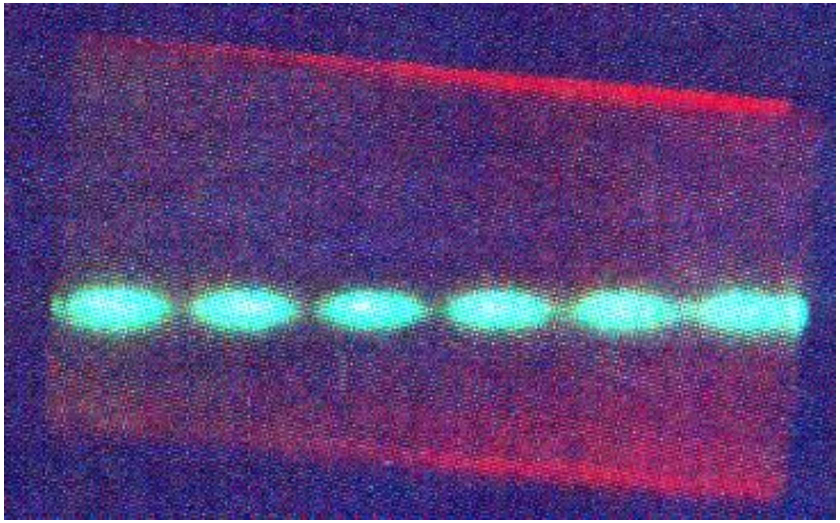


In the non-phase-matched case, the signal intensity will oscillate, the energy being coupled back and forth between pump and signal.

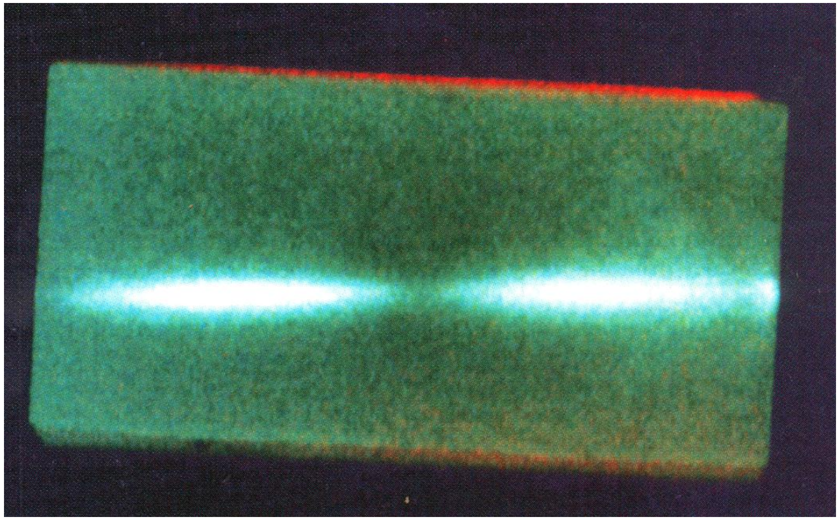
credit: Ency of Laser Physics & Technology, RP Photonics

Phase matching cont.

Large Δk



Small Δk



A phase mismatch is a beating between k_{sig} and k_{pol}.
$2\pi/\Delta k$ is the beat wavelength

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http://frog.gatech.edu/prose.html

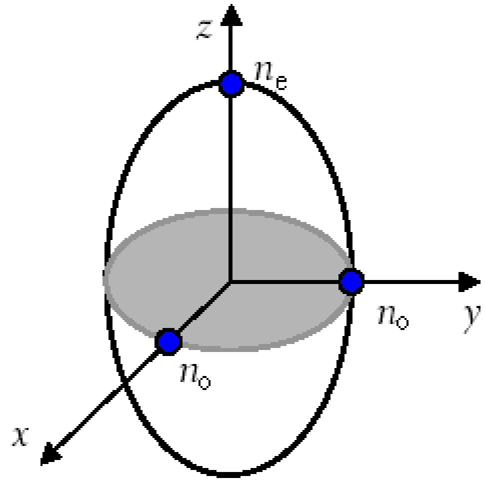
Birefringent Phase Matching

In the absence of dispersion phase matching always occurs e.g:

$$\frac{2\pi\omega_1 n(\omega_1)}{c} \pm \frac{2\pi\omega_2 n(\omega_2)}{c} = \frac{2\pi(\omega_1 \pm \omega_2) n(\omega_1 \pm \omega_2)}{c}, \text{ if } n(\omega) = \text{constant}$$

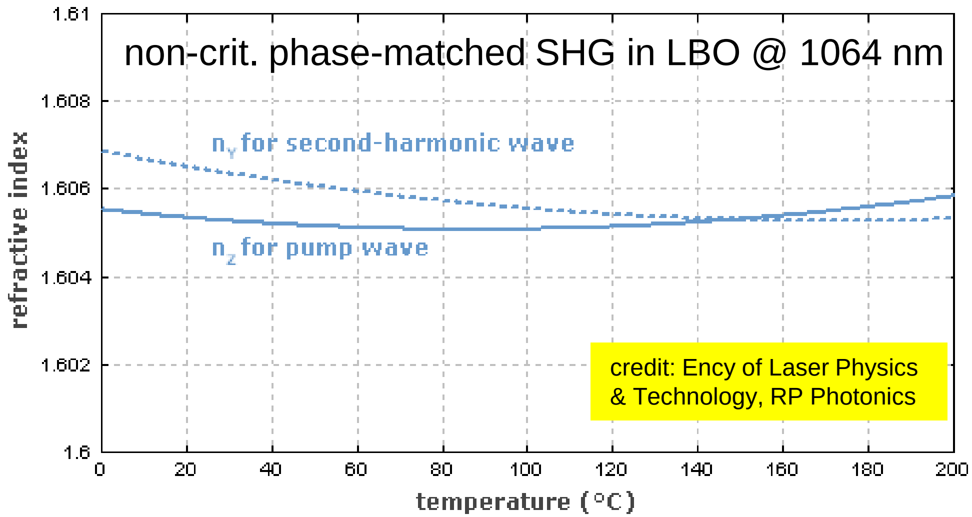
where n is the refractive index

In Birefringent materials, ordinary and extraordinary rays have different *n(ω)* , and their difference on the direction of propagation in the crystal, relative to the optic axis(es). This can be exploited in a number of ways achieve the phase-matching condition.



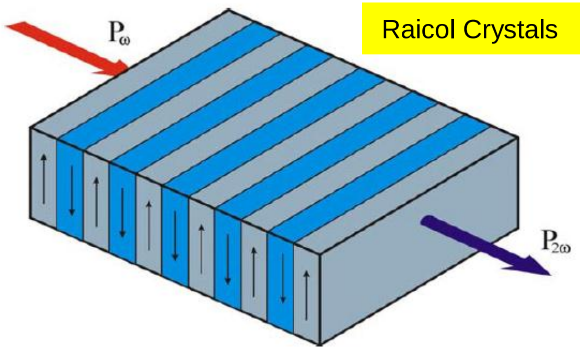
Critical phase matching: use polarization & direction to meet phase-matching condition

Non-critical phase-matching: propagate perpendicular to optic axis, temperature-tune to compensate chromatic dispersion

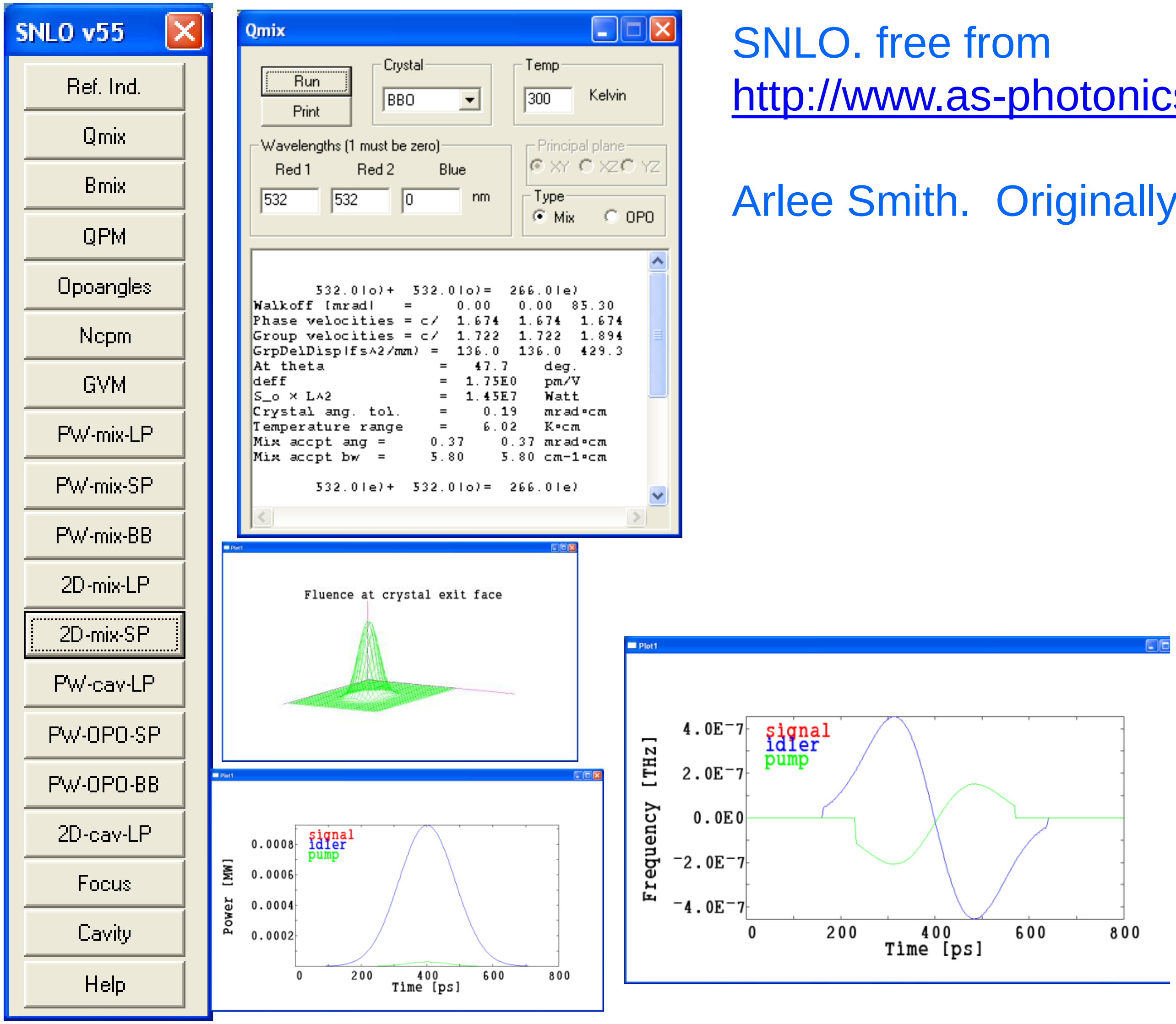


Non-collinear phase-matching (short pulses): matching pulse group velocities

Quasi-phase matching: periodically compensate dephasing by alternately poling the material on a short (10s of um) spatial scale.



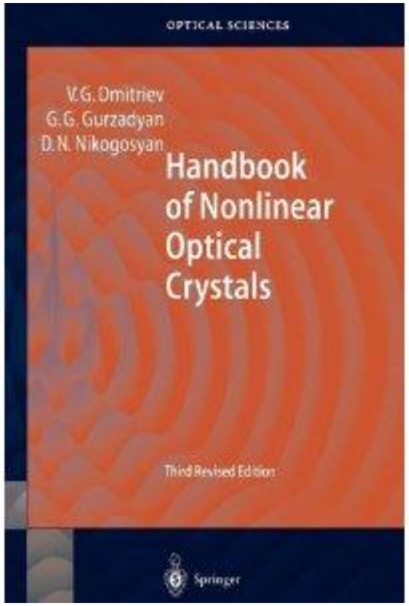
NLO useful resources



SNLO. free from http://www.as-photonics.com/snlo

Arlee Smith. Originally developed at Sandia

Handbook of Nonlinear Optical Crystals (Springer Series in Optical Sciences)



Extra Credit Project(2 people)

Download SNLO and use it to make a study of frequency-doubling a laser that produces 5 Watts of power at 1064 nm wavelength, with a pulse rate of 80 MHz, and a pulse width of 10 picoseconds. Optionally, try doubling a transform-limited100 fsec, 800 nm pulse which has an energy of 100 uJ. Present results to class.

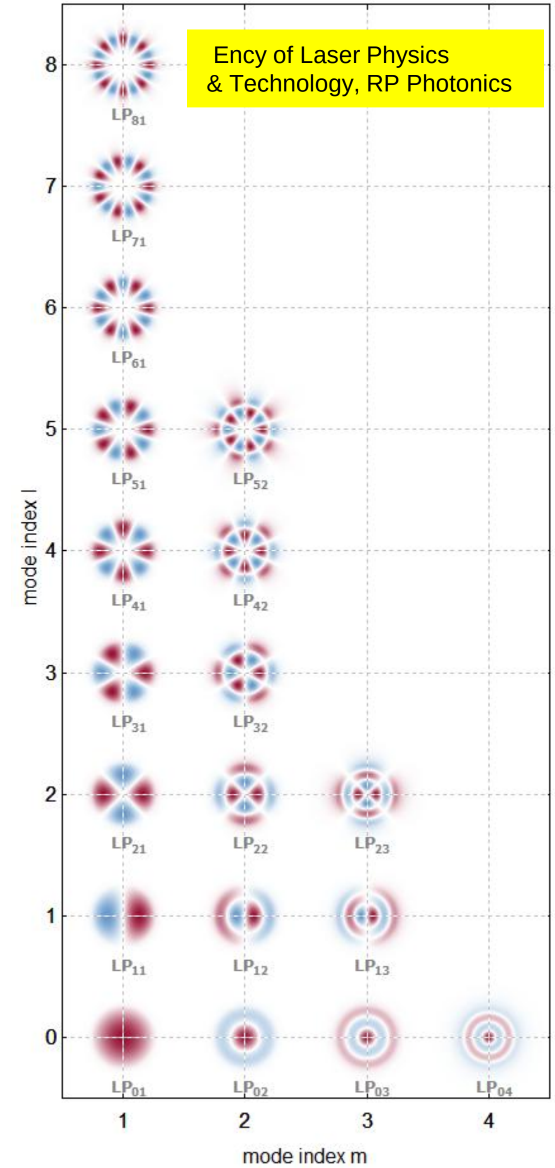
Fiber Lasers

Advantages

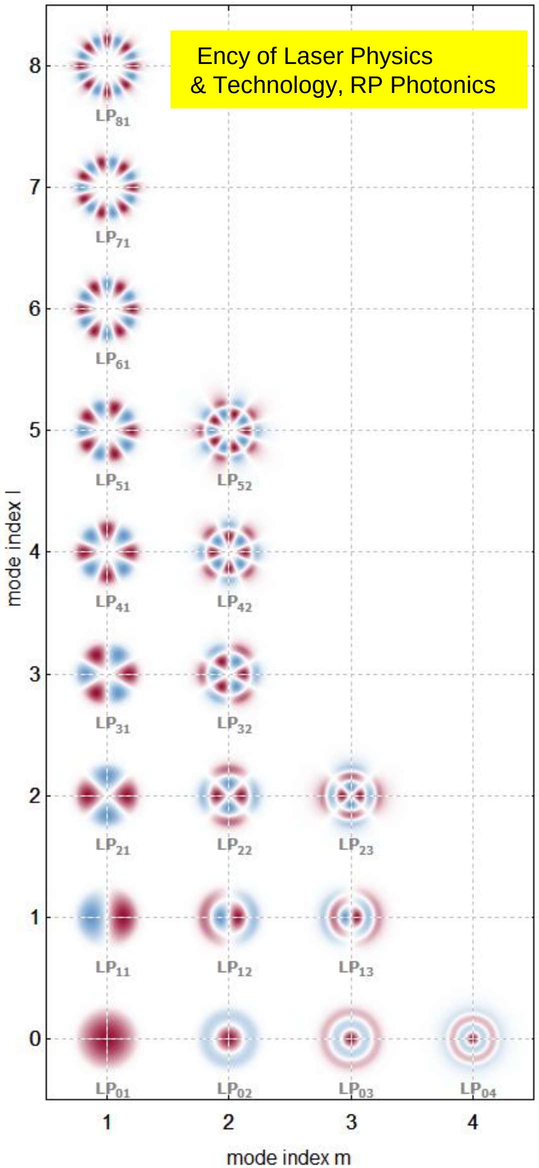
- mode quality
- low-noise
- compactness & reliability
- insensitivity to environment
- efficiency
    - diode pumped, low quantum defect
    - good thermo-optical properties
        - high surface to volume ratio

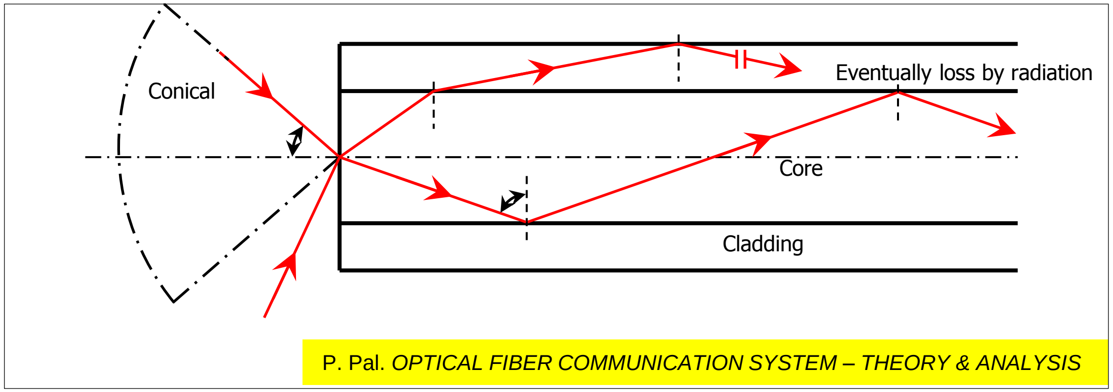
“Issues”

- Peak Power
    - core size
    - damage threshold
    - nonlinearities
        - can also be an advantage
            - Raman amplifiers
            - supercontinuum generation



propagation modes for a step-index fiber





$$\mathrm{NA} = \frac{1}{n_0}\sqrt{n_{core}^2 - n_{clad}^2} = \sin\theta_{\max}$$

$\theta_{\max}$ is the half angle of the acceptance cone for guided light

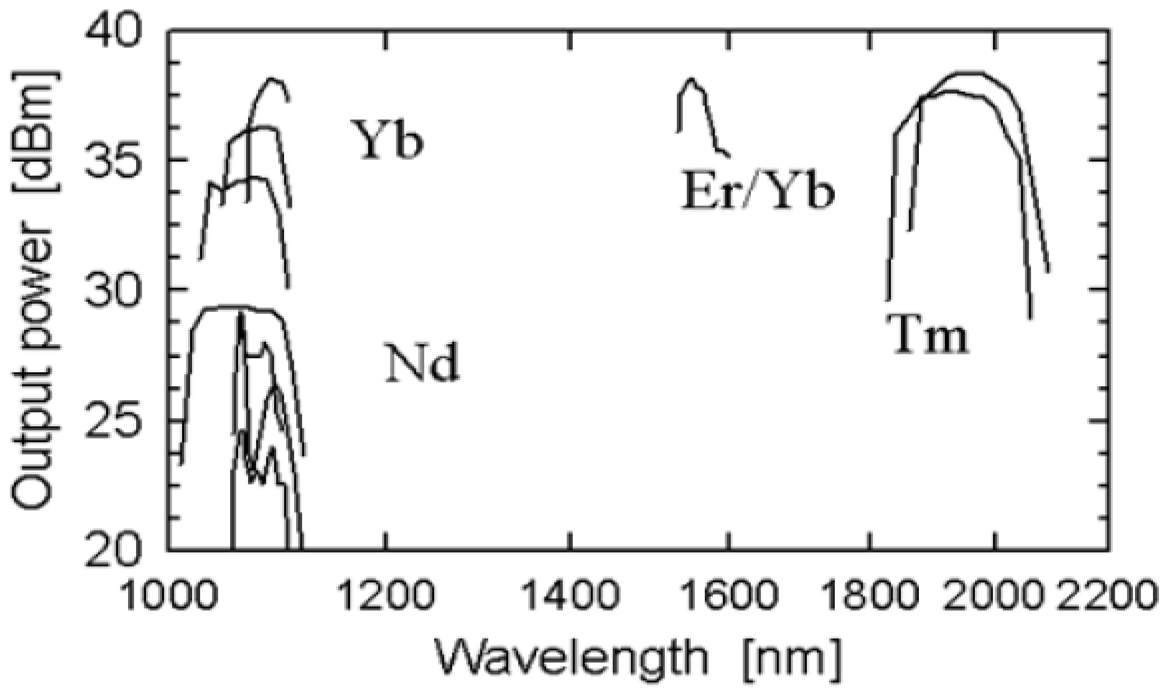
n_0 is the index of refraction of launch medium, usually air, $n_0 \cong 1$

$$V = \frac{2\pi}{\lambda} a\mathrm{NA} = \frac{2\pi}{\lambda n_0} a\sqrt{n_{core}^2 - n_{clad}^2}$$

a is the radius of the core

single mode operation for $V < 2.405$
if λ=1064 nm and Δn=0.005, then
NA=0.12 & <u>a<3.3 um</u>

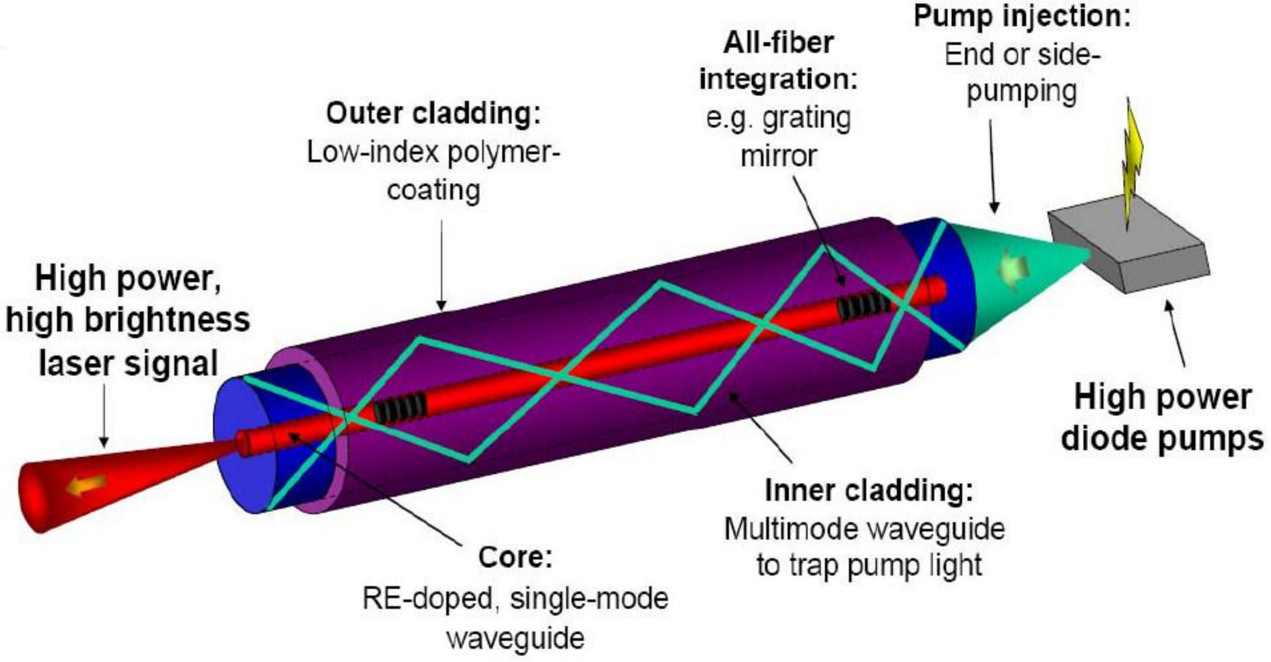
Fiber Laser Gain Materials



- Er and Yb most useful at high power (plot is ca 2008)
- Tm becoming more important as 2 um becomes more interesting
  - in AP, ESASE
  - High Harmonic Generation

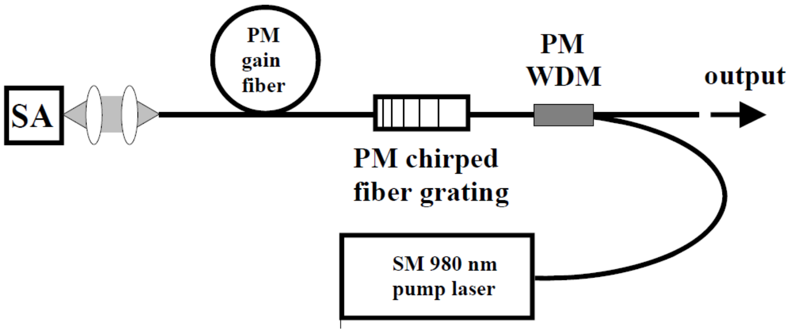
pic: David Richardson via Yuelin Li

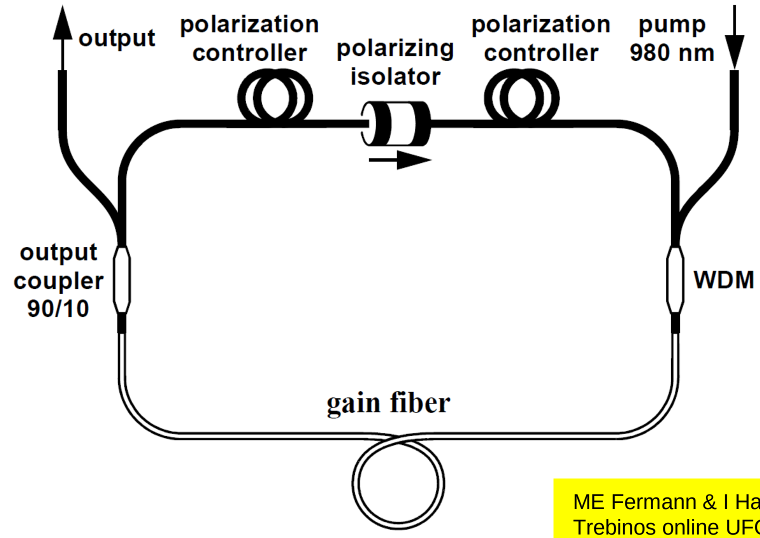
Cladding pumped fiber lasers



credit David Richardson via Yuelin Li USPAS 08

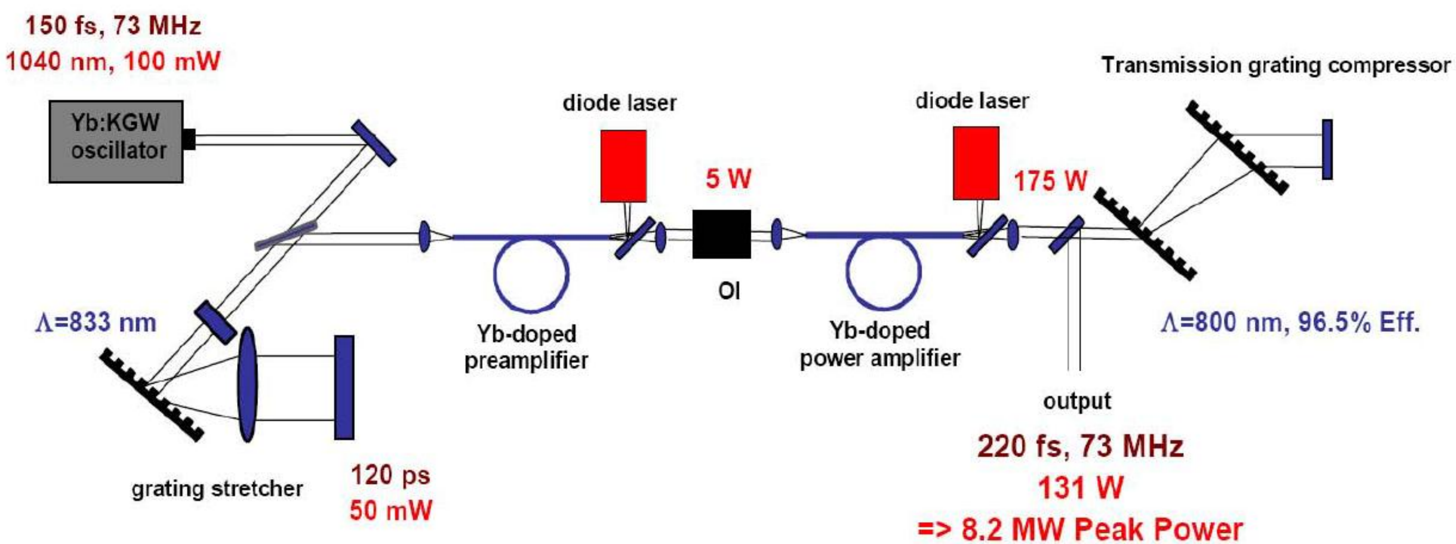
Mode locked Fiber Lasers:





ME Fermann & I Hartl in Trebinos online UFO book, ch 8

Fiber CPA systems

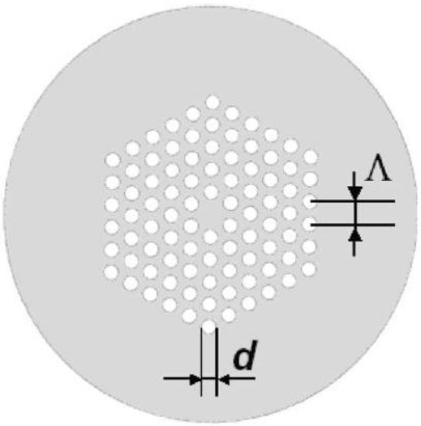


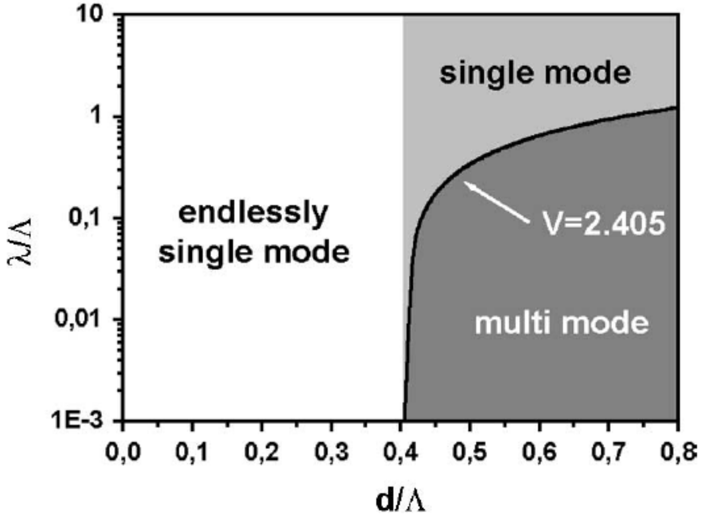
Roeser et al., Opt. Lett. 30, 2754 (2005)

Fiber Lasers cont.

Pushing Back the peak power frontier

- CPA – keeps the peak power low
- Large Mode Area Fibers:
    - lower NA -> larger core, but weaker guidance
    - ‘effectively single mode’ – a few higher order modes allowed, but are lossy and weakly coupled to the lowest order mode
- Photonic crystal fibers: HOMs lie in the photonic bandgap





J. Limpiert *et al* IEEE Xplore 12, 233 (2006)