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Laser applications for accelerators

Laser Basics

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USPAS 2008 Summer Session, Annapolis,
June 23-27, 2008

U.S. Department
of Energy

UChicago ▸
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Office of Science
U.S. DEPARTMENT OF ENERGY

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Content

- Laser and accelerator history
- Map of laser application in accelerators
- Laser basics
  - Rate equations
  - Laser configurations
  - Gaussian beam optics and ABCD law
  - Laser cavity and laser modes
- Laser configurations
  - Mode-lokcing and q-switch
  - MOPA
  - CPA and dispersion
- Laser materials
- Other lasers
  - Semiconductor lasers
  - Fiber lasers
- Frequency conversion and short wavelength lasers

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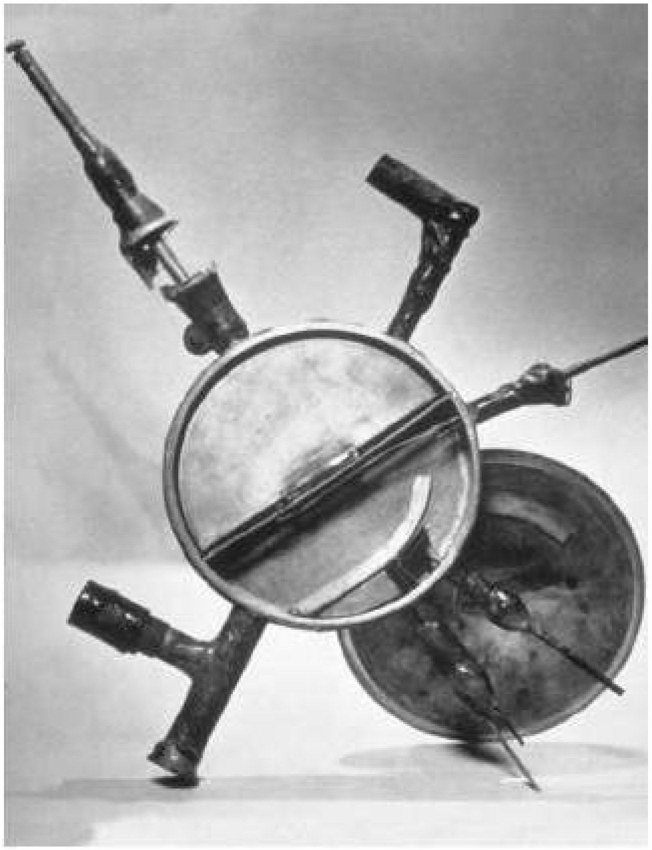
Lasers and accelerators at birth

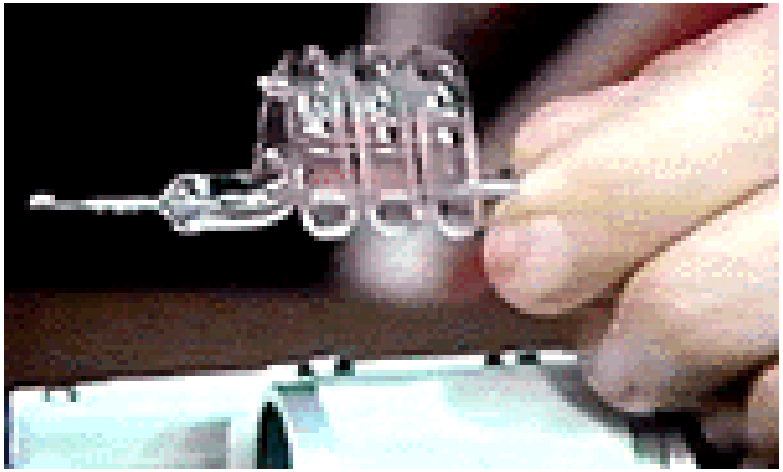
Ancient: a cave man's bow

…………………

1929, Cyclotron, Lawrence

1939, Nobel Prize, Lawrence





Ancient: Let there be light

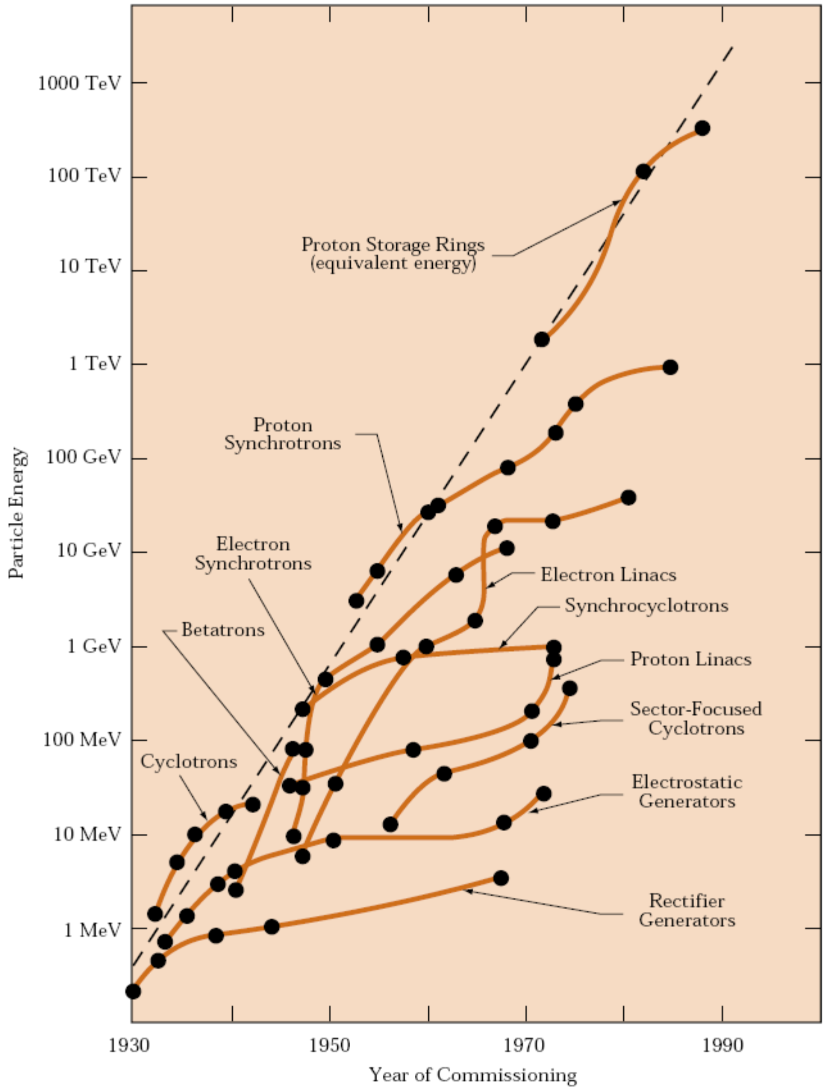
……………………..

1917, theory of stimulated radiation by Einstein

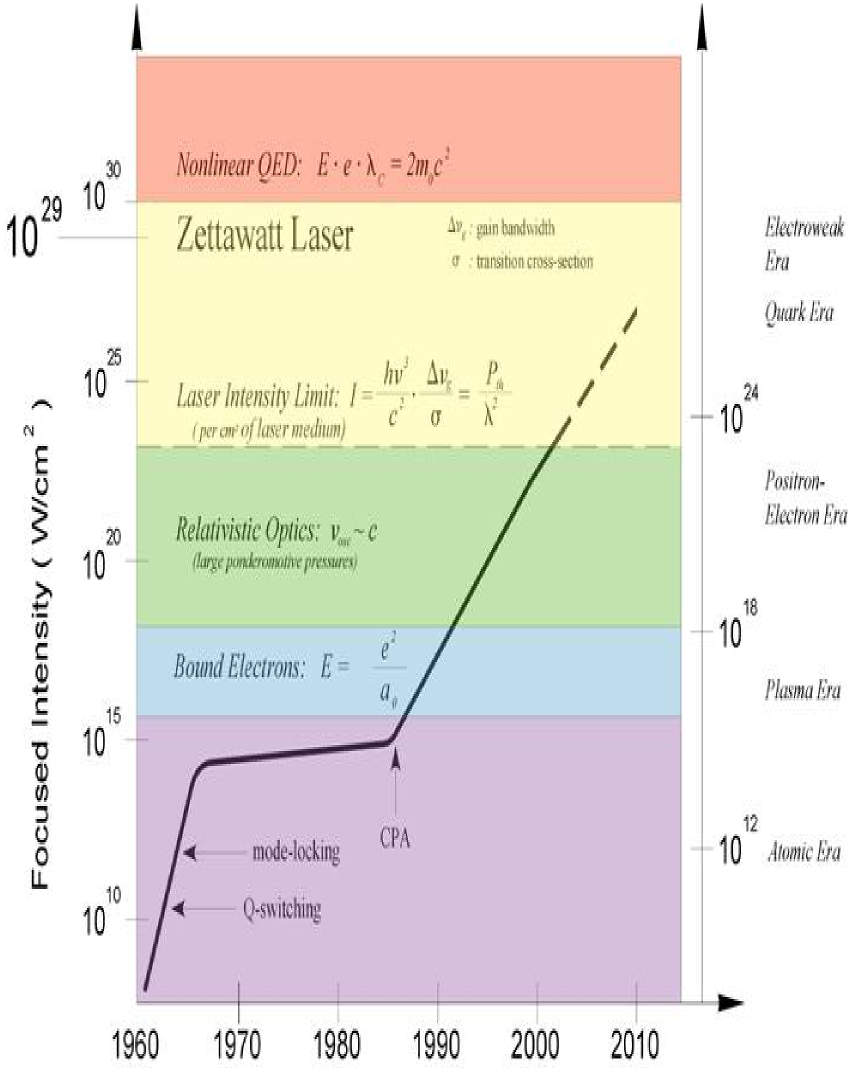
1960, flash-lamp pumped ruby, Dr. Mainman

1964, Nobel Prize, Towne, Basov, and Prokhorov

Today’s lasers and accelerators
Aiming for higher energy/intensity and better control



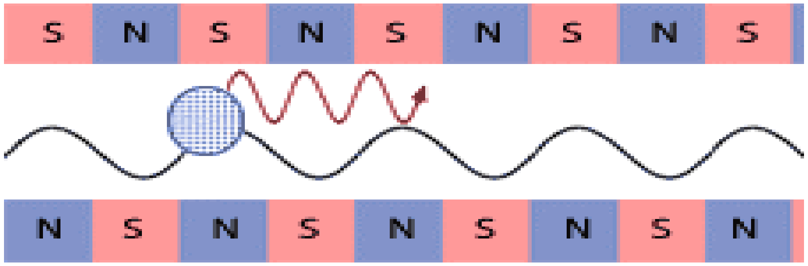
(Panofsky, http://www.slac.stanford.edu/pubs/beamline)

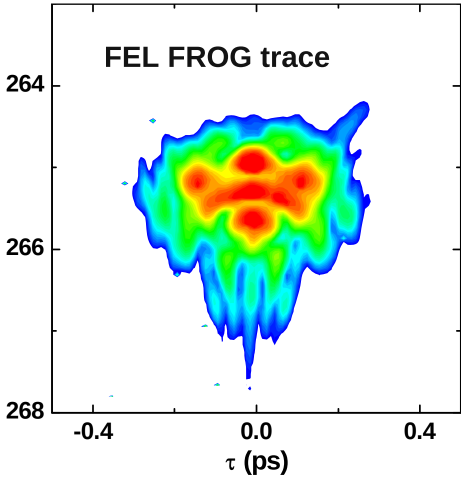


(http://www.eecs.umich.edu/CUOS)

Newest developments

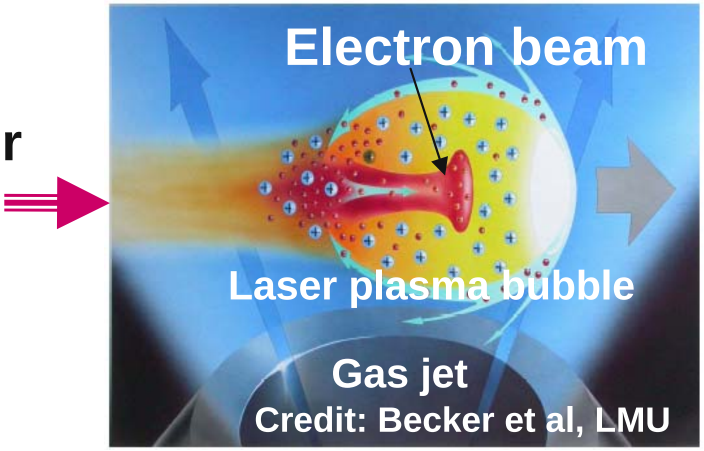
- **Accelerator-generated lasers: a free-electron laser**



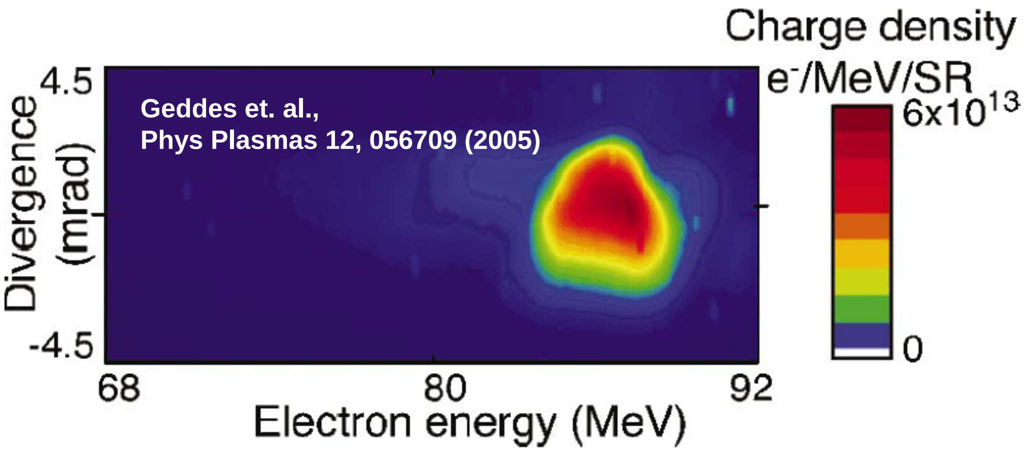


- **Laser as an accelerator: a compact accelerator**

Laser



Credit: Becker et al, LMU



**Geddes et. al.,
Phys Plasmas 12, 056709 (2005)**

S.P.D. Mangles et al. Nature 431, 535 (2004); C.G.R. Geddes et al. Nature 431, 538 (2004); J. Faure et al. Nature 431, 541 (2004)

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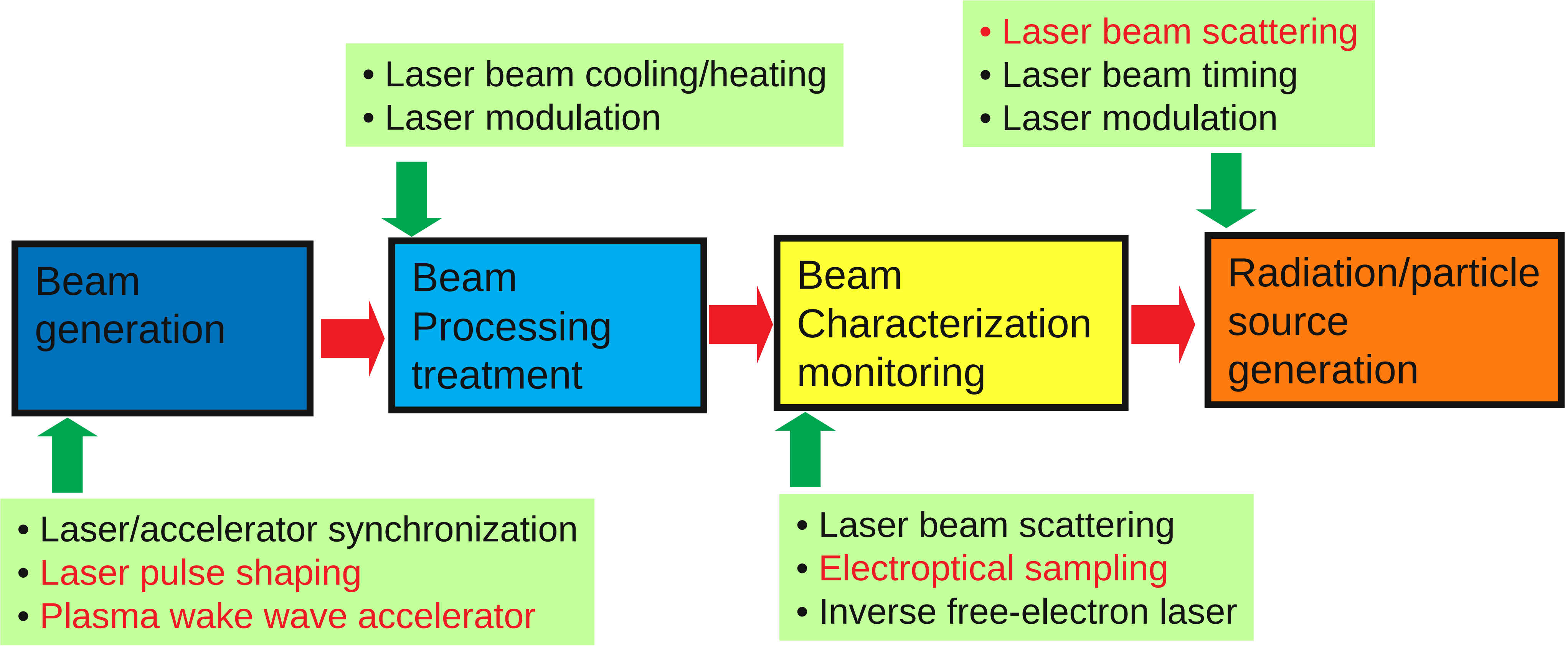
A map for laser applications in accelerators



- Laser beam cooling/heating
- Laser modulation

- Laser beam scattering
- Laser beam timing
- Laser modulation

Beam generation

Beam Processing treatment

Beam Characterization monitoring

Radiation/particle source generation

- Laser/accelerator synchronization
- Laser pulse shaping
- Plasma wake wave accelerator

- Laser beam scattering
- Electroptical sampling
- Inverse free-electron laser

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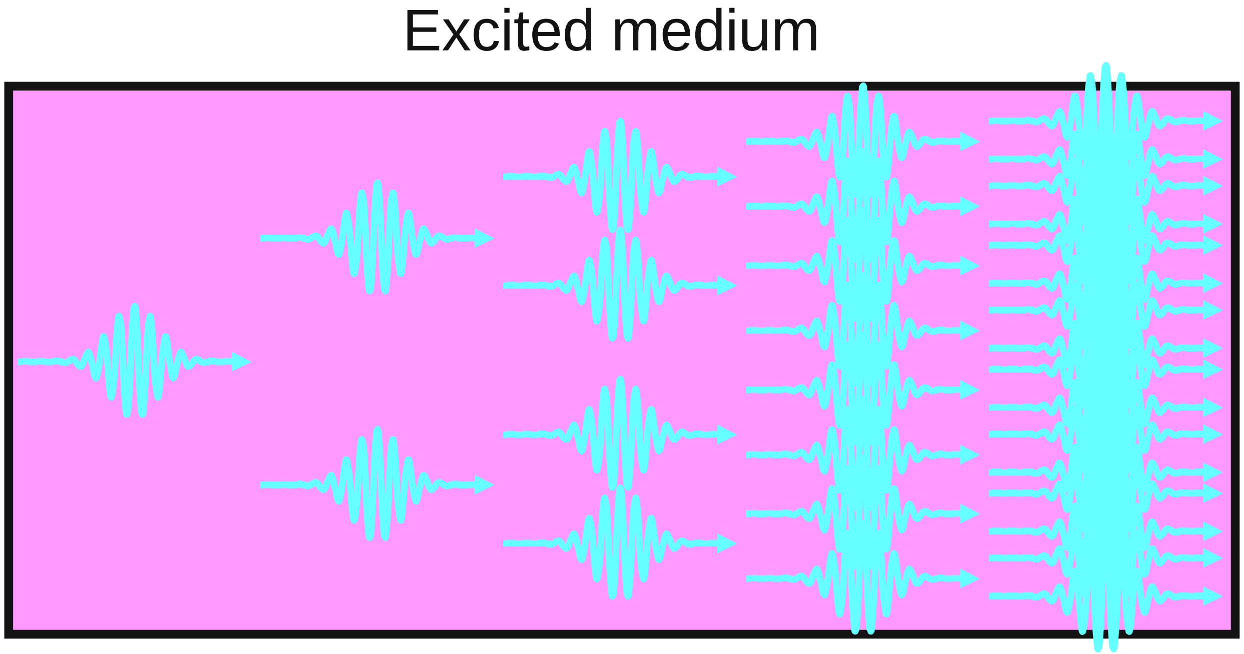
Laser

Light Amplification by Stimulated Emission of Radiation

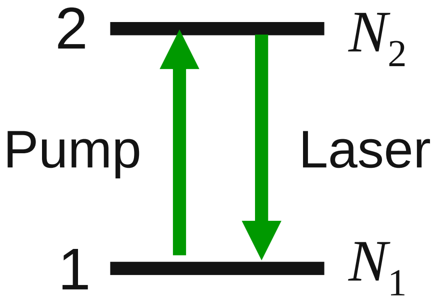
If a medium has many excited molecules, one photon can become many.



This is the essence of the laser. The factor by which an input beam is amplified by a medium is called the gain and is represented by G.

Credit: R. Trebino

Rate equations for a two-level system



Rate equations for the densities of the two states:

Absorption   Stimulated emission   Spontaneous emission

$$\frac{dN_2}{dt} = BI(N_1 - N_2) - AN_2$$

Pump intensity

$$\frac{dN_1}{dt} = BI(N_2 - N_1) + AN_2$$

If the total number of molecules is N:

$$N \equiv N_1 + N_2$$

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

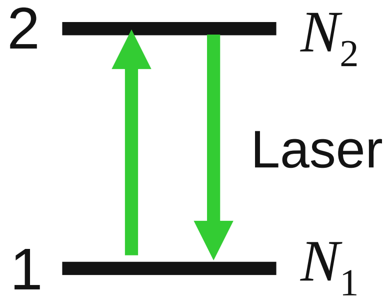
$$\Rightarrow \quad \frac{d\Delta N}{dt} = -2BI\Delta N + 2AN_2$$

$$2N_2 = (N_1 + N_2) - (N_1 - N_2)$$
$$= N - \Delta N$$

$$\Rightarrow \quad \frac{d\Delta N}{dt} = -2BI\Delta N + AN - A\Delta N$$

Credit: R. Trebino

Why inversion is impossible in a two-level system



$$\frac{d\Delta N}{dt} = -2BI\Delta N + AN - A\Delta N$$

In steady-state: $0 = -2BI\Delta N + AN - A\Delta N$

$$\Rightarrow (A+2BI)\Delta N = AN$$

$$\Rightarrow \Delta N = AN/(A+2BI)$$

$$\Rightarrow \Delta N = N/(1+2BI/A)$$

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

where: $I_{sat} = A/2B$

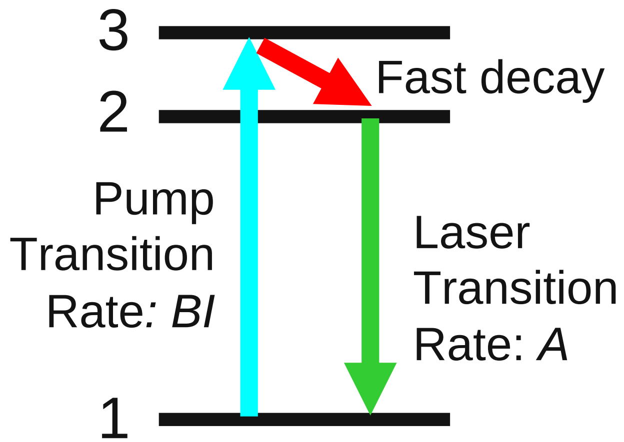
I_{sat} is the **saturation intensity**.

ΔN is always positive, no matter how high I is!

It’s impossible to achieve an inversion in a two-level system!

Credit: R. Trebino

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.

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

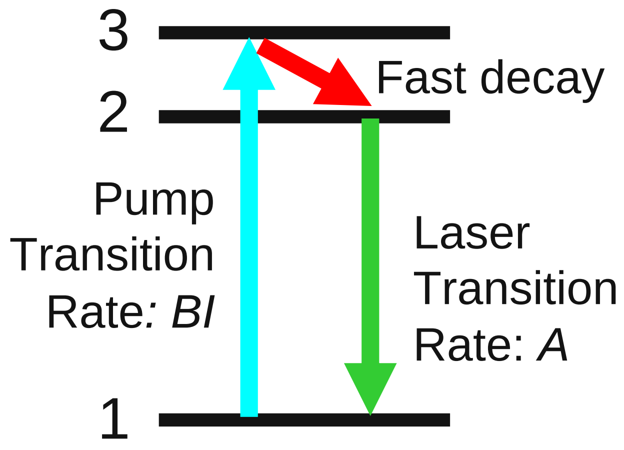
$$2N_2 = N - \Delta N$$

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

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

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: $I_{sat} = A/B$

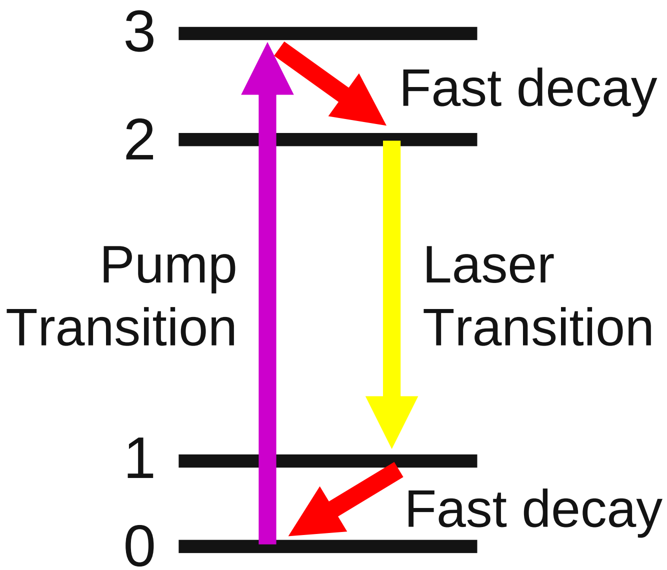
I_{sat} is the **saturation intensity**.

Now if $I > I_{sat}$, ΔN is negative!

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

Credit: R. Trebino

Rate equations for a four-level system



Now assume the lower laser level 1 also rapidly decays to a ground level 0.

As before: $$\frac{dN_2}{dt} = BIN_0 - AN_2$$

The total number of molecules is N:

$$N \equiv N_0 + N_2$$

$$N_0 = N - N_2$$

$$\frac{dN_2}{dt} = BI(N - N_2) - AN_2$$

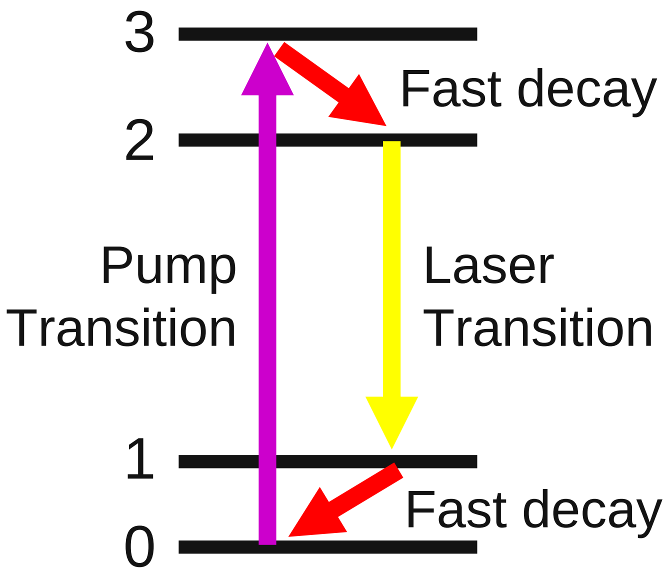
Because $N_1 \approx 0,\quad \Delta N \approx -N_2$

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

At steady state: $$0 = BIN + BI\,\Delta N + A\Delta N$$

Credit: R. Trebino

Population inversion in a four-level system (cont'd)



$$0 = BIN + BI\Delta N + A\Delta N$$

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

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

$$\Rightarrow \quad \Delta N = -(BIN/A)/(1 + BI/A)$$

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

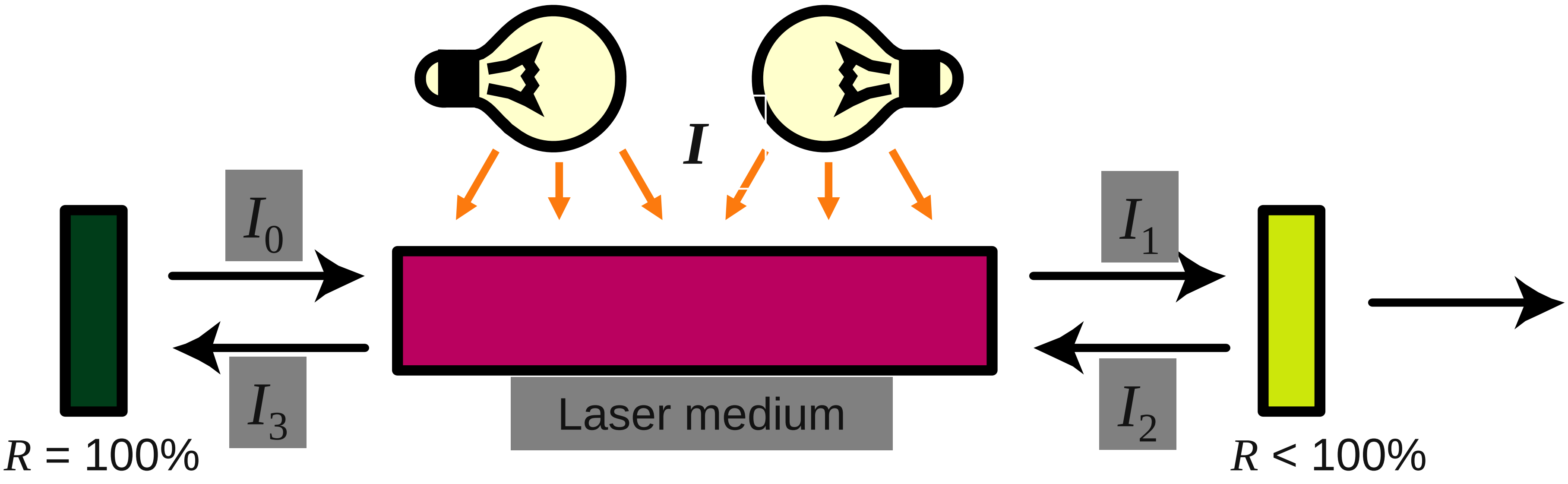
where: $I_{sat} = A/B$

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

Now, ΔN is negative—always!

Credit: R. Trebino

How to build a laser



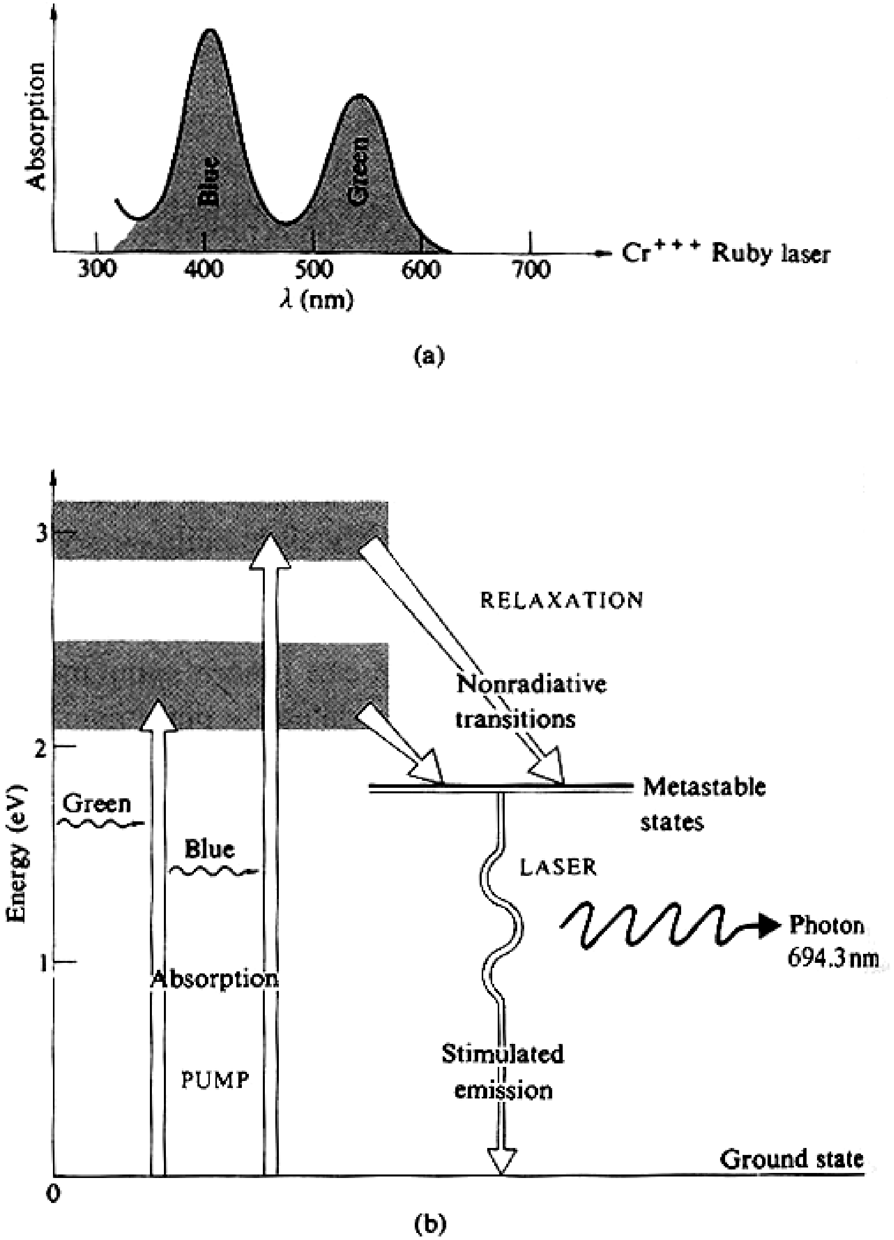
- Laser medium
  - Depends on wavelength, pulse duration, power
- Pump it: ASE
  - Multimode in time and space
- Add resonator: laser oscillation
  - Mode selection

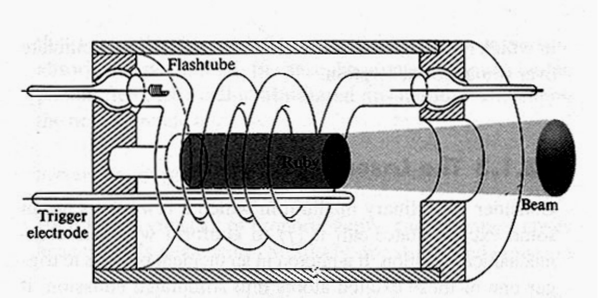
Credit: R. Trebino

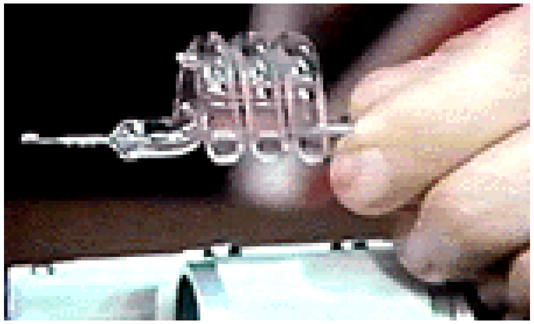
The historic ruby laser

Invented in 1960 by Ted Maiman at Hughes Research Labs, it was the first laser.

Ruby is a three-level system, so you have to hit it hard.







Credit: R. Trebino

Helmholtz Equation: Gaussian beam optics

Wave equation

$$\left(\nabla^2 - \frac{n^2}{c^2}\frac{\partial^2}{\partial t^2}\right)E(x,y,z,t)=0$$

$$E(x,y,z,t)=A(x,y,z)e^{i(k_z z-\omega t)}$$

$$\left(\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial x^2}+\cancel{\frac{\partial^2}{\partial z^2}}\right)A-\cancel{k_z^2}A+i2k_z\frac{\partial}{\partial z}A+\cancel{\frac{n^2\omega^2}{c^2}}A=0$$

Paraxial condition

$$\frac{\partial^2}{\partial z^2}A<<\frac{\partial}{\partial z}A,\quad k_z^2=\frac{n^2\omega^2}{c^2}=n\frac{2\pi}{\lambda}$$

Paraxial Helmholtz equation

$$\left(\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}\right)A+i2k_z\frac{\partial}{\partial z}A=0$$

Gaussian beam optics

Paraxial Helmholtz equation

$$\left(\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}\right)A+i2k_z\frac{\partial}{\partial z}A=0$$

Fourier transform

$$a(k_x,k_y,z)=\iint A(x,y,z)e^{-i(k_x x+k_y y)}dxdy$$

$$\rightarrow A(x,y,z)=\frac{1}{4\pi^2}\iint a(k_x,k_y,z)e^{i(k_x x+k_y y)}dk_x dk_y$$

Thus

$$\cancel{\frac{1}{4\pi^2}\iint}\left[\left(-k_x^2-k_y^2\right)a+i2k_z\frac{\partial}{\partial z}a\right]\cancel{e^{i(k_x x+k_y y)}}\cancel{dk_x dk_y}=0$$

$$\rightarrow\frac{\partial}{\partial z}a=-i\frac{k_x^2+k_y^2}{2k_z}a$$

$$\rightarrow a(k_x,k_y,z)=a_0(k_x,k_y,0)e^{-i\frac{k_x^2+k_y^2}{2k_z}z}$$

Gaussian beam optics

Let

$$A(x,y,0) = A_0 e^{-\frac{x^2+y^2}{w_0^2}} = A_0 e^{-\frac{r^2}{w_0^2}}.$$

Fourier transform

$$a(k_x,k_y,0) = \iint A_0 e^{-\frac{x^2+y^2}{w_0^2}} e^{-i(k_x x+k_y y)} dk_x dk_y$$

$$= \pi w_0^2 A_0 e^{-\frac{k_x^2+k_y^2}{4} w_0^2}$$

Thus

$$a(k_x,k_y,z) = a_0(k_x,k_y,0) e^{-i\frac{k_x^2+k_y^2}{2k_z} z}$$

$$= \pi w_0^2 A_0 e^{-\frac{k_x^2+k_y^2}{4} w_0^2} e^{-i\frac{k_x^2+k_y^2}{2k_z} z}$$

$$= \pi w_0^2 A_0 e^{-\frac{w_0^2}{4}\left(k_x^2+k_y^2\right)\left(1+i\frac{z}{z_0}\right)}$$

Rayleigh length (diffraction length)

$$z_0 = \frac{k_z w_0^2}{2} = \pi\frac{w_0^2}{\lambda}$$

Gaussian beam optics

Inverse Fourier transform

$$A(x,y,z)=\frac{1}{4\pi^2}\iint a(k_x,k_y,z)e^{i(k_xx+k_yy)}dk_xdk_y$$

$$=\frac{1}{4\pi^2}\iint \pi w_0^2A_0e^{-\frac{w_0^2}{4}\left(k_x^2+k_y^2\right)\left(1+i\frac{z}{z_0}\right)}e^{i(k_xx+k_yy)}dk_xdk_y$$

$$\boxed{\begin{aligned}\frac{1}{1+iz/z_0}&=\frac{1}{1+z^2/z_0^2}\left(1-i\frac{z}{z_0}\right)\\&=\frac{1}{\sqrt{1+z^2/z_0^2}}e^{-i\tan^{-1}\frac{z}{z_0}}\end{aligned}}$$

$$=\frac{1}{4\pi}w_0^2A_0\iint e^{-\frac{\left(w_0\sqrt{1+iz/z_0}\right)^2}{4}\left(k_x^2+k_y^2\right)}e^{i(k_xx+k_yy)}dk_xdk_y$$

$$=\frac{A_0}{\underline{1+iz/z_0}}e^{-\frac{x^2+y^2}{\underline{w_0^2(1+iz/z_0)}}}=\frac{A_0}{\sqrt{1+z^2/z_0^2}}e^{-i\tan^{-1}\frac{z}{z_0}}e^{-\frac{x^2+y^2}{w(z)^2}\left(1-i\frac{z}{z_0}\right)}$$

$$=\frac{A_0w_0}{w(z)}e^{-\frac{x^2+y^2}{w(z)^2}\left(1-i\frac{z}{z_0}\right)-i\eta}=\frac{A_0w_0}{w(z)}e^{-\frac{x^2+y^2}{w(z)^2}}e^{ik\frac{x^2+y^2}{2R(z)}-i\eta}$$

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

Beam radius

Wave front radius of curvature

Gaussian optics: summary

- Gaussian distribution is the solution of paraxial Helmholtz equation
- TM00 mode

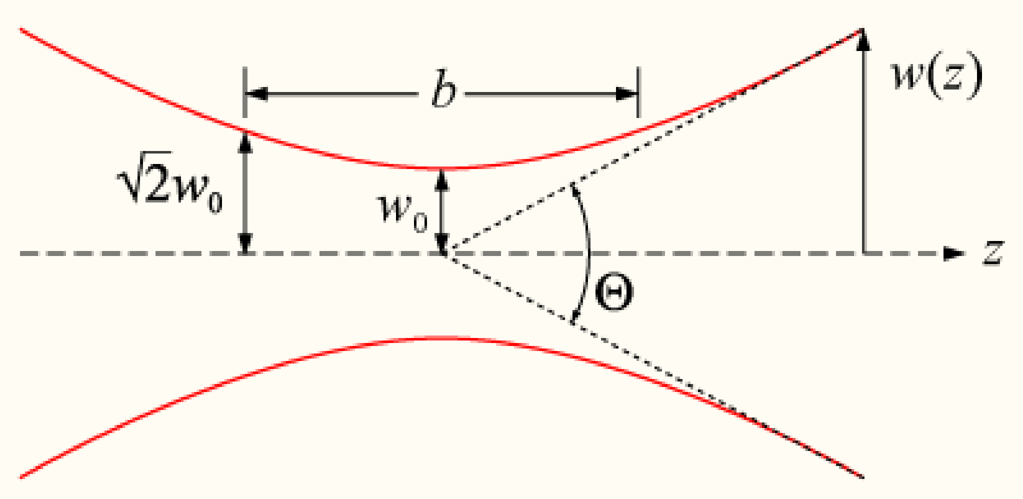
$$E(r,z) = E_0 \frac{w_0}{w(z)} \exp\left(-\frac{r^2}{w^2(z)} \right),$$

$$w(z) = w_0 \sqrt{1 + \left(\frac{z}{z_0} \right)^2},$$

$$z_0 = \frac{\pi w_0^2}{\lambda},$$

$$w_0 = \frac{2\lambda}{\pi \Theta},$$

$$b = 2z_0.$$



w_0: beam waist
z_0: Rayleigh range
b: confocal parameter

Beam propagation: ABCD matrices

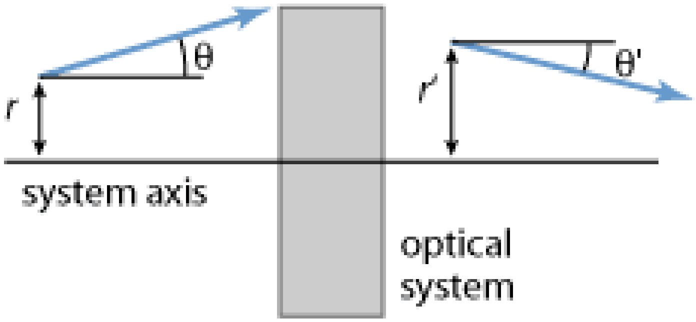
$$\begin{pmatrix} r' \\ \theta' \end{pmatrix} = \begin{pmatrix} A & B \\ C & D \end{pmatrix} \begin{pmatrix} r \\ \theta \end{pmatrix}$$

For a thin lens

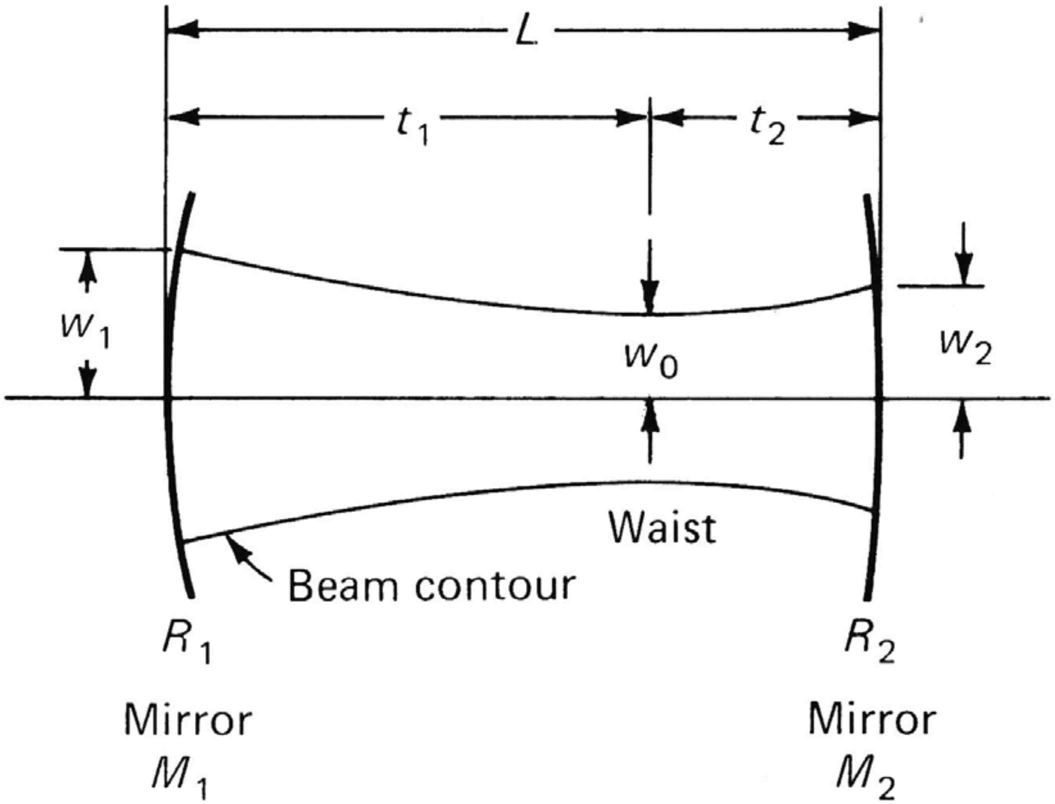
$$\begin{pmatrix} A & B \\ C & D \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ -1/f & 1 \end{pmatrix}$$

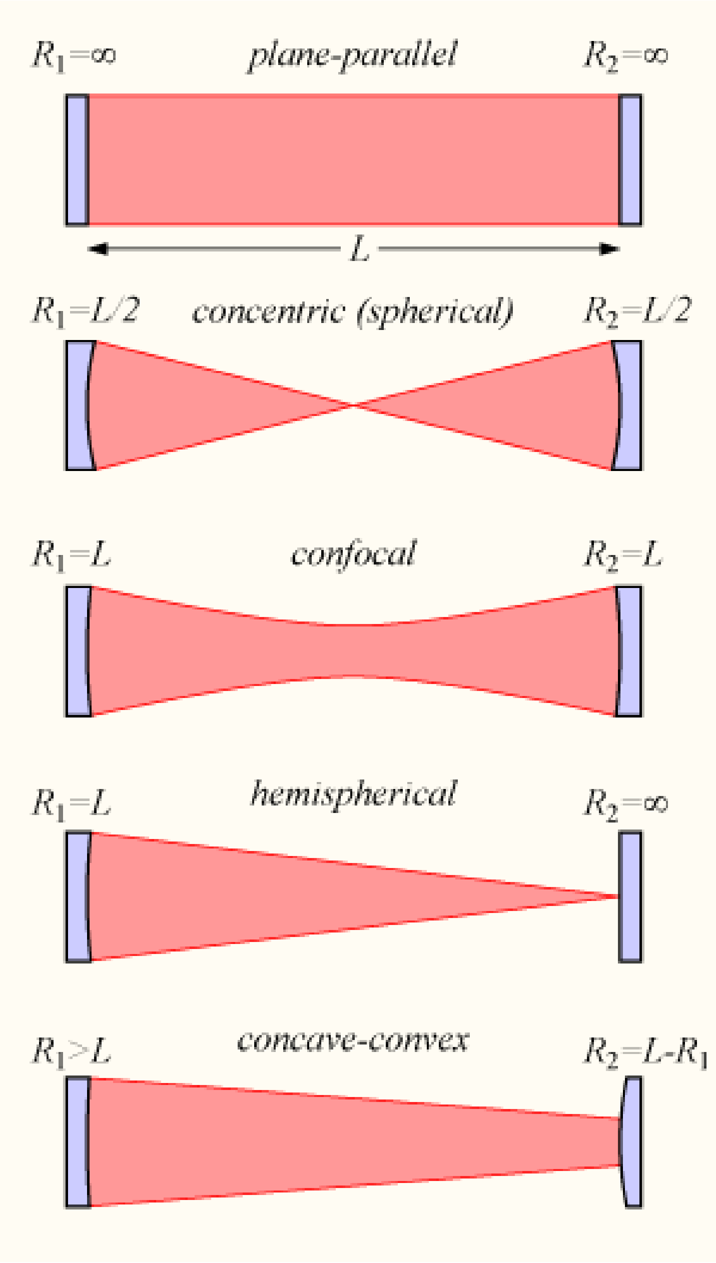
For free space (drift space)

$$\begin{pmatrix} A & B \\ C & D \end{pmatrix} = \begin{pmatrix} 1 & d \\ 0 & 1 \end{pmatrix}$$



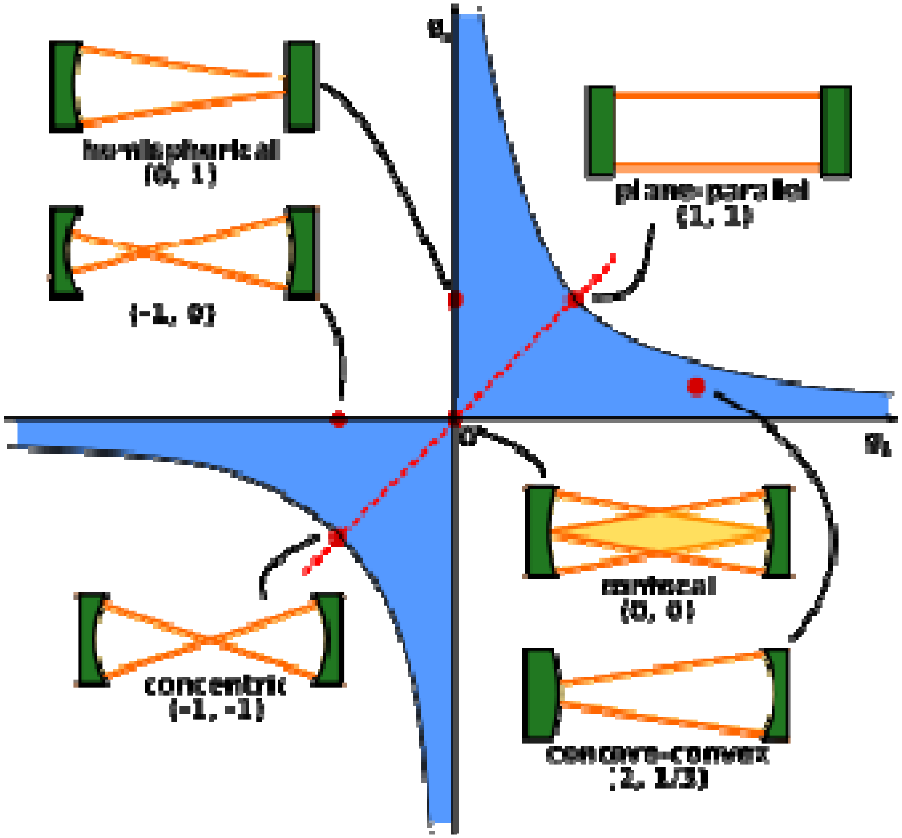
Cavity: Optical resonators

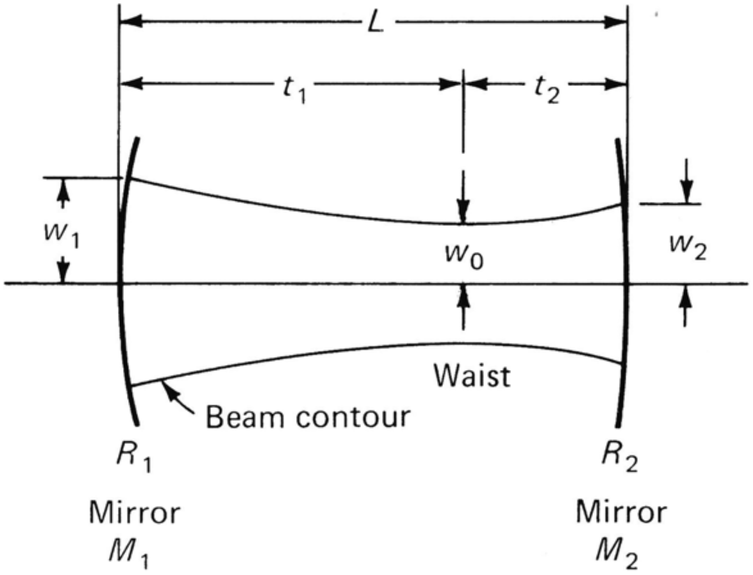




Credit: W. Koechner: Solid State Laser engineering,
Credit: Wekipedia

Stability of laser resonators





$$0 < \left(1 - \frac{L}{R_1}\right)\left(1 - \frac{L}{R_2}\right) < 2,$$

$$g_1 = 1 - \frac{L}{R_1},$$

$$g_2 = 1 - \frac{L}{R_2}.$$

Credit: W. Koechner: Solid State Laser engineering,
Credit: Wekipedia

High order modes

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

Hermite polynomials

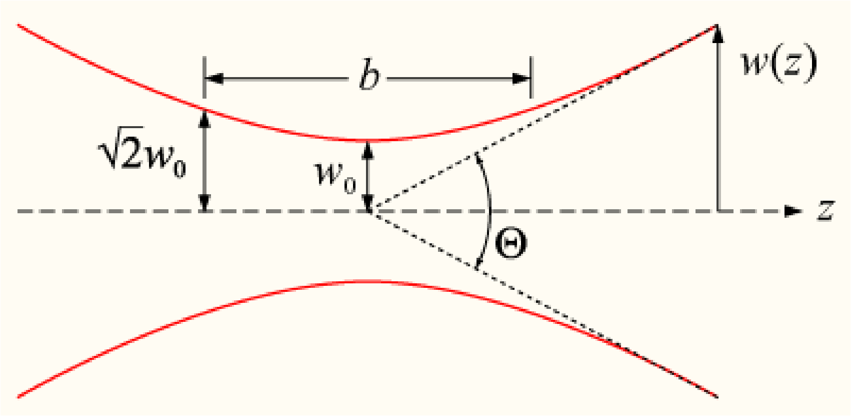
$$H_0(x)=1$$

$$H_1(x)=2x$$

$$H_2(x)=4x^2-2$$

$$H_3(x)=8x^3-12x$$

$$\ldots$$



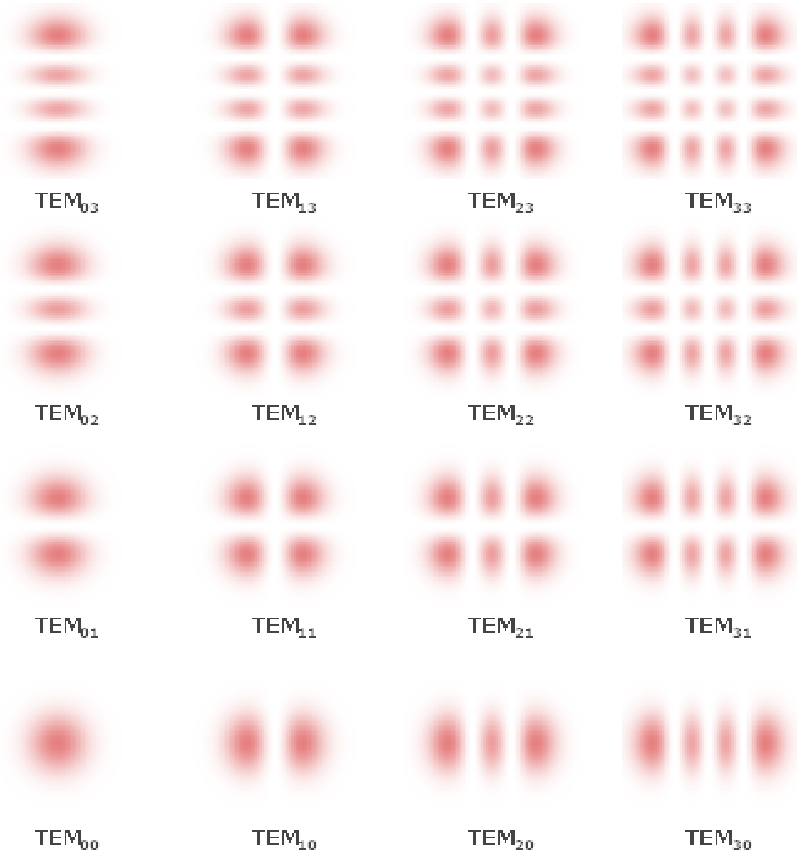
The M² factor

$$\theta=\frac{\Theta}{2}=M^2\frac{\lambda}{\pi w_0}$$

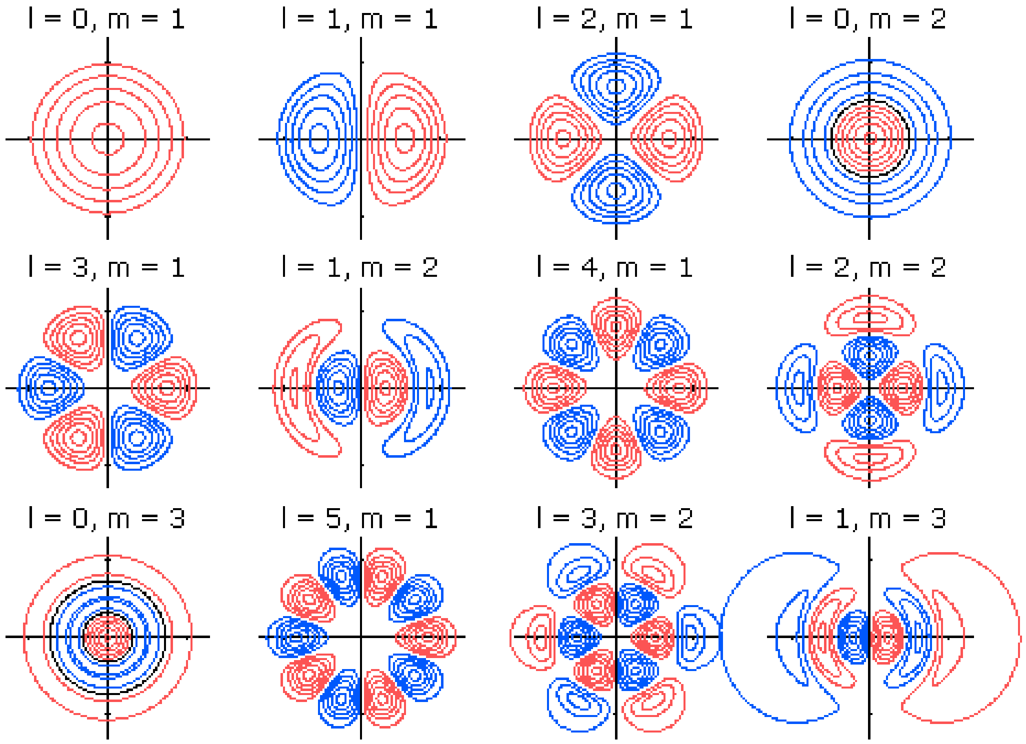
M²=1=diffraction limited; M² >1, M2 times diffractions limited

High order modes

Hermite-Gaussian modes
Intensity profile

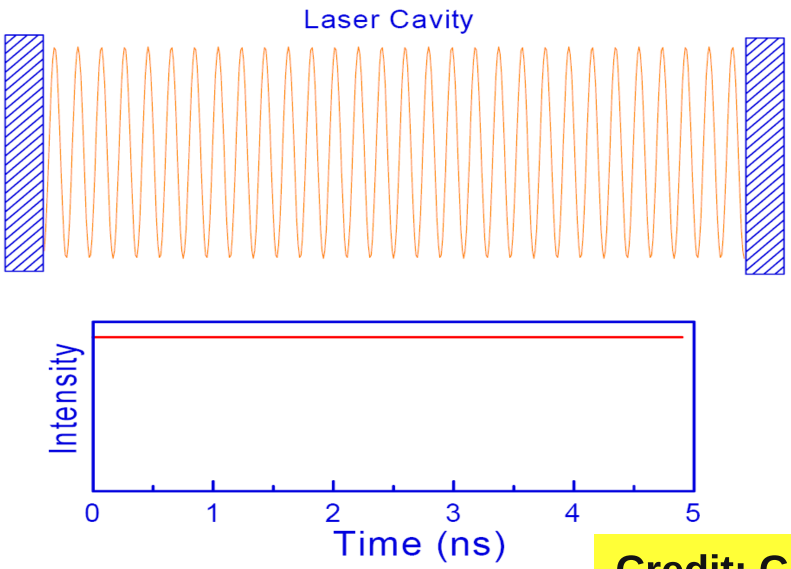


Guided modes in fibers
Field

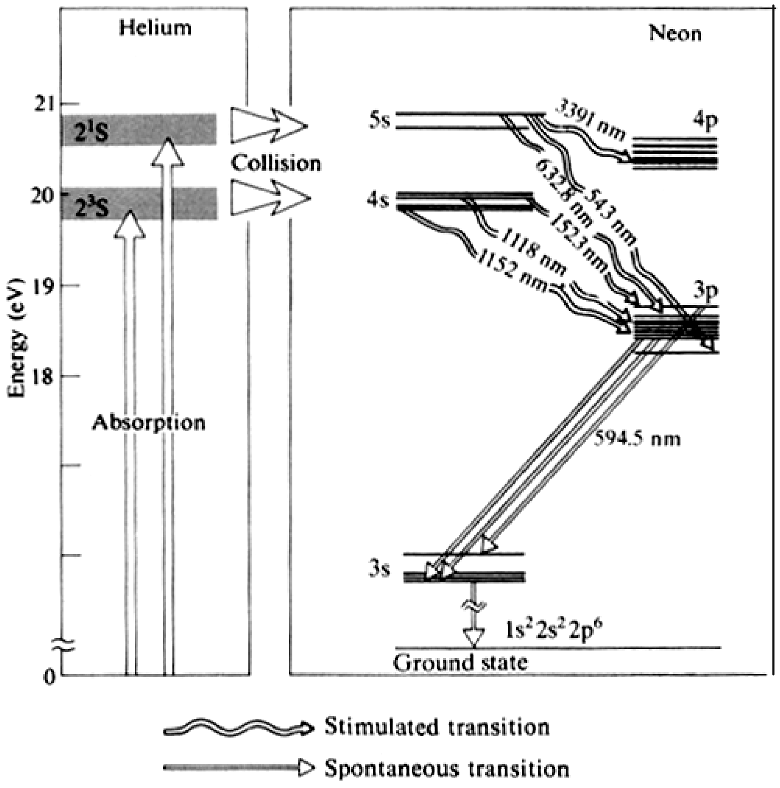


Encyclopedia of Laser Physics and Technology
http://www.rp-photonics.com/higher_order_modes.html

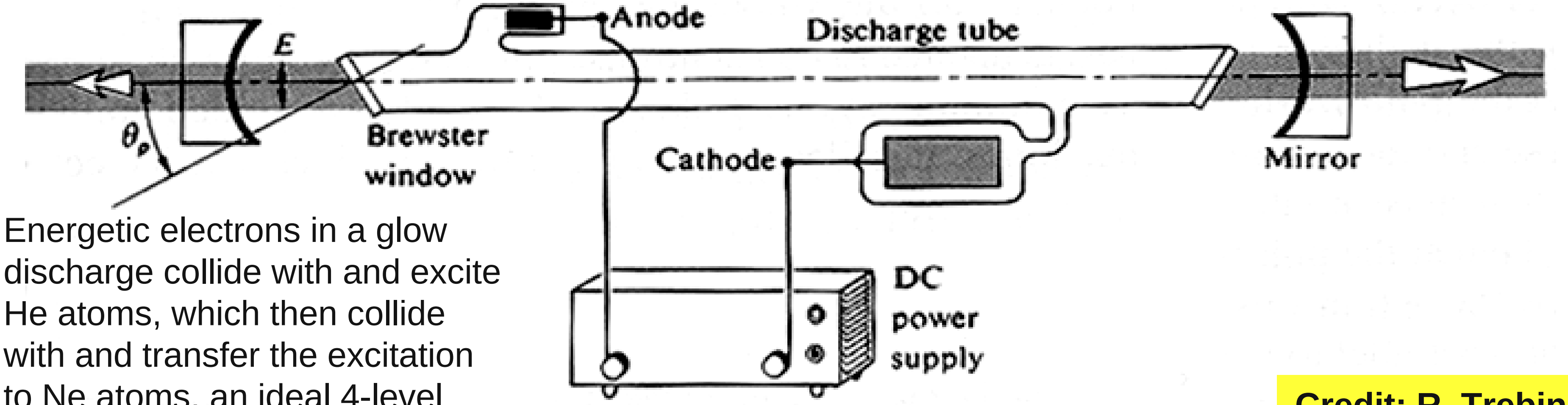
A cavity and laser oscillator



Credit: Cundiff, UCB



Resonant condition for cavity: L=nλ



Energetic electrons in a glow discharge collide with and excite He atoms, which then collide with and transfer the excitation to Ne atoms, an ideal 4-level system.

Credit: R. Trebino

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- Laser and accelerator history
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  - Rate equations
  - Laser configurations
  - Gaussian beam optics and ABCD law
  - Laser cavity and laser modes
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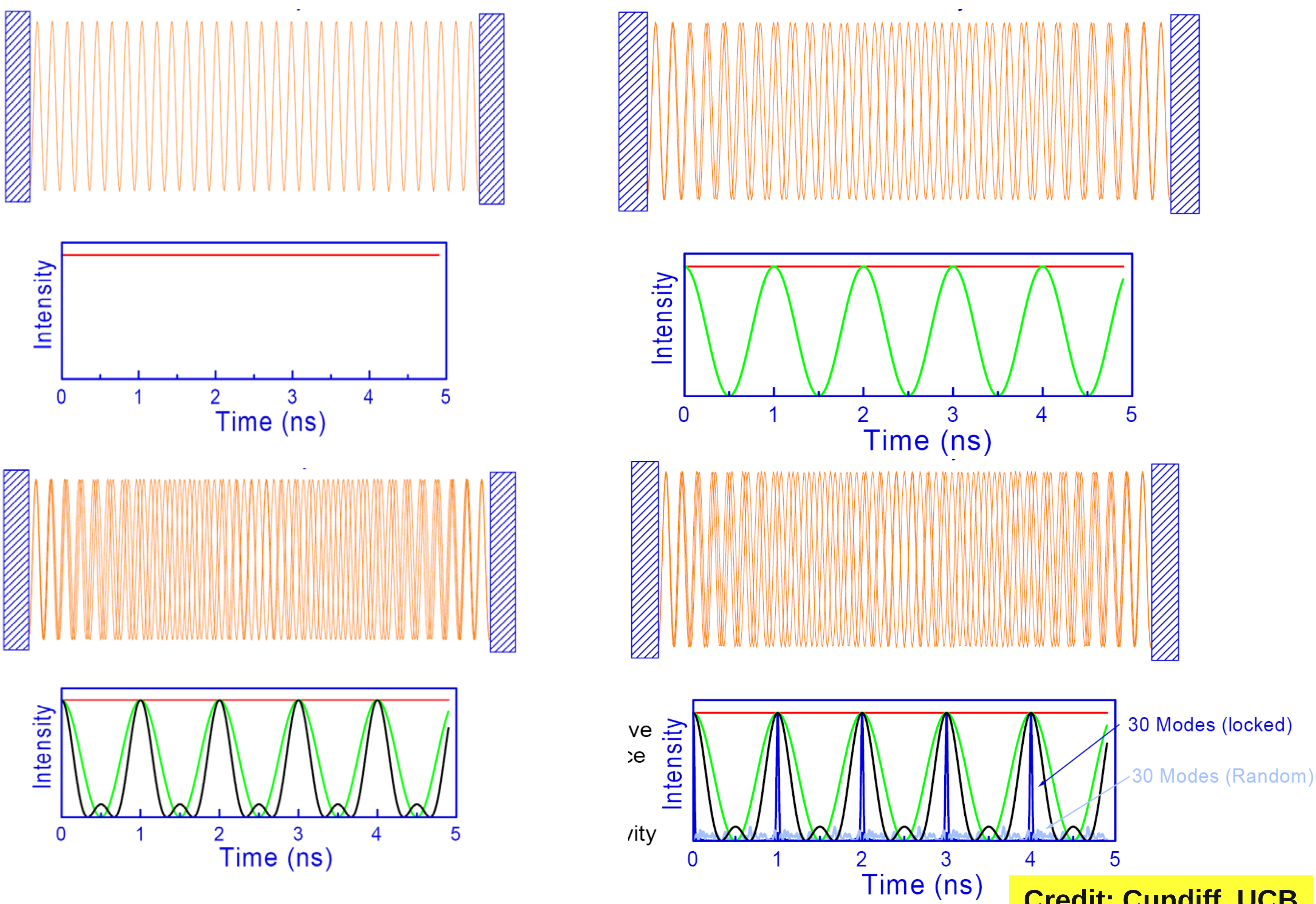
  - Mode-locking and Q-switch
  - MOPA
  - CPA and dispersion
- Laser materials
- Other lasers
  - Semiconductor lasers
  - Fiber lasers
- Frequency conversion and short wavelength lasers

Mode locking: what



Credit: Cundiff, UCB

Mode locking: how

Introduce amplitude or phase modulation/control

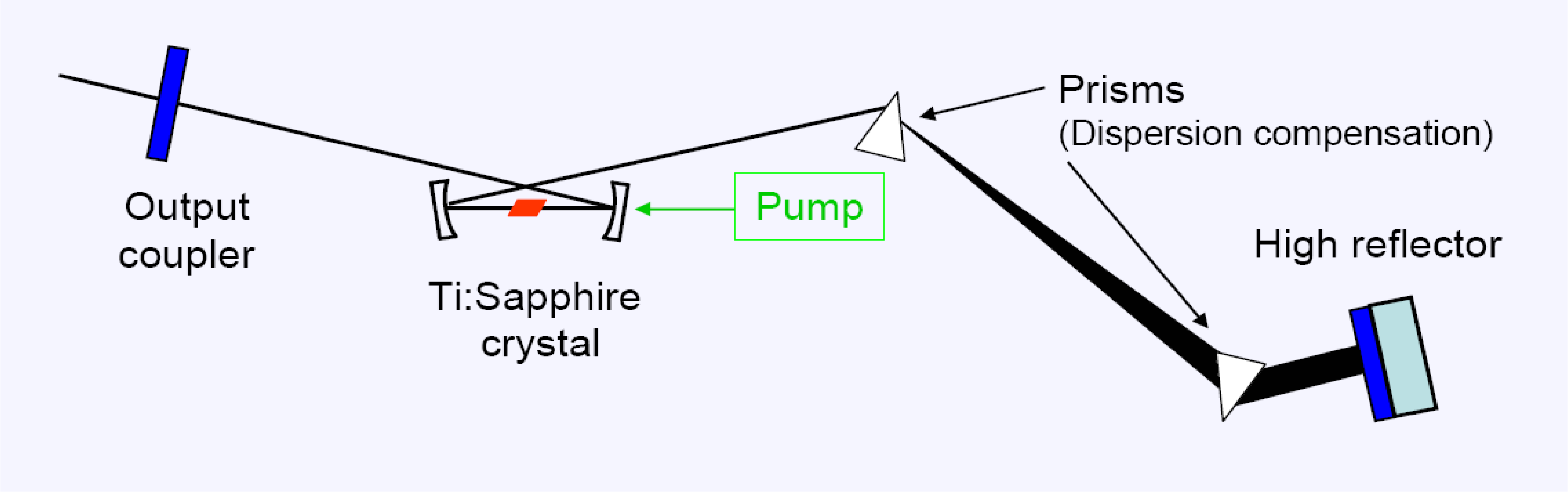
Active mode locking
- Acousto-optic modulator, drive with RF

Passive mode locking
- Saturable absorption
- Nonlinear lensing + aperture
- Nonlinear polarization rotation + polarizer

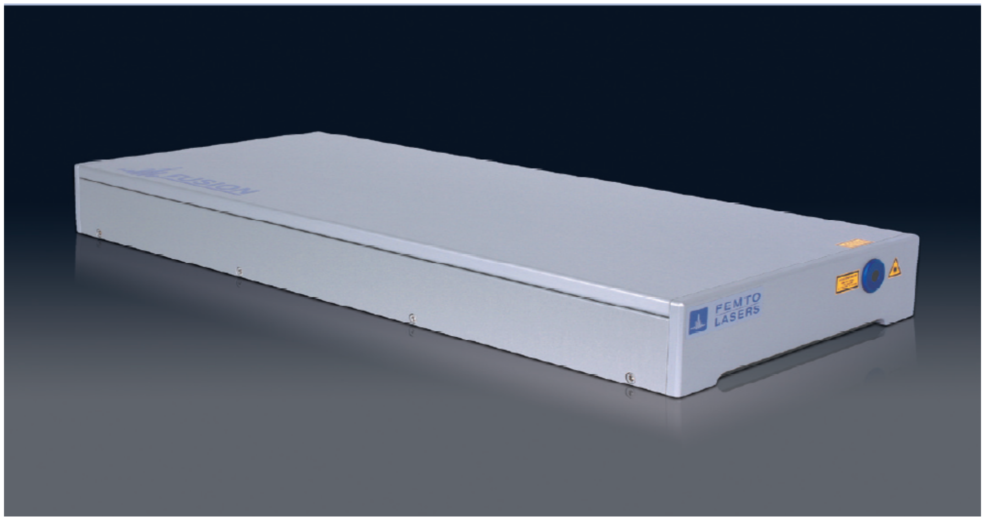
Mode locking: result

- Shorter pulse, high intensity, larger bandwidth
- Single mode
- Accurate timing at round trip time

Ti: Sapphire oscillator: an example



M.T. Asaki, et al, Opt. Lett. 18, 977 (1993)



Femtolasers: Fusion

(28”x12”x3”)

Pulse duration	< 10 fs
Bandwidth (FWHM) @ 800 nm	> 100 nm
Mode locked output power (av.)	150 - 500 mW
Output energy @ 75 MHz	2 - 6.5 nJ
Peak power @ 75 MHz	200 - 650 kW

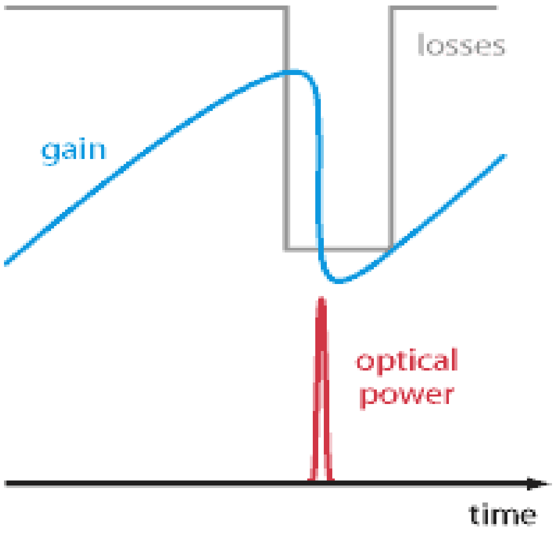
Q-switch

Q factor of a resonator

$$Q = \nu T \frac{2\pi}{L}$$

T: round trip time; ν: optical frequency;
l: fraction power loss per round trip

Q switch: reducing the loss

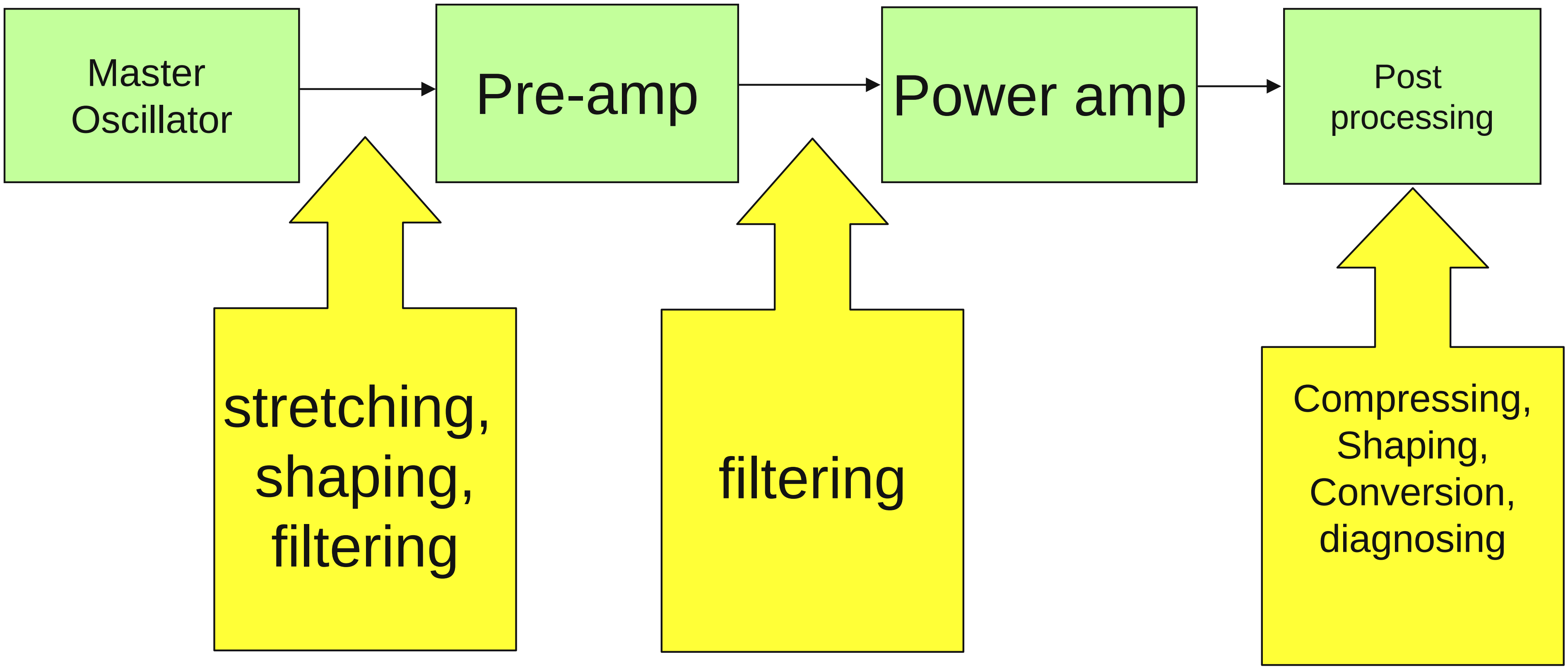


Active: accousto-optical, electro-optical, and mechanical

Passive: saturable absorbers

A MOPA system
Master Oscillator – Power Amplifier

- An oscillator usually does not have enough energy, thus needs amplification
- A MOPA is expected to carry over the characteristics of an OSC
- Pulse duration is limited at 10 ps due to damage



Master Oscillator

Pre-amp

Power amp

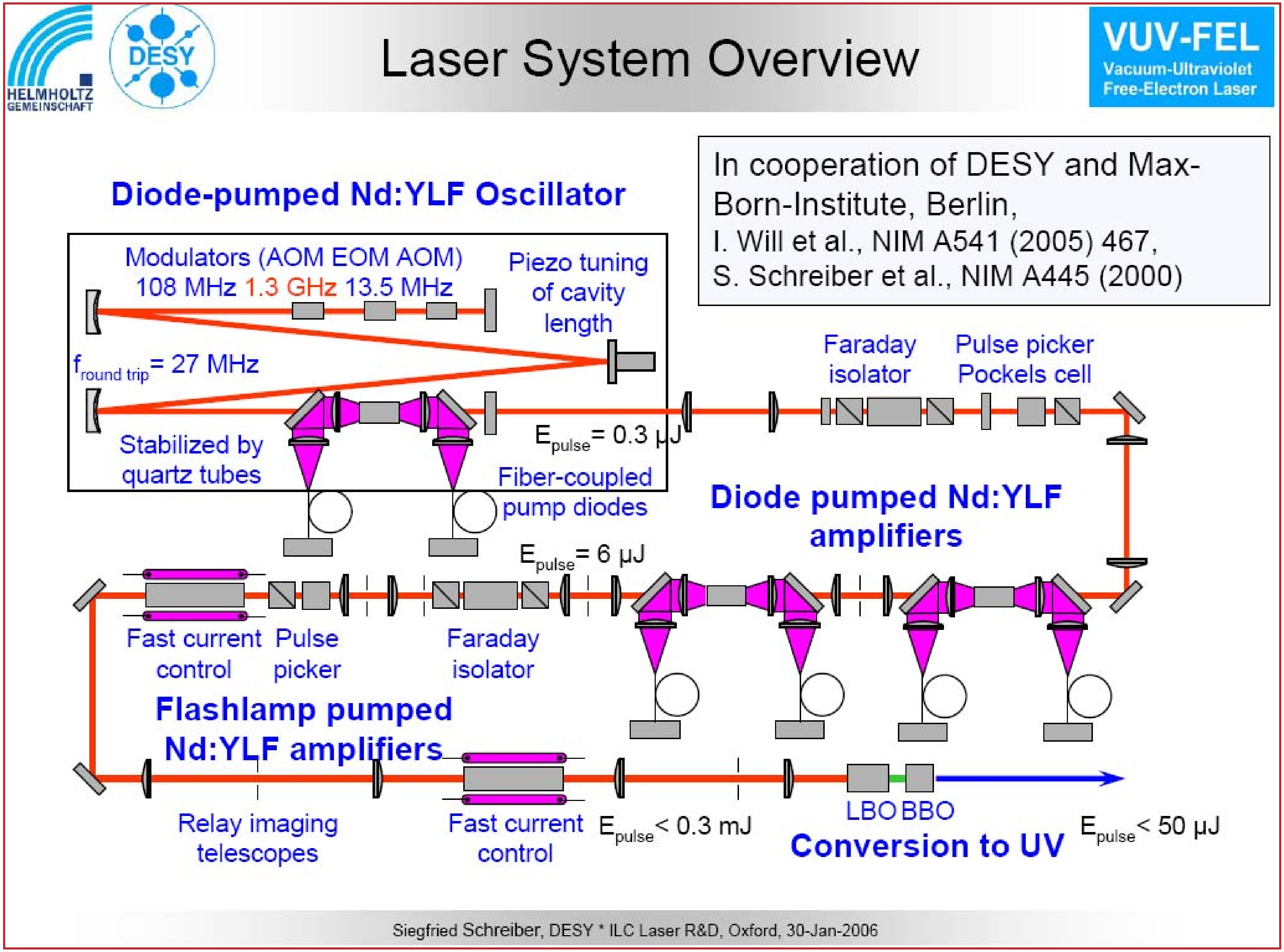
Post processing

stretching, shaping, filtering

filtering

Compressing, Shaping, Conversion, diagnosing

A MOPA example: Flash drive laser



Laser System Overview

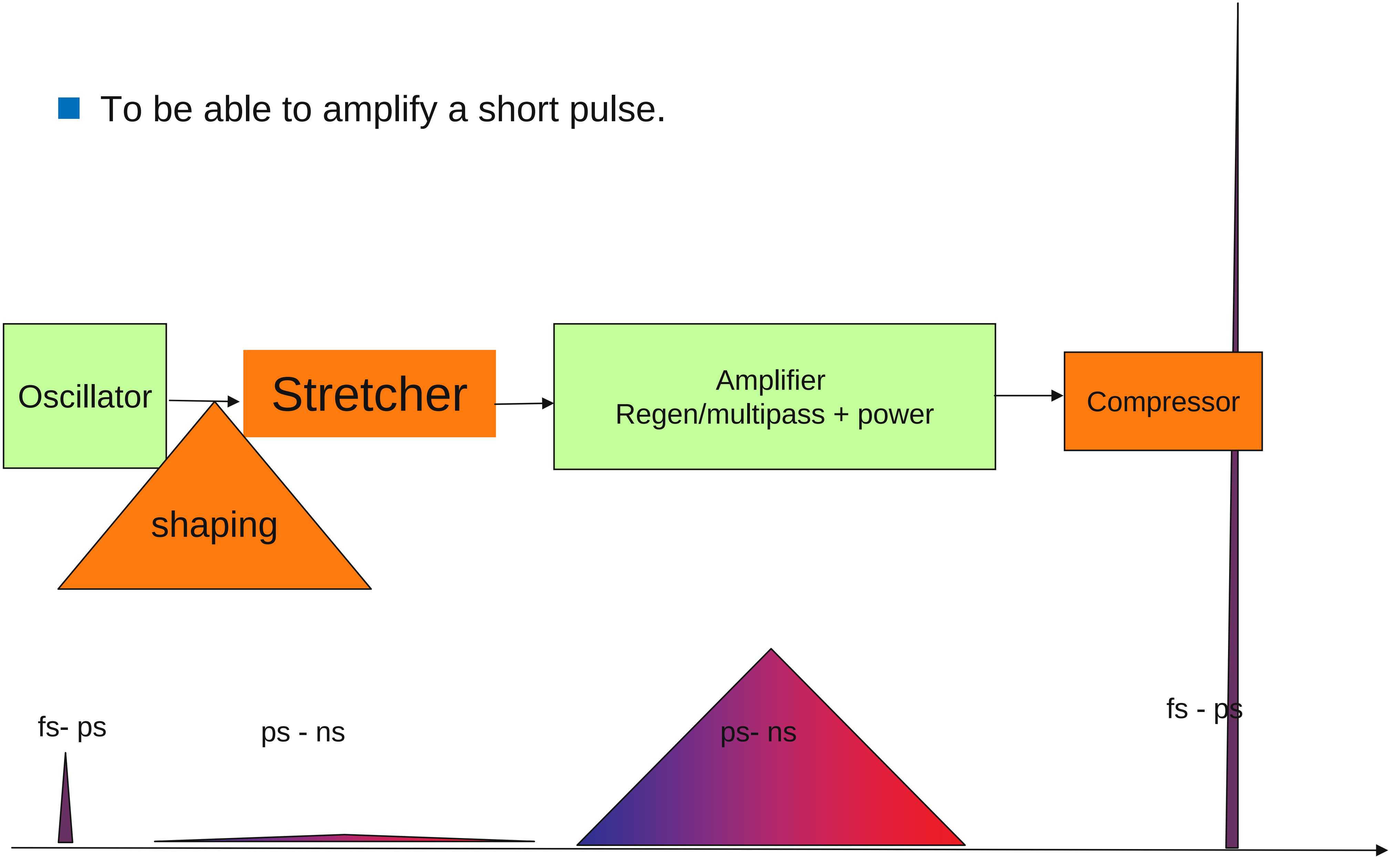
VUV-FEL
Vacuum-Ultraviolet
Free-Electron Laser

In cooperation of DESY and Max-Born-Institute, Berlin,
I. Will et al., NIM A541 (2005) 467,
S. Schreiber et al., NIM A445 (2000)

Siegfried Schreiber, DESY * ILC Laser R&D, Oxford, 30-Jan-2006

Chirped pulse amplification

- To be able to amplify a short pulse.



A CPA example

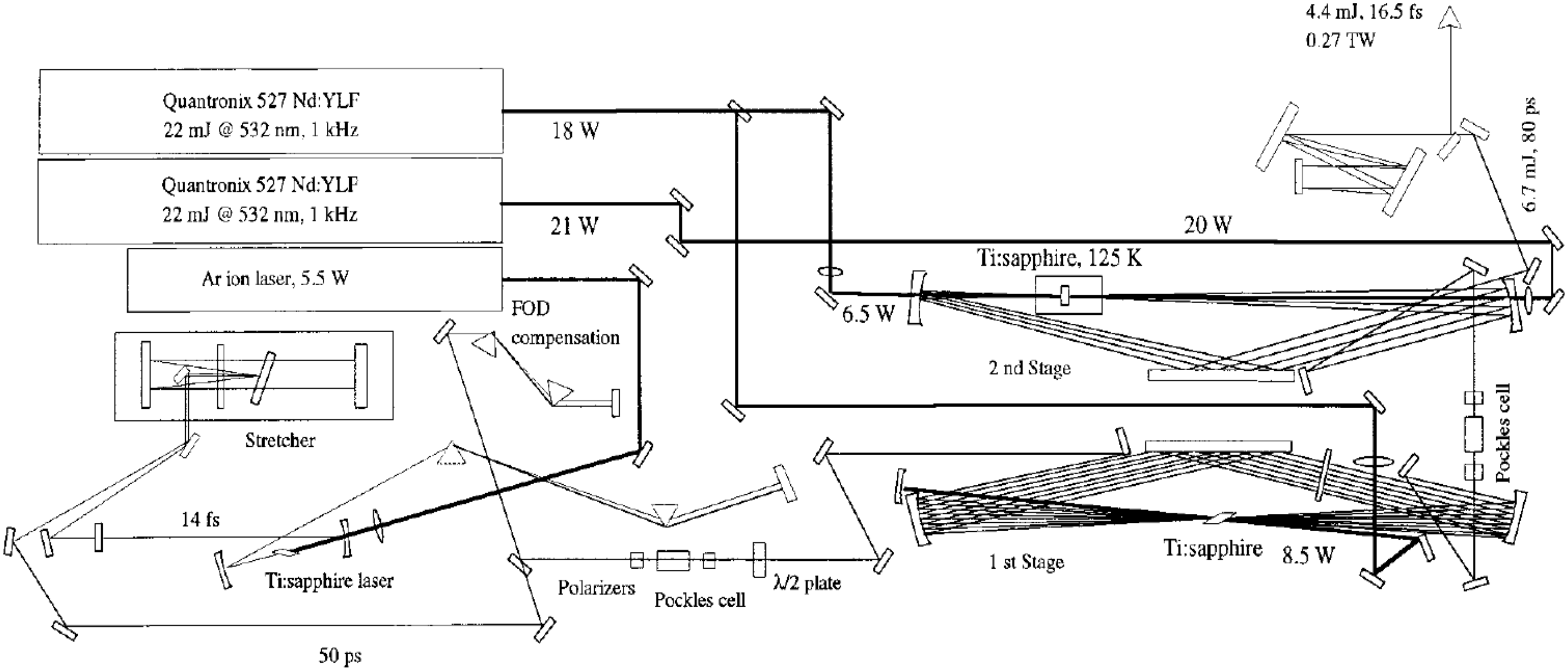


FIG. 7. Schematic diagram of a kHz repetition rate, 0.2 TW Ti:sapphire CPA system.

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

How to stretch/compress a pulse: adding second order phase

- A transform-limited Gaussian pulse in the time and frequency domain

$$E(t) = E_0 \exp\left[-\frac{1}{2}\left(\frac{t}{\tau}\right)^2\right] \Leftrightarrow E(\omega) = E_0 \exp\left[-\frac{1}{2}\left(\frac{\omega}{\Delta\omega}\right)^2\right]$$

- Add a second order phase, which is to 'chirp' a pulse

$$E'(\omega) = E_0 \exp\left[-\frac{1}{2}\left(\frac{\omega}{\Delta\omega}\right)^2 + ia\omega^2\right]$$

- What is the new pulse form in the time domain? How does the frequency change as function of time? (Home work)

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

Stretcher and compressor

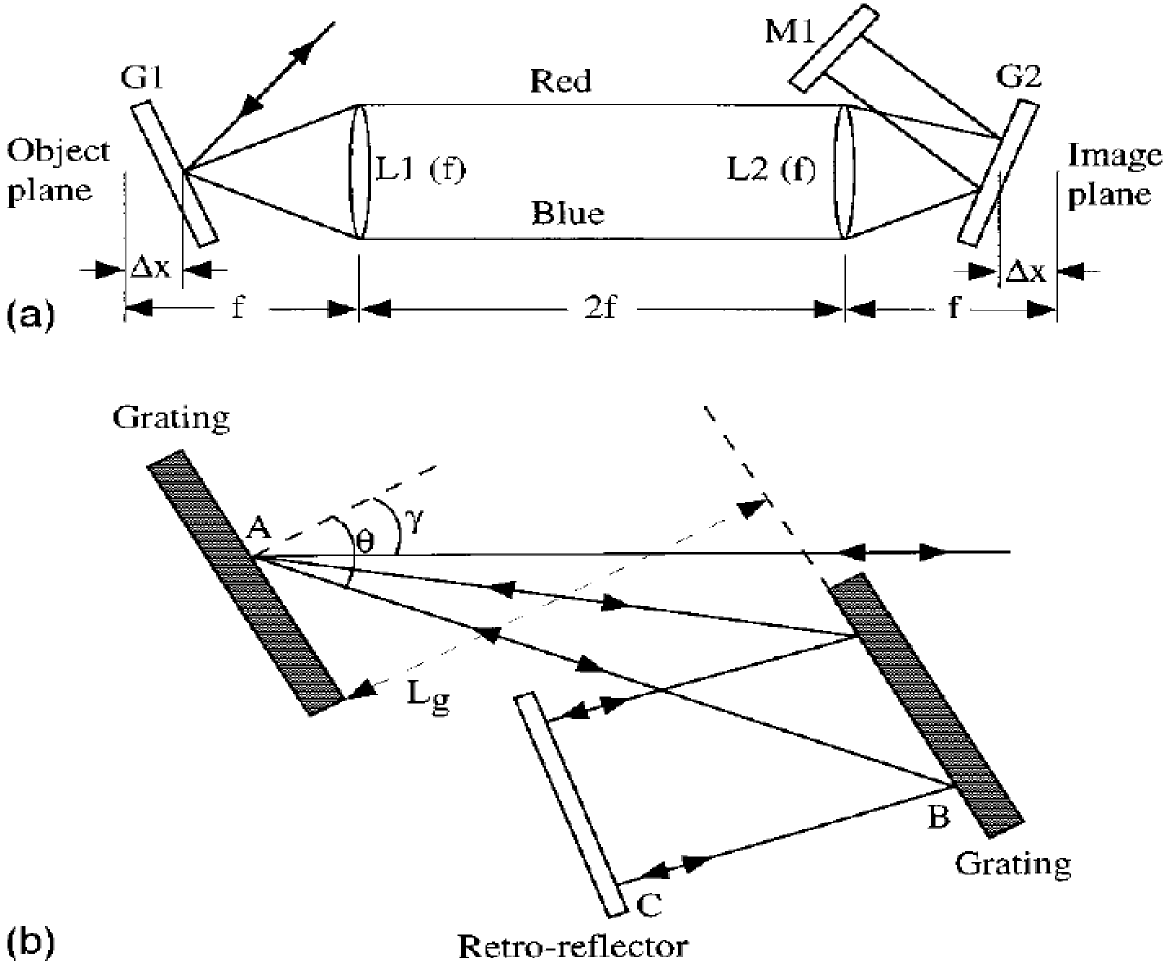
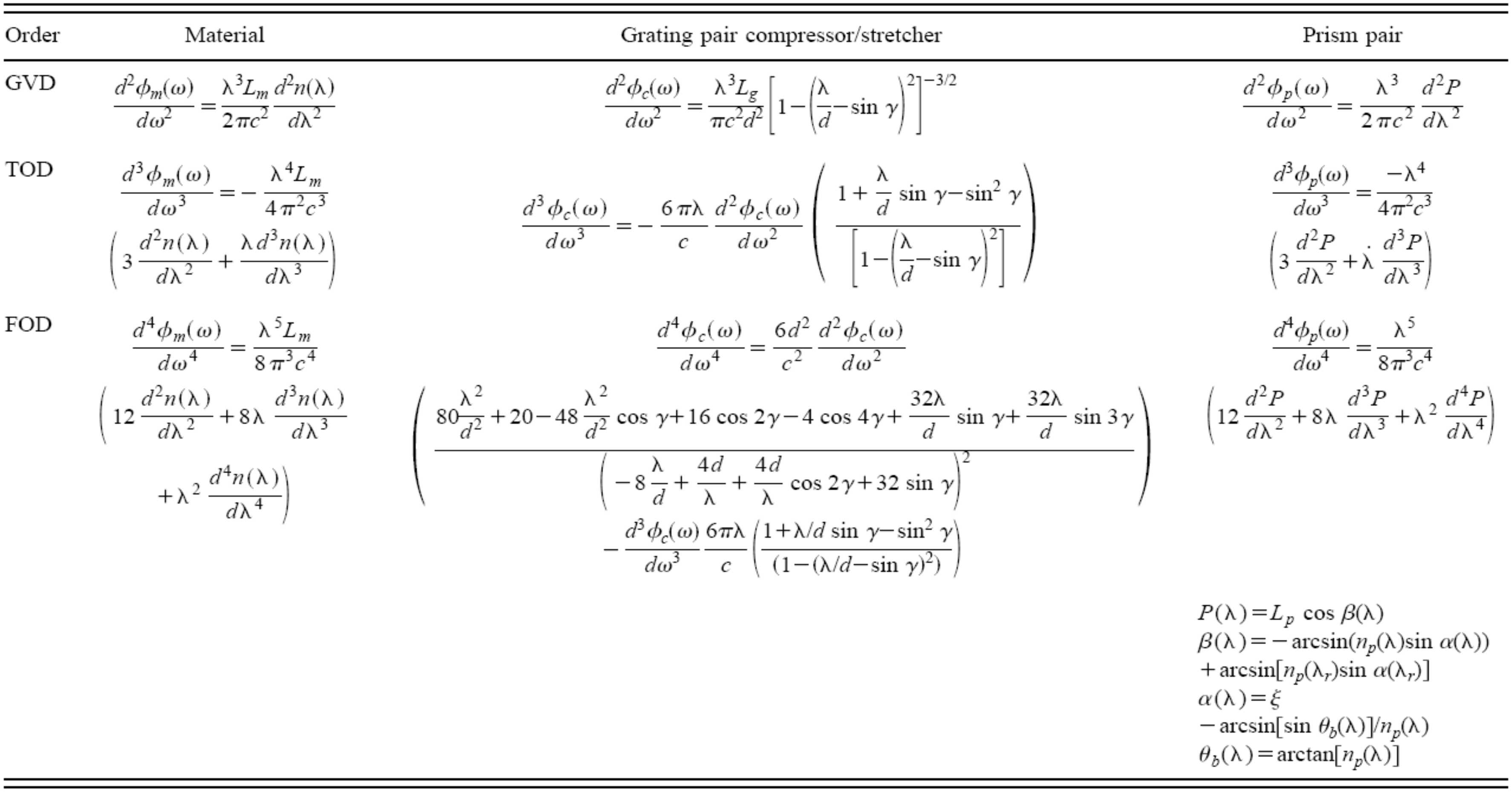


FIG. 3. Schematic diagrams of (a) a pulse stretcher and (b) a pulse compressor.

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

Stretcher and compressor

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

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

Dispersions

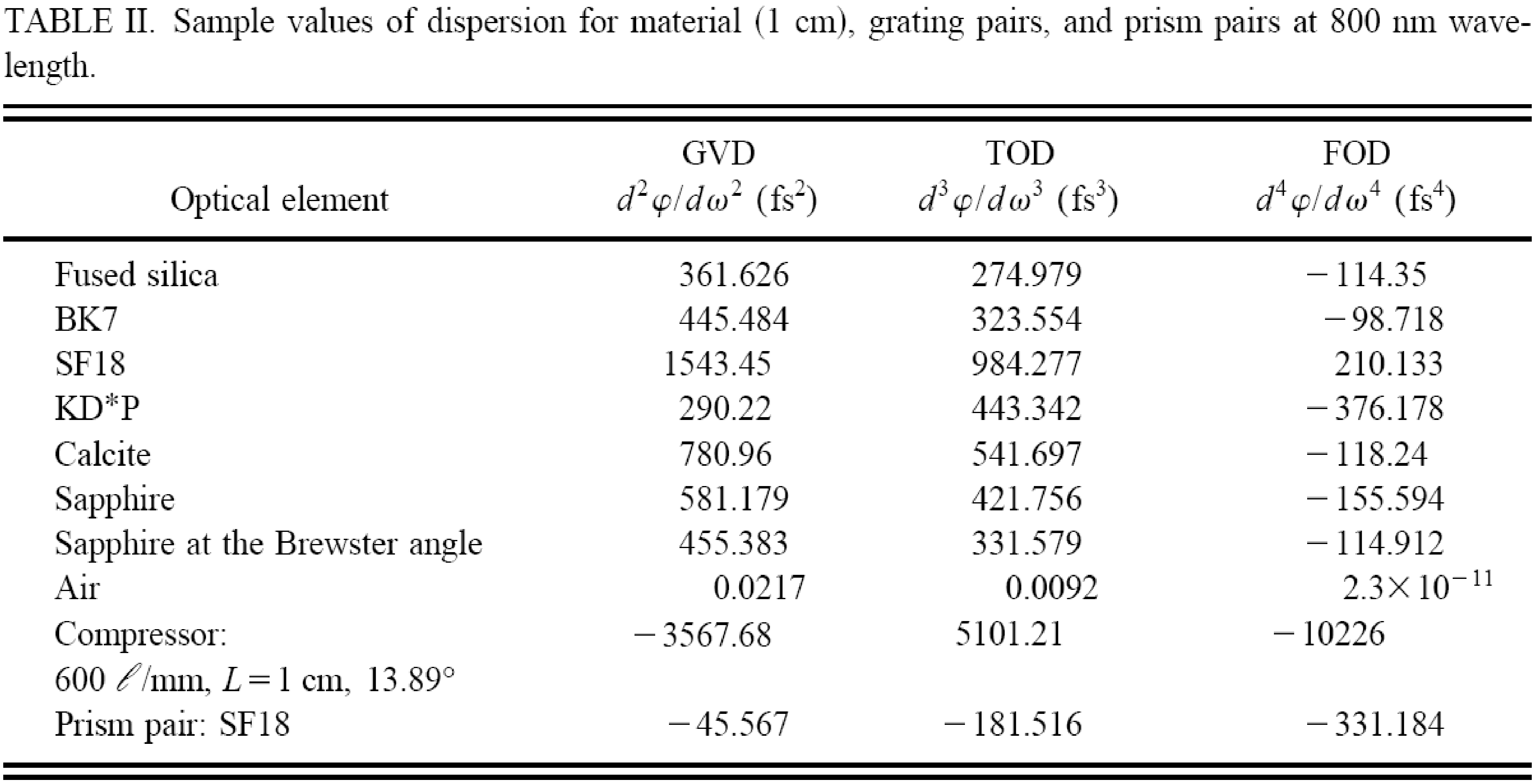


TABLE II. Sample values of dispersion for material (1 cm), grating pairs, and prism pairs at 800 nm wavelength.

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. Instrum. 69, 1207 (1998).

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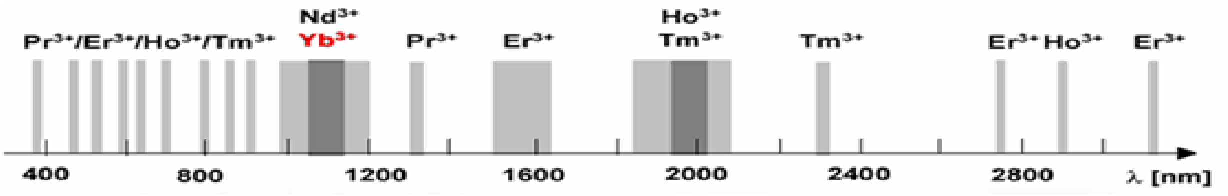
Laser materials

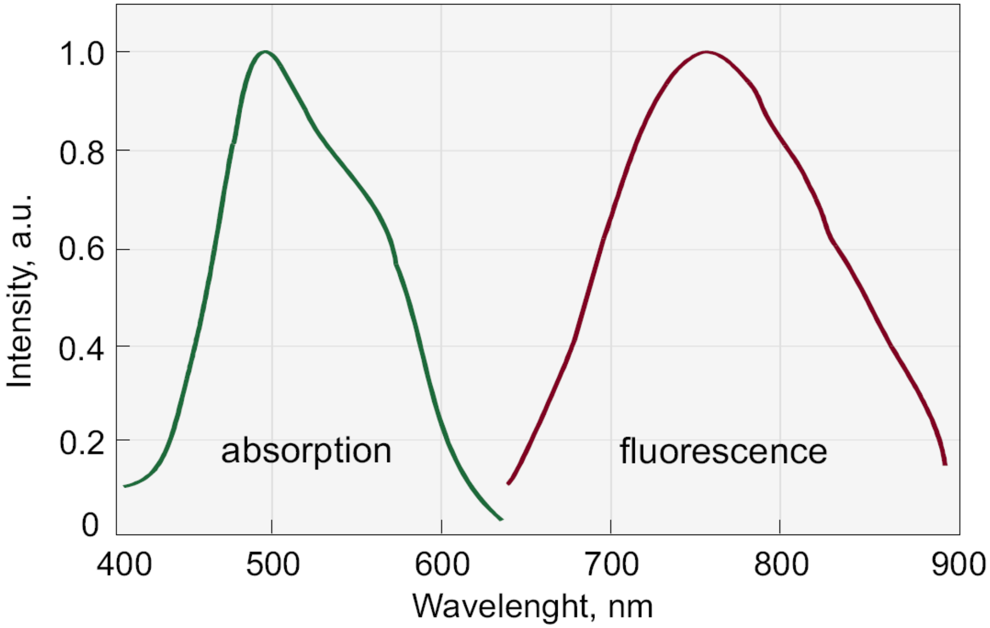
- What we care
  - Lasing mechanism: four-level systems is always preferred
  - Lasing wavelength: tunable is better
  - Lasing bandwidth: bigger is better but not always
  - Pump requirement: visible preferred
  - Gain lifetime: longer is better
  - Damage threshold: higher is better
  - Saturation flux: higher is better
  - Heat conductivity: as high as possible
  - Thermal stability: as small as possible
  - Form: solid is always preferred

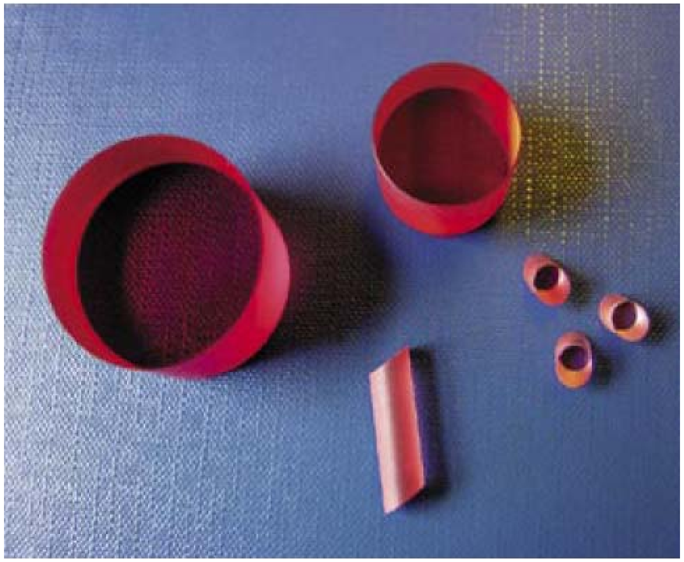
Laser materials

- Host + active ions
- Host
  - Crystalline solids (Sapphire, Garnets, Fluoride, Aluminate, etc.)
    - *Difficult to grow to large size*
    - *Narrow line width thus lower lasing threshold, and narrow absorption band*
    - *Good thermal conductivity*
  - Glass (property varies by make, and processing)
    - *Easy to make in large size and large quantities*
    - *No well defined bonding field thus larger line width and higher lasing threshold, large absorption band*
    - *Lower thermal conductivity thus severe thermal birefringence and thermal lensing, lower duty cycle*
- Active ions
  - Rare earth ions: No. 58-71, most importantly, Nd^{3+}, Er^{3+}…
  - Transition metals: Ti^{3+}, Cr^{3+},



Laser material: Ti: Saaphire ($Al_2O_3:Ti^{3+}$*)*



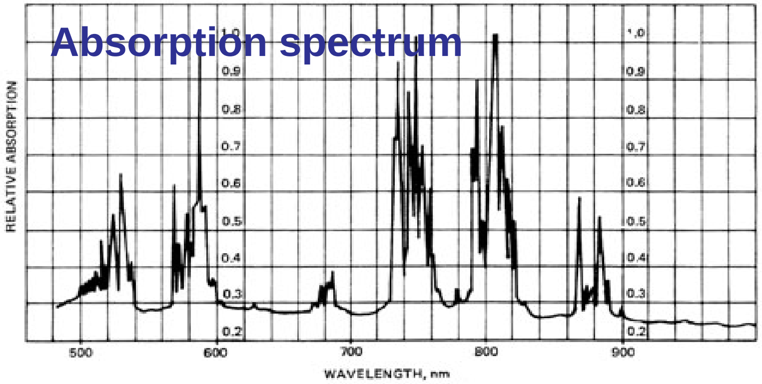


MATERIAL PHYSICAL AND LASER PROPERTIES

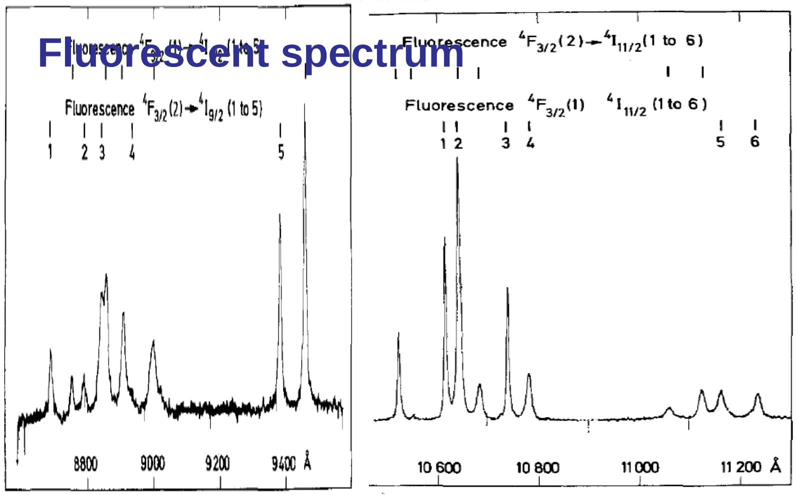
Chemical formula	$Ti^{3+}:Al_2O_3$
Crystal structure	Hexagonal
Lattice constants	a=4.748, c=12.957
Density	3.98 g/cm^3
Mohs hardness	9
Thermal conductivity	0.11 cal/(°C×sec×cm)
Specific heat	0.10 cal/g
Melting point	2050 °C
Laser action	4-Level Vibronic
Fluorescence lifetime	3.2 μsec (T=300K)
Tuning range	660–1050 nm
Absorbtion range	400–600 nm
Emission peak	795 nm
Absorption peak	488 nm
Refractive index	1.76 @ 800 nm

- Giving shortest pulse so far
- Wonderful tunability
- Good thermal properties
- Short gain lifetime (has to be pumped by a ns-pulsed green laser)

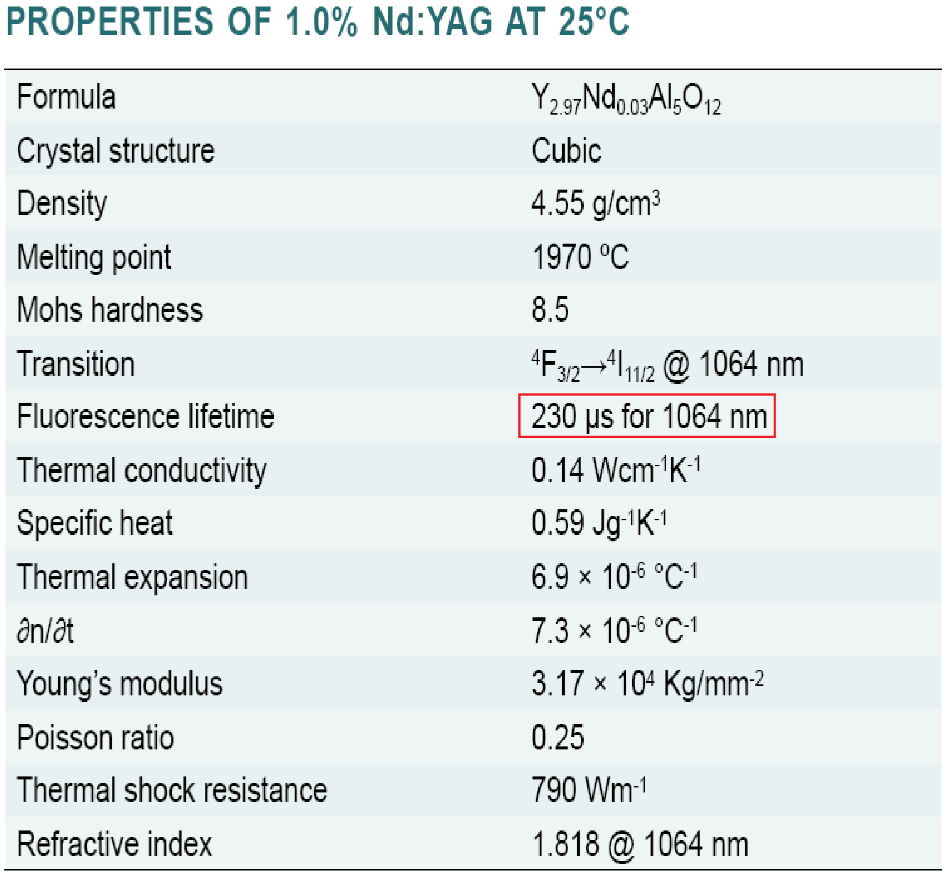
Laser material (Nd:YAG)



Absorption spectrum



Fluorescent spectrum



PROPERTIES OF 1.0% Nd:YAG AT 25°C

Formula	$Y_{2.97}Nd_{0.03}Al_5O_{12}$
Crystal structure	Cubic
Density	4.55 g/cm^3
Melting point	1970 °C
Mohs hardness	8.5
Transition	$^4F_{3/2} \rightarrow {}^4I_{11/2}$ @ 1064 nm
Fluorescence lifetime	230 μs for 1064 nm
Thermal conductivity	0.14 Wcm^{-1}K^{-1}
Specific heat	0.59 Jg^{-1}K^{-1}
Thermal expansion	6.9 × 10^{-6} °C^{-1}
∂n/∂t	7.3 × 10^{-6} °C^{-1}
Young's modulus	3.17 × 10^4 Kg/mm^{-2}
Poisson ratio	0.25
Thermal shock resistance	790 Wm^{-1}
Refractive index	1.818 @ 1064 nm

- High saturation flux
- Narrow bandwidth (0.15 nm), thus long pulse (>10 ps), high gain
- Good thermal properties
- Long gain lifetime (diode pump)

Laser material: (Nd:Glass)

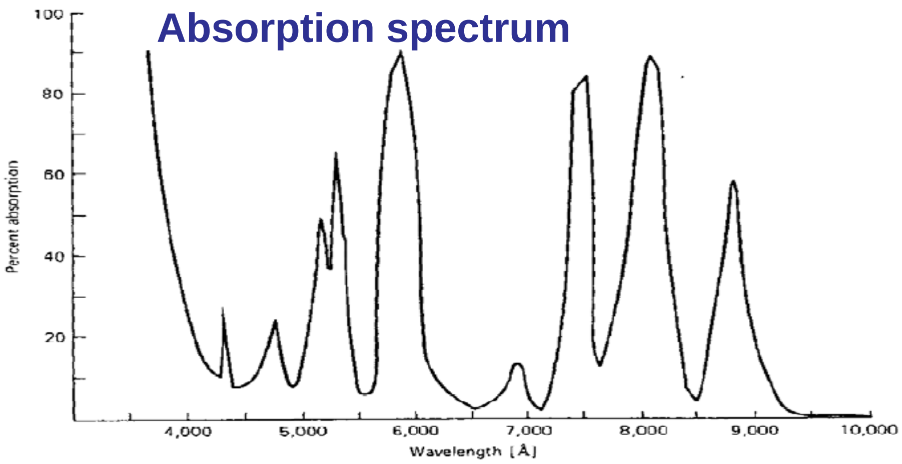
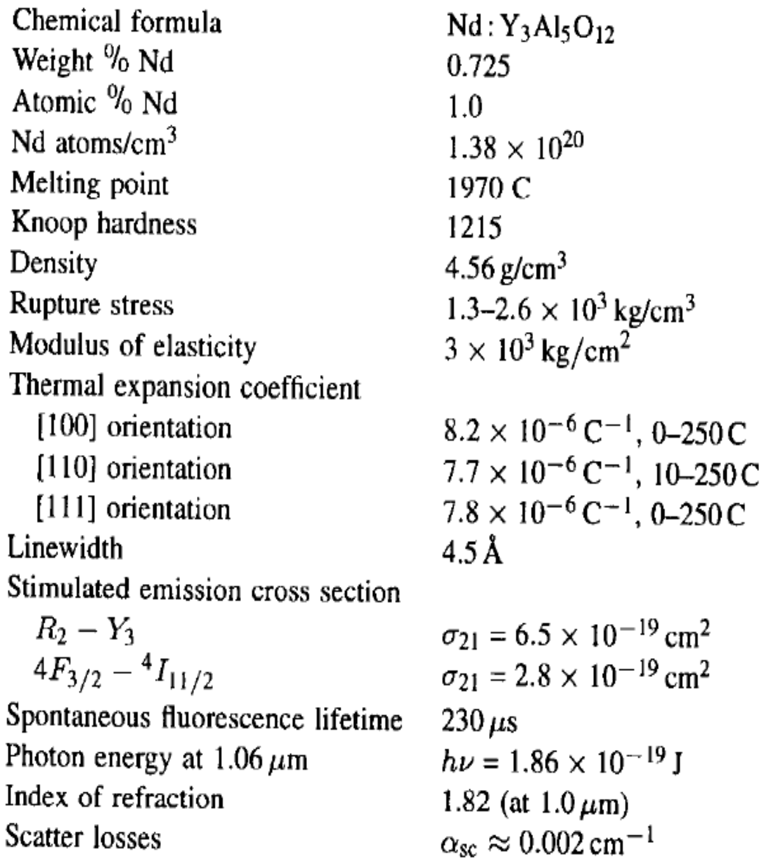


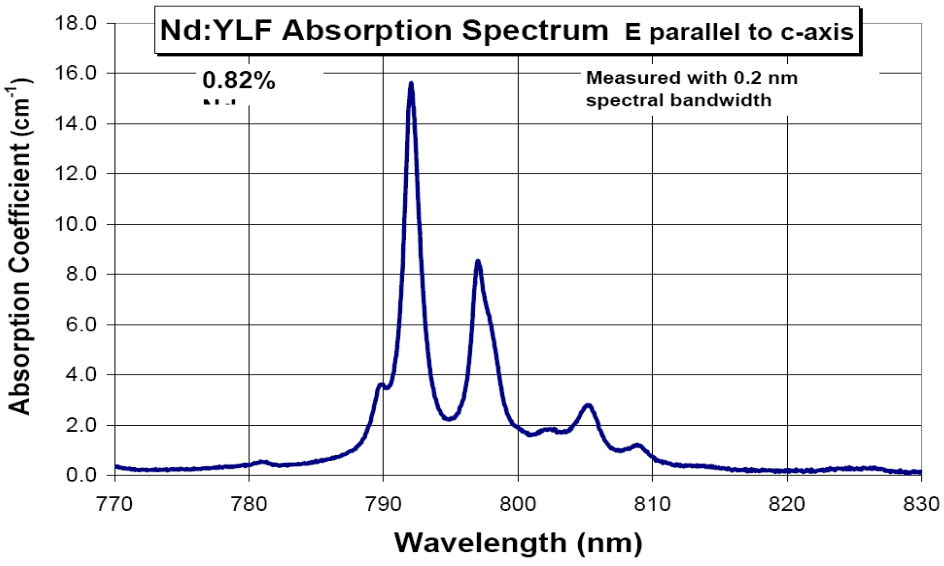
Fig. 2.9. Absorption versus wavelength of Nd: glass. (Material: ED-2; thickness: 6.3 mm)



Chemical formula	$Nd:Y_3Al_5O_{12}$
Weight % Nd	0.725
Atomic % Nd	1.0
Nd atoms/cm^3	1.38×10^{20}
Melting point	1970 C
Knoop hardness	1215
Density	4.56 g/cm^3
Rupture stress	$1.3\text{–}2.6 \times 10^3$ kg/cm^3
Modulus of elasticity	3×10^3 kg/cm^2
Thermal expansion coefficient	
[100] orientation	$8.2 \times 10^{-6}\,C^{-1}$, 0–250 C
[110] orientation	$7.7 \times 10^{-6}\,C^{-1}$, 10–250 C
[111] orientation	$7.8 \times 10^{-6}\,C^{-1}$, 0–250 C
Linewidth	4.5 Å
Stimulated emission cross section	
$R_2 - Y_3$	$\sigma_{21} = 6.5 \times 10^{-19}$ cm^2
$4F_{3/2} - {}^4I_{11/2}$	$\sigma_{21} = 2.8 \times 10^{-19}$ cm^2
Spontaneous fluorescence lifetime	230 μs
Photon energy at 1.06 μm	$h\nu = 1.86 \times 10^{-19}$ J
Index of refraction	1.82 (at 1.0 μm)
Scatter losses	$\alpha_{sc} \approx 0.002\,\text{cm}^{-1}$

- High saturation flux
- large bandwidth (20 nm), thus short pulse (<1 ps),
- Poor thermal
- Long gain lifetime (diode pump)
- Only for big lasers now (PW or MJ)

Laser Material: Nd:YLF



- High saturation flux
- Narrow bandwidth (0.15 nm), thus long pulse (>10 ps), high gain
- Good thermal properties
- Long gain lifetime (diode pump)
- Difficult to handle

Physical Properties	
Chemical Formula	$LiY_{1.0\text{-}x}Nd_xF_4$
Lattice Parameters	a=5.16Å b=10.85Å
Crystal Structure	Tetragonal
Space Group	$I4_1/a$
Nd atoms/cm3	1.40x10^{20} atoms/cm^3 for 1% Nd doping,
Mohs Hardness	4 ~ 5
Melting Point	819℃
Density	3.99 g/cm^3
Modulus of Elasticity	85 GPa
Thermal Expansion Coefficient	8.3x10^{-6}/k ⊥c, ac=13.3x10^{-6}/k ||c
Thermal Conductivity Coefficient	0.063 W/cm K
Specific Heat	0.79 J/g K
Optical Properties	
Transparency Region	180nm to 6.7μm
Peak Simulation Emission Cross Section	1.8x$10^{-19}$$cm^2$ (E \|\| c) at 1.047μm 1.2x$10^{-19}$$cm^2$ (E ⊥ c) at 1.053μm
Spontaneous Fluorescence Lifetime	485μs for 1% Nd doping
Scatter Losses	<0.2% / cm
Peak Absorption Coefficient	α=10.8cm^{-1} (792.0 nm E || c) α=3.59cm^{-1} (797.0 nm E ⊥ c)
Refractive Indices	Wavelength (nm) n_e n_e 262 1.485 1.511 350 1.473 1.491 525 1.456 1.479 1050 1.448 1.470 2065 1.442 1.464
Sellmeier Equations	$n_i^2(\lambda) = A + B\lambda^2/(\lambda^2\text{-}C) - D\lambda^2/(\lambda^2\text{-}E)$ A B C D E n_o 3.38757 0.70757 0.00931 0.18849 50.99741 n_2 1.31021 0.84903 0.00876 0.53607 134.9566

Laser materials: summary

	Ti:Sa Al_2O_3:Ti	Nd:YAG $Y_{3.0-x}Nd_xAL_5O_{12}$	Nd:Glass (Kigre Q-88) $Y_3Al_5O_{12}$:Nd	Nd:YLF $LiY_{1.0-x}Nd_xF_4$
Fluorescence life time (μs)	3.2	230	330	485
Peak wavelength (nm)	780	1064	1054	1047,1053
Line width (nm)	220	0.15	22	1
Emission cross section (10^{-19} cm^2)	3	6.5	0.4	1.8
Saturation flux (J/cm^2)	0.9	0.6	4.5	.43
Thermal conductivity (w cm^{-1} K^{-1})	0.5	0.14	0.0084	0.06
Thermal expansion coef (10^{-6}/°C)		7.5	10	10
n	1.76	1.8	1.55	1.5
dn/dT (10^{-6}/°C)		7.3	-0.5	

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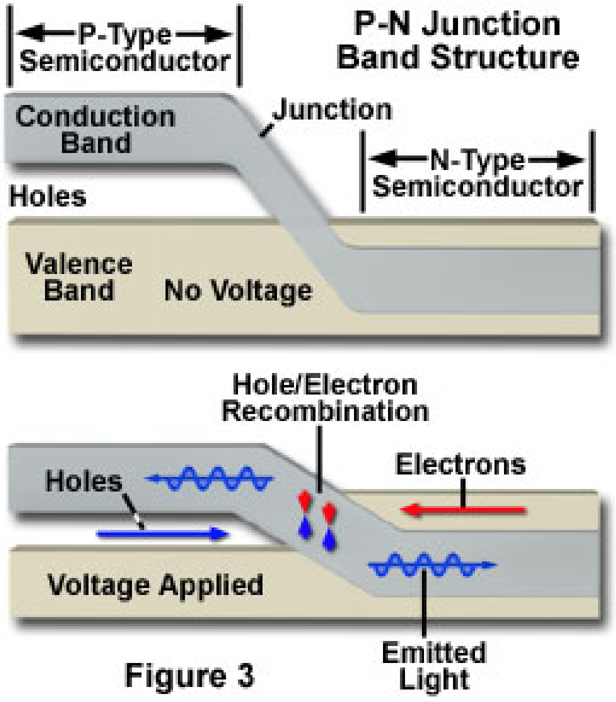
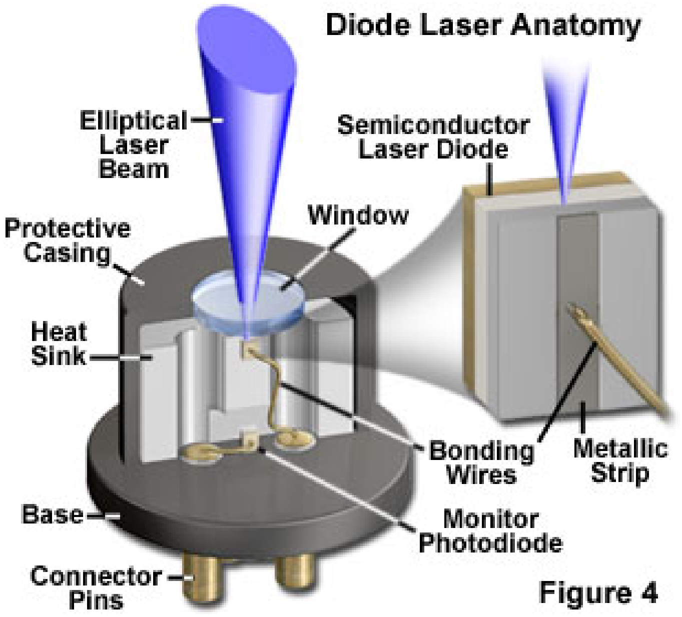
Semiconductor laser: laser diode

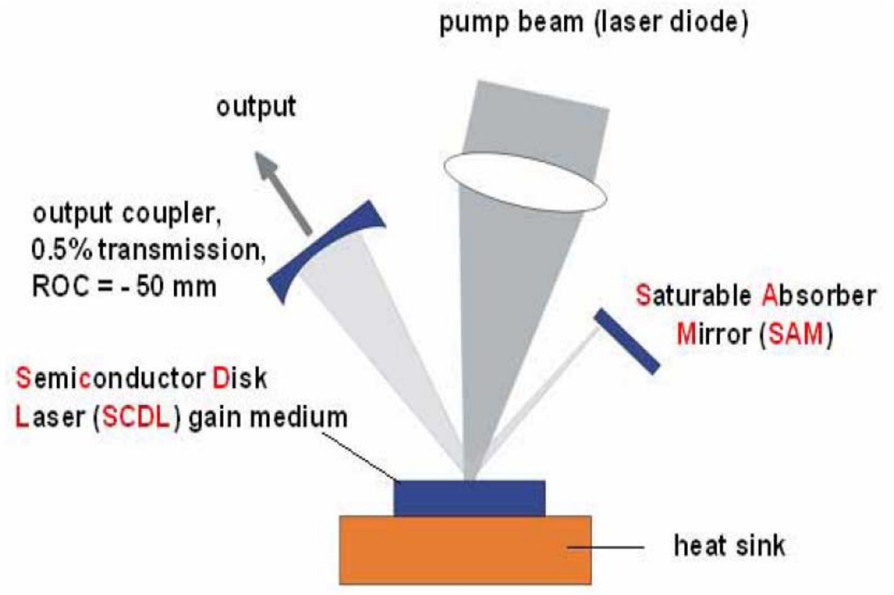


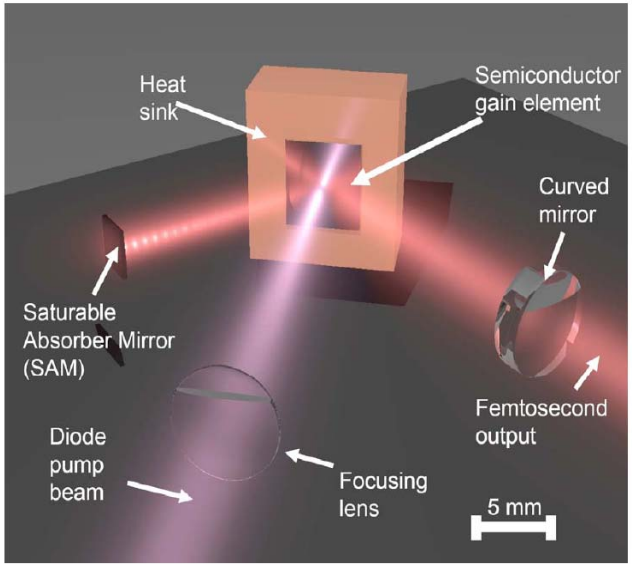


- Convert current into light, can be tuned by junction temperature
- Used mostly for pumping other lasers, also CD and DVD players
- VCSELs and VECSELs (virtical cavity surface emission lasers and virtical exteranl cavity surface emission lasers)
- Also for seeding pulse fiber lasers (next page)

Credit: http://www.olympusmicro.com/

Mode-locked semiconductor lasers: (using V)





$\lambda_{laser} \approx$ **1040 nm**

$\lambda_{pump} =$ **840 nm**

290-fs pulses from a semiconductor disk laser

Peter Klopp[1], Florian Saas[1], Martin Zorn[2], Markus Weyers[2], and Uwe Griebner[1*]

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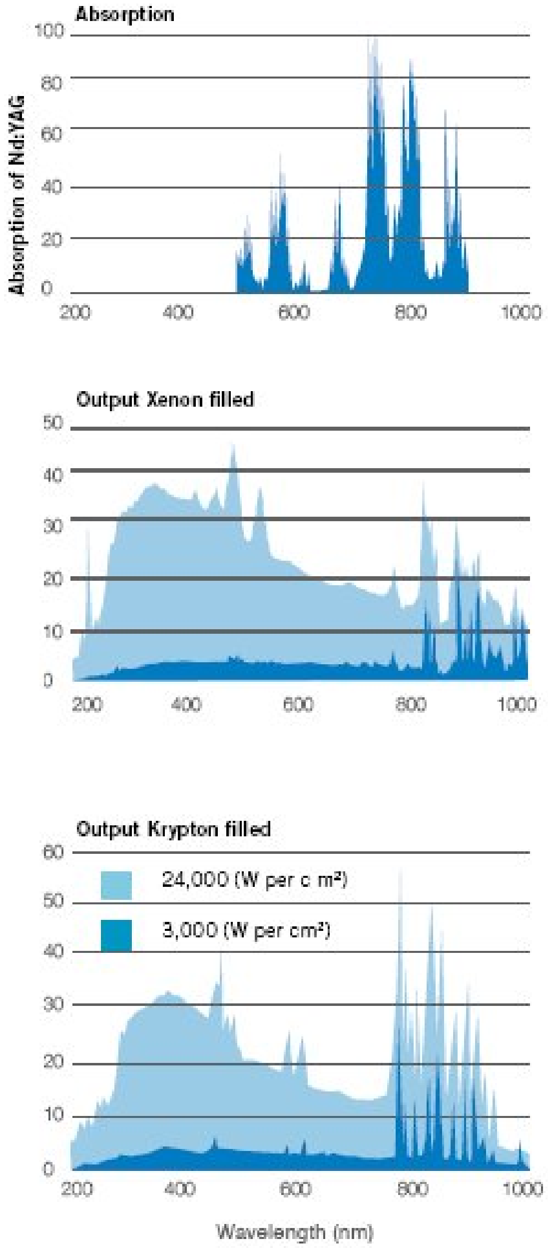
[2]Ferdinand-Braun-Institute, Gustav-Kirchhoff-Straße 4, D-12489 Berlin, Germany
**Corresponding author: griebner@mbi-berlin.de*

Opt. Express 16, 5770 (2008)

- Can achieve sub picosecond pulse duration
- 500 mW power
- Widely tunable
- Very high rep rate, up to 100 GHz

Pump for lasers

- Flash lamps:
  - Converts electrical power to light
  - Cheap, low pumping efficiency, and poor stability.
  - Still opted for situations when high energy capacity is the key (NIF), suitable for ruby laser, Nd:Glass, Nd:YAG, Nd:YLF, etc.
- Laser diodes:
  - converts electrical current into light
  - High efficiency, high stability especially in CW mode.
  - Opted now for most off the shelf KHz system and fiber lasers
- Pump lasers (Nd:YAG or Nd: YLF)
  - Both pumped by flash lamps and diodes
  - Normally for Ti: Sapphire system.



Fiber lasers

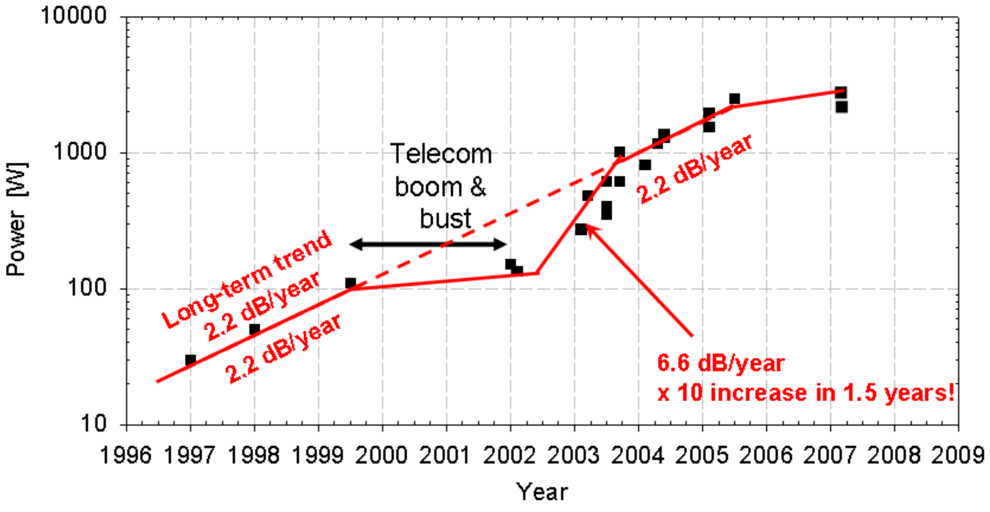
Power progress in fiber laser sources

Average power over 2 kW

limited by available pump

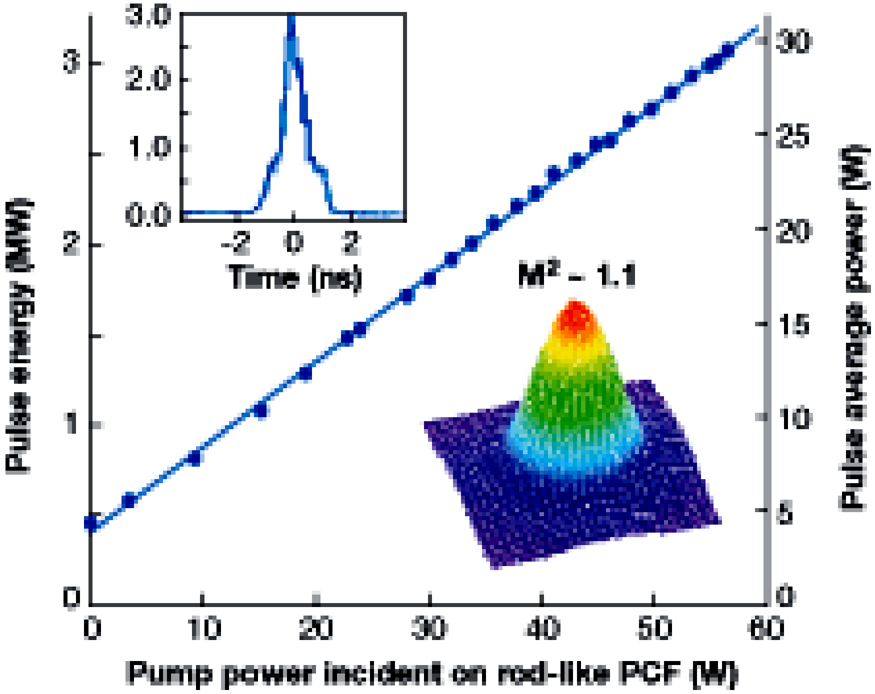
Peak Power over 1 MW

Ultra-high powers from fibres



Wavelength ~ 1.1 μm

Credit: David Richardson

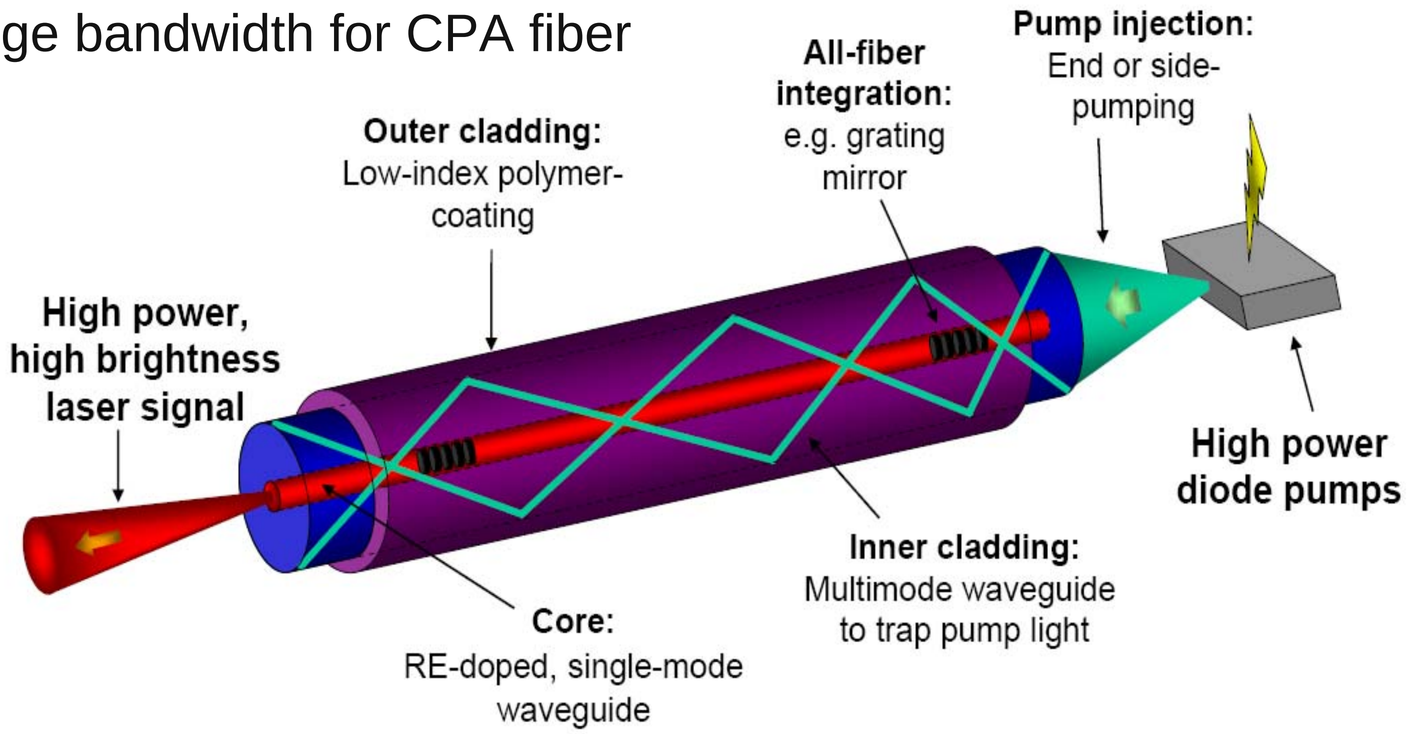


Teodoro et al, Laser Focus World, Nov. 2006

E. Snitzer, "Neodymium glass laser," Proc. of the Third International conference on Solid Lasers, Paris, page 999 (1963).
C.J. Koester and E.Snitzer, "Amplification in a fiber laser," Appl. Opt. 3, 10, 1182 (1964).

Laser configuration: Fiber lasers

- Can be a straight MOPA or a CPA
- Low threshold, high efficiency, high rep rate, high power
- No thermal problem, good stability
- Relatively large bandwidth for CPA fiber



Pump injection: End or side-pumping

All-fiber integration: e.g. grating mirror

Outer cladding: Low-index polymer-coating

High power, high brightness laser signal

High power diode pumps

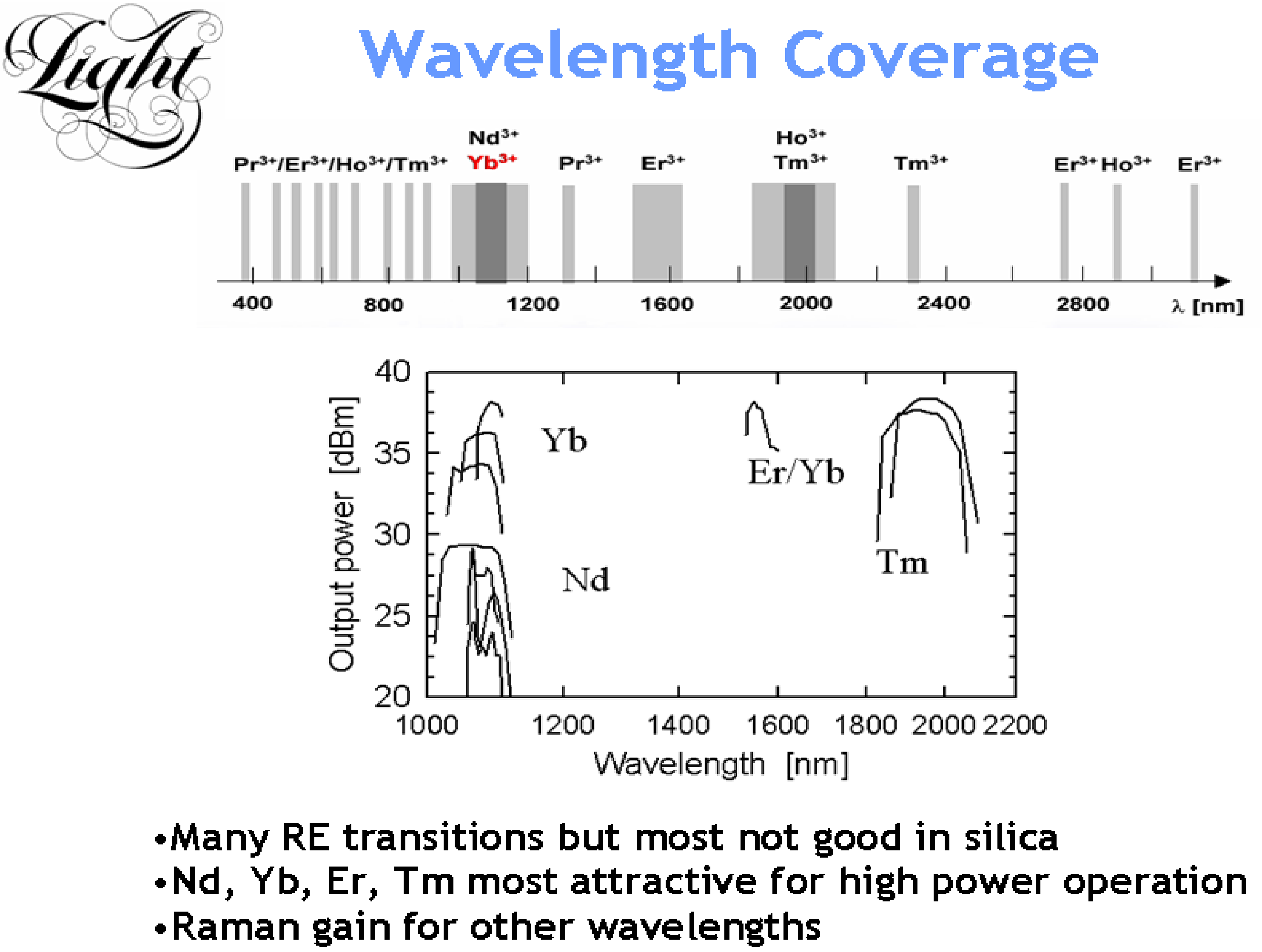
Inner cladding: Multimode waveguide to trap pump light

Core: RE-doped, single-mode waveguide

Rare-earth-doped core converts multimode pump energy to high brightness, *diffraction-limited*, signal beam

Credit: David Richardson
J. Limpert et al., 'High-power ultrafast fiber laser systems,' IEEE Xplore 12, 233 (2006).

Fiber laser wavelength



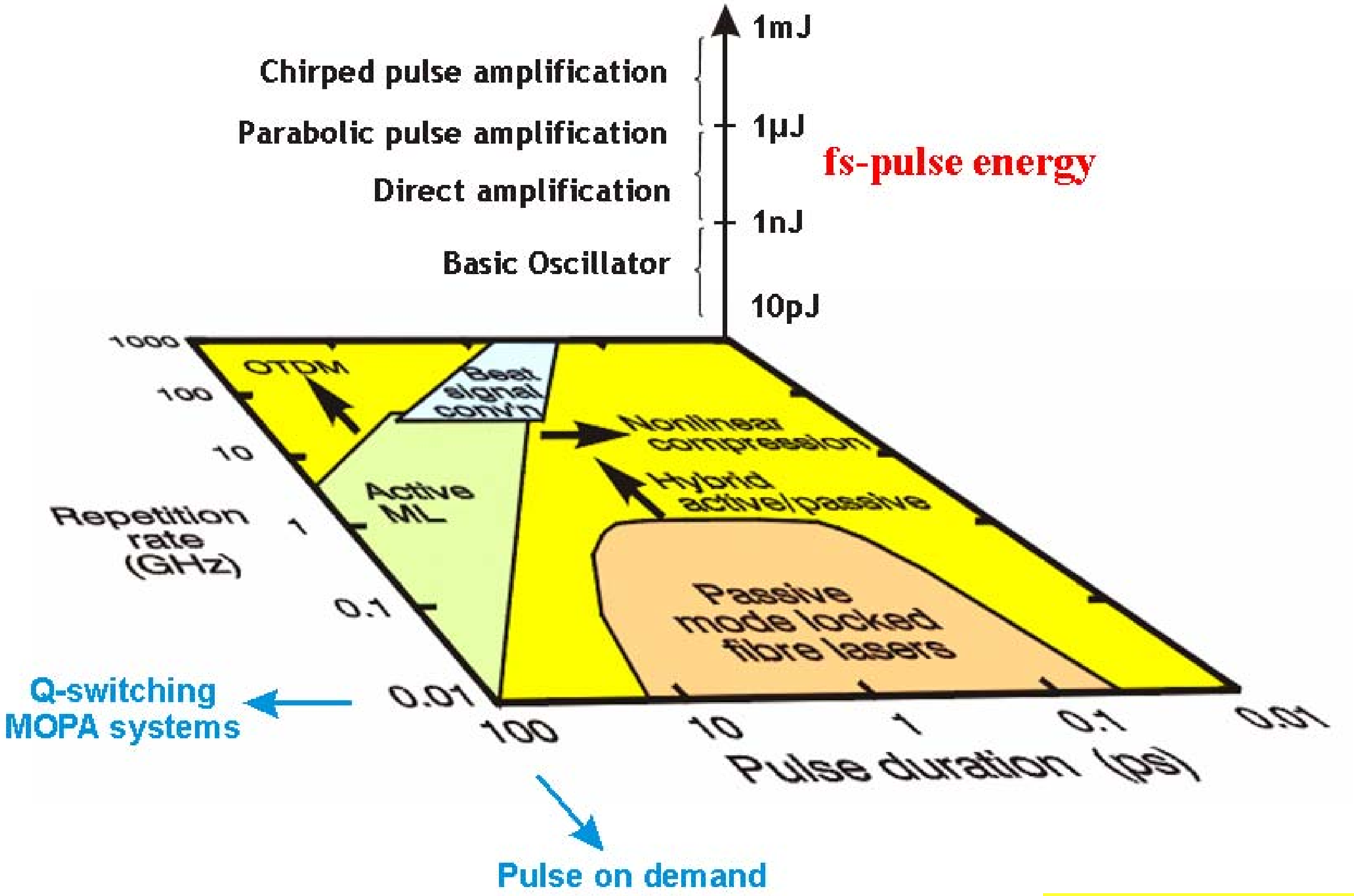
Wavelength Coverage

- Many RE transitions but most not good in silica
- Nd, Yb, Er, Tm most attractive for high power operation
- Raman gain for other wavelengths

Credit: David Richardson

Fiber laser capabilities

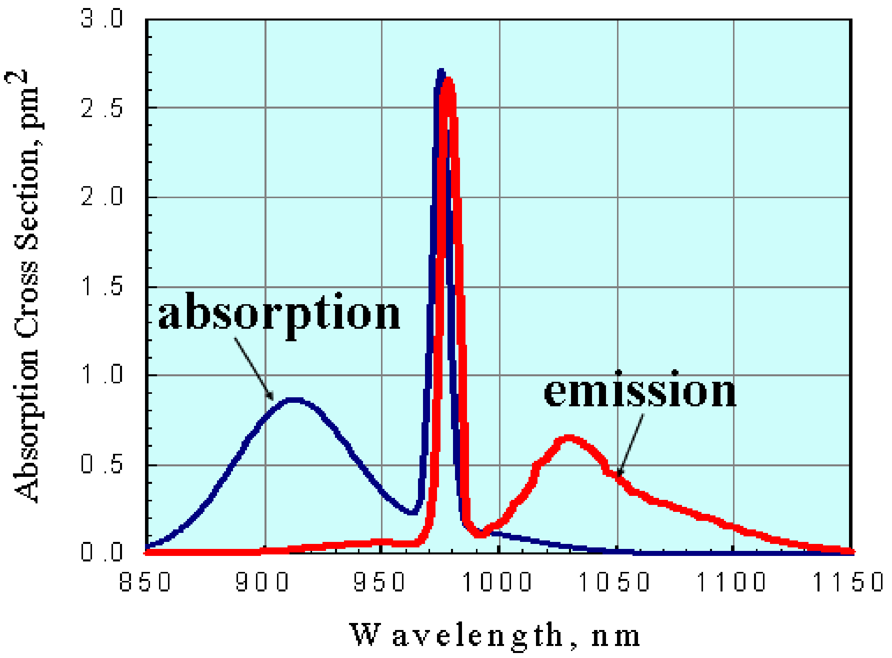
Operating regimes of fibre based ultrashort pulse sources



Credit: David Richardson

Fiber laser architecture

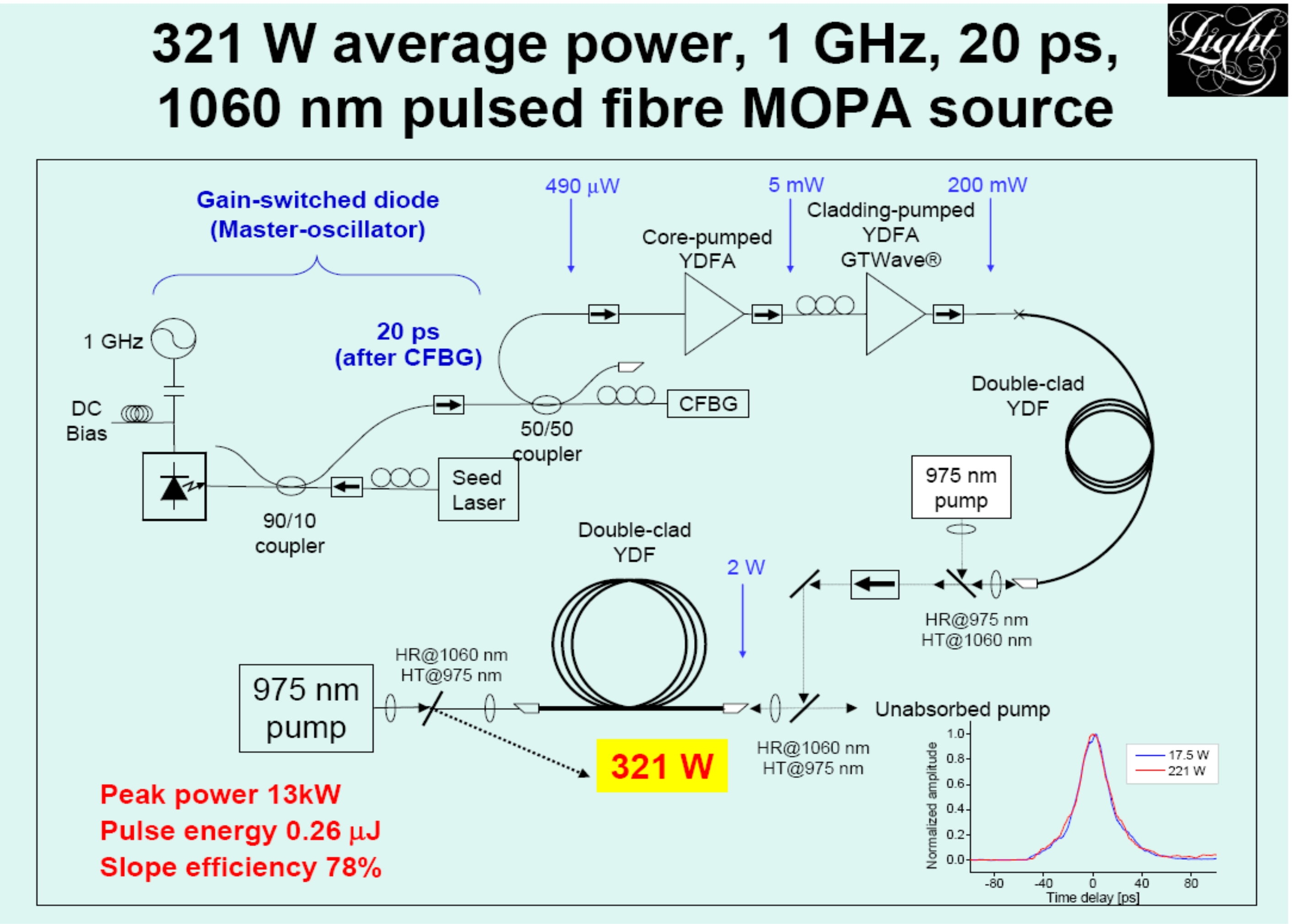
Yb-doped fibres for cladding pumping



- Pump bands at 915nm and 976nm
- Broad gain bandwidths around 1060nm
- Small quantum defect and high efficiency (~85%)

Credit: David Richardson

A short pulse MOPA fiber laser example
1 GHz, 20 ps, 321 W average and 13 kW peak power

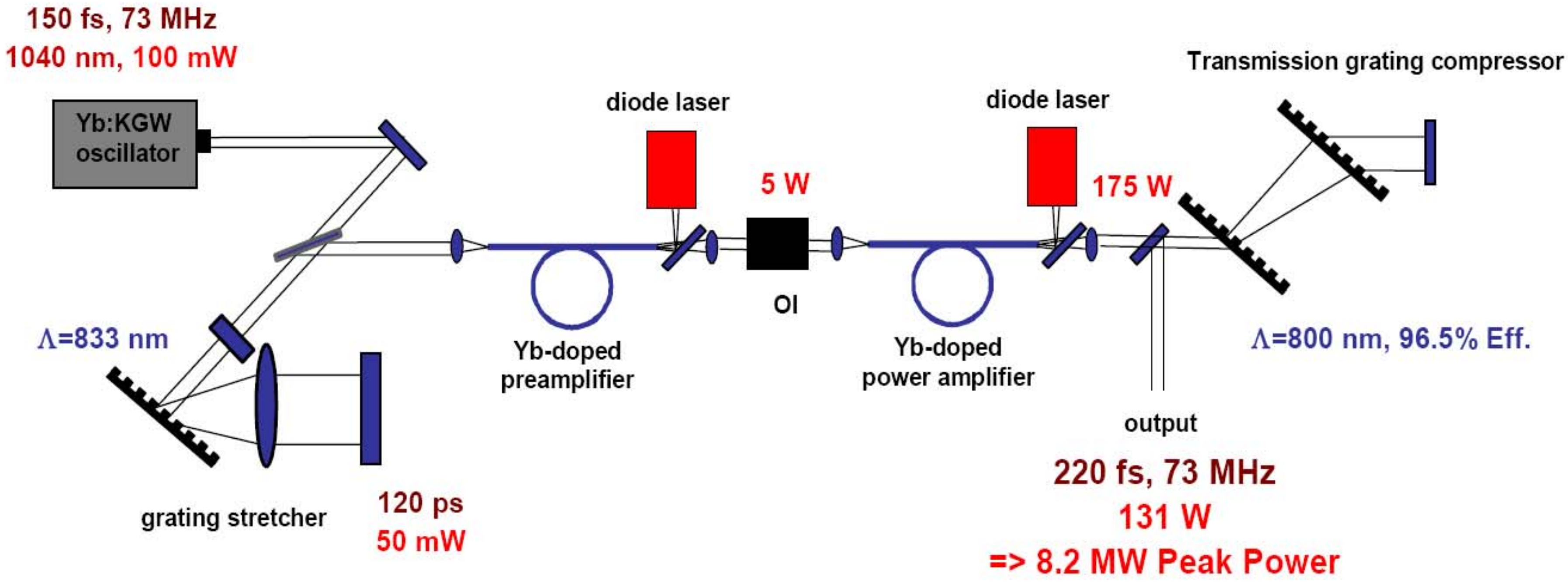


321 W average power, 1 GHz, 20 ps, 1060 nm pulsed fibre MOPA source

Peak power 13kW
Pulse energy 0.26 μJ
Slope efficiency 78%

Dupriez et al, http://www.ofcnfoec.org/materials/PDP3.pdf

A CPA fiber laser example
73 MHz, 220 fs, 131 W average and 8.2 MW peak power



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

Fig. 9: Schematic setup of the high average power fiber CPA system.

1 μm, 1 mJ, 1 ps, 50 kHz has been achieved, F. Roeser et al, Opt. Lett. 32, 3294 (2007)

J. Limpert et al., 'High-power ultrafast fiber laser systems,' IEEE Xplore 12, 233 (2006).

Content

- Laser and accelerator history
- Map of laser application in accelerators
- Laser basics
  - Rate equations
  - Laser configurations
  - Gaussian beam optics and ABCD law
  - Laser cavity and laser modes
- Laser configurations
  - Mode-lokcing and q-switch
  - MOPA
  - CPA and dispersion
- Laser materials
- Other lasers
  - Semiconductor lasers
  - Fiber lasers
- Frequency conversion and short wavelength lasers

Maxwell equation in a medium

The induced polarization, P, contains the effect of the medium:

$$\vec{\nabla} \cdot \vec{E} = 0 \qquad \vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

$$\vec{\nabla} \cdot \vec{B} = 0 \qquad \vec{\nabla} \times \vec{B} = \mu_0 \varepsilon_0 \frac{\partial \vec{E}}{\partial t} + \mu_0 \frac{\partial \vec{P}}{\partial t}$$

The induced polarization in Maxwell's Equations yields another term in the wave equation:

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

As we've learned, this is the "Inhomogeneous Wave Equation."

The polarization is the driving term for a new solution to this equation.

Credit: R. Trebino

Maxwell equation in a nonlinear medium

Nonlinear optics is what happens when the polarization is the result of higher-order (nonlinear!) terms in the field:

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

What are the effects of such nonlinear terms?
Consider the second-order term:

Since $\mathscr{E}(t) \propto E \exp(i\omega t) + E^* \exp(-i\omega t)$,

$$\mathscr{E}(t)^2 \propto \underset{\uparrow}{E^2 \exp(2i\omega t)} + 2|E|^2 + \underset{\uparrow}{E^{*2} \exp(-2i\omega t)}$$

2ω = 2nd harmonic!

Harmonic generation is one of many exotic effects that can arise!

Credit: R. Trebino

Sum and difference frequency generation

Suppose there are two different-color beams present:

$$E_1 \exp(i\omega_1 t) + E_1^* \exp(-i\omega_1 t) \qquad E_2 \exp(i\omega_2 t) + E_2^* \exp(-i\omega_2 t)$$

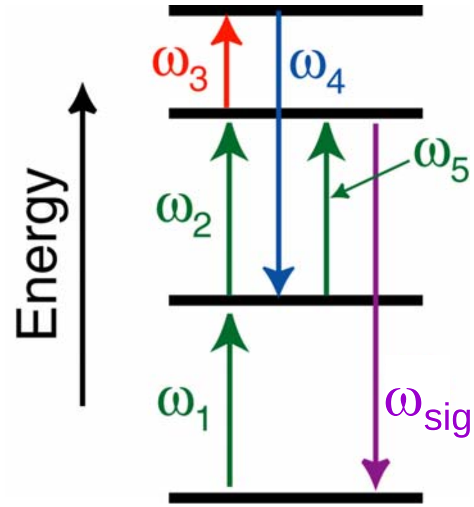
So:

$$\begin{aligned}
E(t)^2 \propto\; & E_1^2 \exp(2i\omega_1 t) + E_1^{*2} \exp(-2i\omega_1 t) && \textbf{2nd-harmonic gen} \\
& + E_2^2 \exp(2i\omega_2 t) + E_2^{*2} \exp(-2i\omega_2 t) && \textbf{2nd-harmonic gen} \\
& + 2E_1E_2 \exp\left[i(\omega_1+\omega_2)t\right] + 2E_1^*E_2^* \exp\left[-i(\omega_1+\omega_2)t\right] && \textbf{Sum-freq gen} \\
& + 2E_1E_2^* \exp\left[i(\omega_1-\omega_2)t\right] + 2E_1^*E_2 \exp\left[-i(\omega_1-\omega_2)t\right] && \textbf{Diff-freq gen} \\
& + 2\left|E_1\right|^2 + 2\left|E_2\right|^2 && \textbf{dc rectification}
\end{aligned}$$

Note also that, when ω_i is negative inside the exp, the E in front has a *.

Credit: R. Trebino

Conservation laws and phase matching

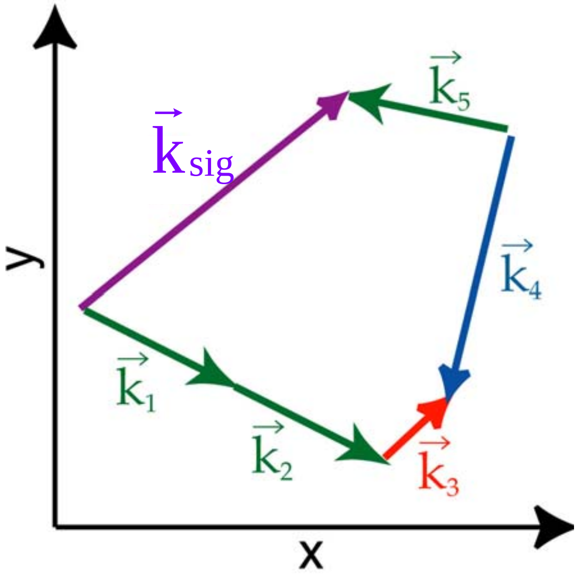


Energy must be conserved:

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

Momentum must also be conserved:

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



Unfortunately, $\vec{k}_{sig}$ may not correspond to a light wave at frequency ω_{sig}!

Satisfying these two relations simultaneously is called "**phase-matching**."

Credit: R. Trebino

Phase matching and conversion efficiency

- Small signal second harmonic conversion efficiency

$$I_{2\omega} = C^2 L^2 I_\omega^2 \frac{\sin^2 \frac{\Delta k L}{2}}{\left(\frac{\Delta k L}{2}\right)^2} = C^2 L^2 I_\omega^2 \sin c^2 \frac{\pi L}{2 l_c},$$

$$C^2 = \frac{8\pi^2 d_{eff}^2}{\varepsilon_0 c \lambda_0^2 n_0^3} = 5.46 \frac{d_{eff}}{\lambda_0 n^{3/2}}$$

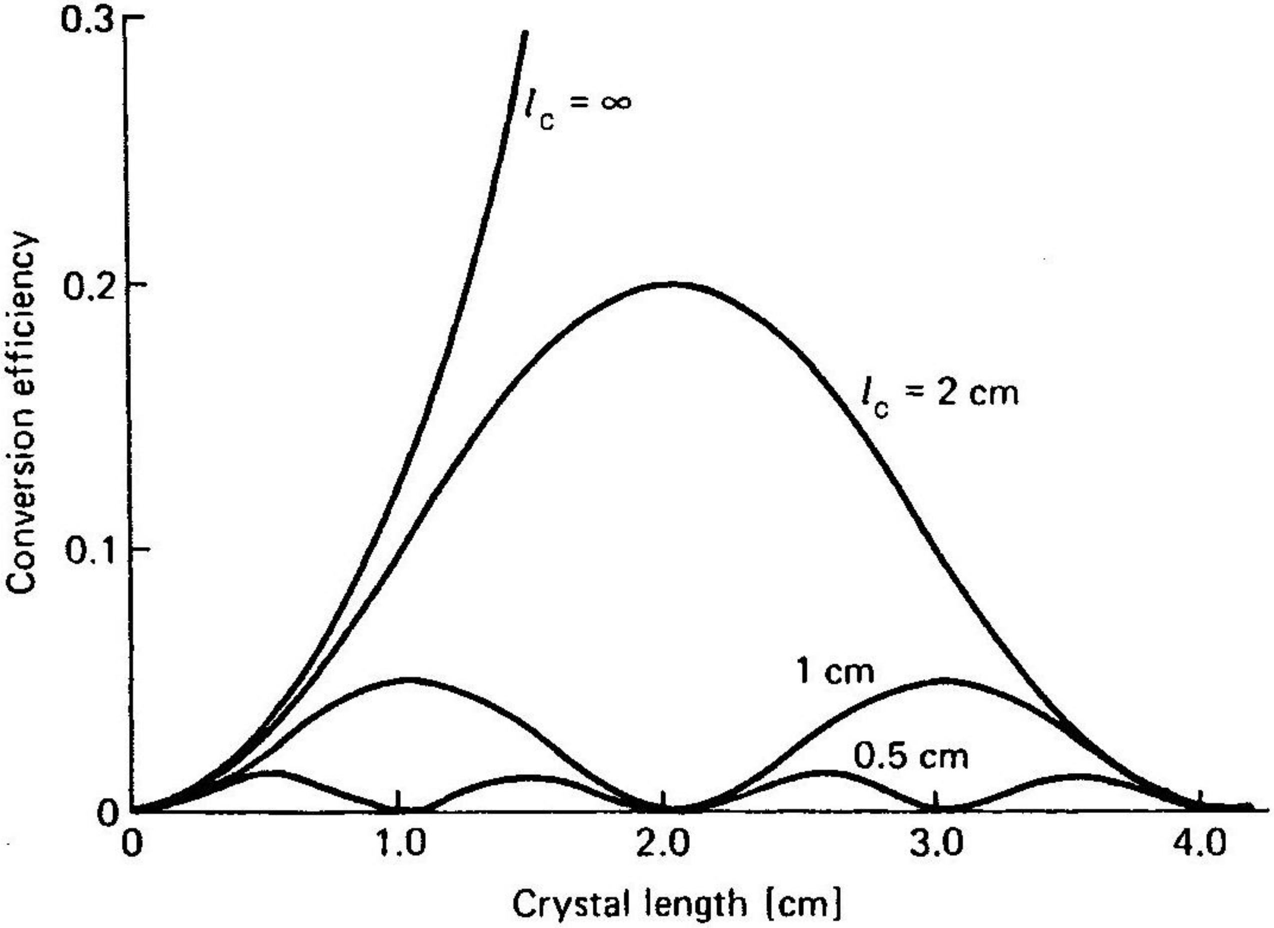
$\Delta k = 4\pi/\lambda_1 (n_1 - n_2)$: difference in wave umber
L: crystal length
$l_c = \pi/\Delta k$, coherence length (when phase is matched)
d_{eff}: effective nonlinear coefficient, in m/V

Credit: W. Koechner: Solid State Laser engineering,

Conversion efficiency at small signal

- The small signal conversion efficiency and effect of phase mismatch

$$\eta = C^2 L^2 \sin c^2 \frac{\pi L}{2 l_c}$$

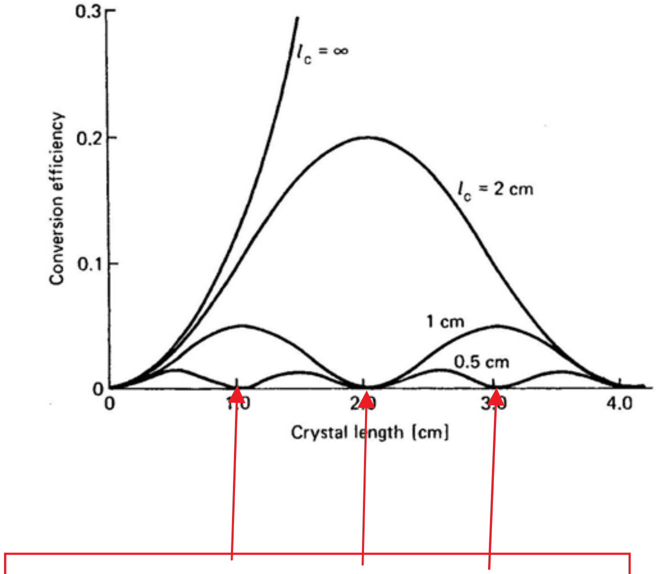


Credit: W. Koechner: Solid State Laser engineering,

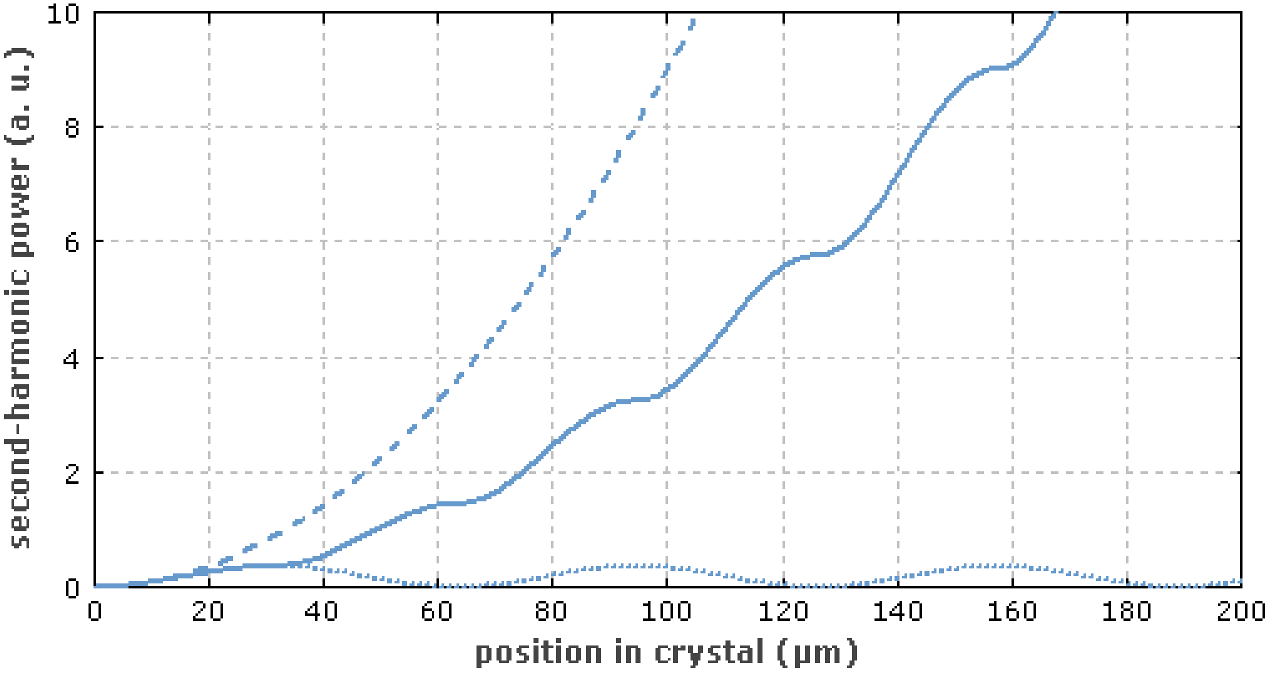
Quasi phase matching

- Quasi-phase matching

  Achieve phase matching by modulating the spatial nonlinear property



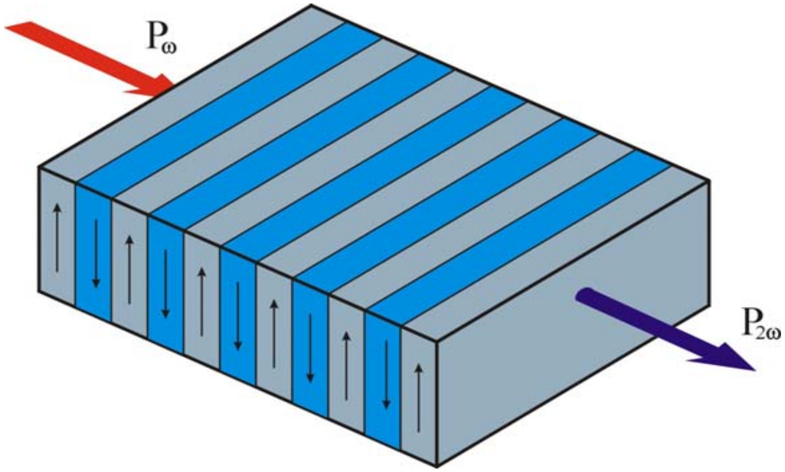
Tune the interaction here

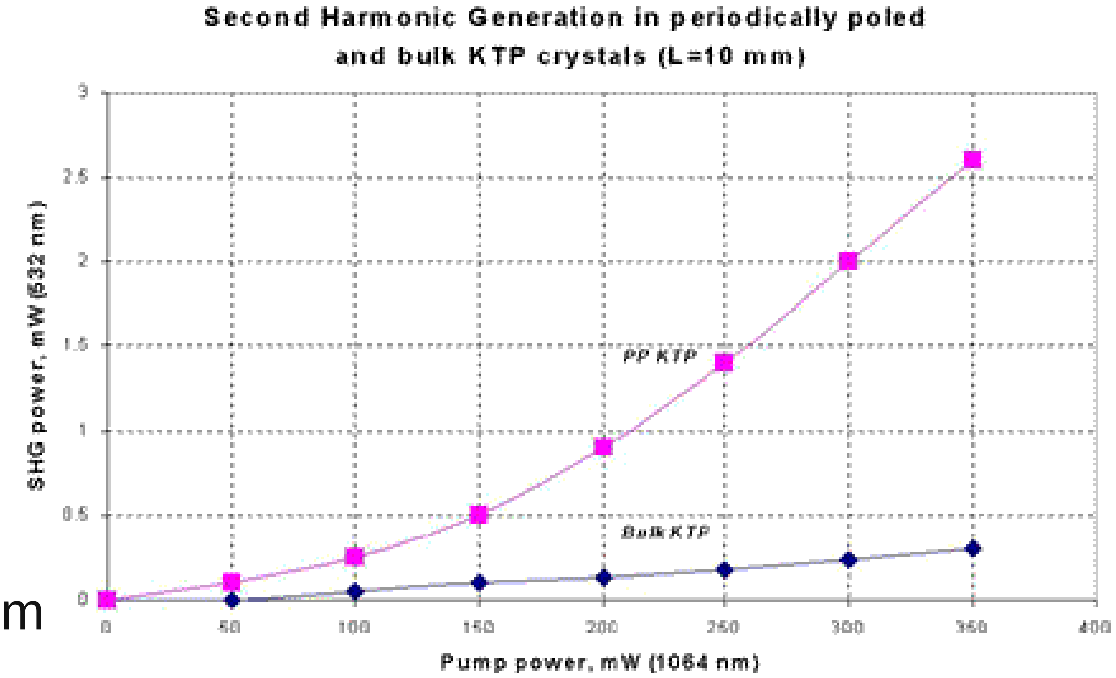


Encyclopedia of Laser Physics and Technology
http://www.rp-photonics.com

Quasi-phase matching: Periodically poling crystals

- The most popular technique for generating quasi-phase-matched crystals is periodic poling of ferroelectric nonlinear crystal materials





Wavelength Range: 400-4000 nm
Dimensions:
    Thickness: up to 1 mm
    Width (typical): 2 mm
    Length: up to 30 mm

Credit: www.raicol.com/products.asp

Pump depletion and signal saturation

- Phase match, with pump depletion

$$I_{2\omega} = I_{\omega} \tanh^2\left(CLI_{\omega}^{1/2} \sin c \frac{\pi L}{2l_c} \right),$$

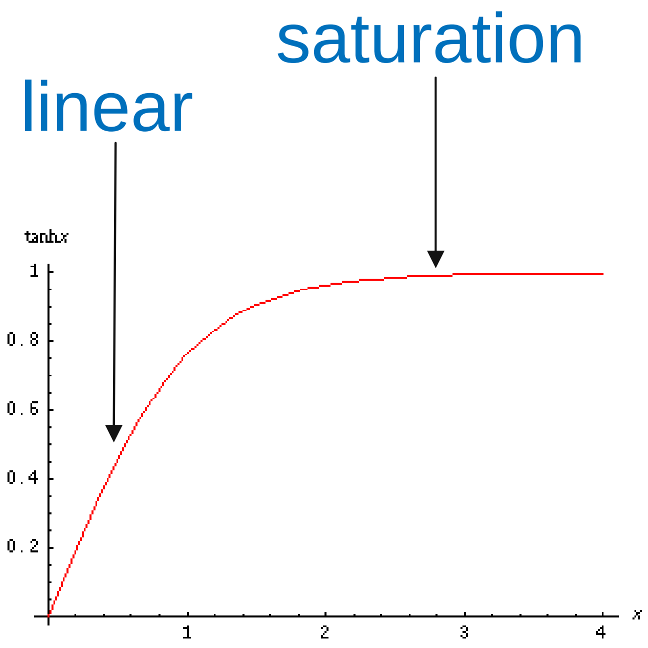
- Consider frequency quadrupling
  - At low pump power, highly nonlinear

$$I_{2\omega} \propto I_{\omega}^2$$

$$\Rightarrow I_{4\omega} \propto I_{2\omega}^2 \propto I_{\omega}^4$$

- Consider frequency quadrupling
  - At high pump power, linear, desired

$$\boxed{\begin{aligned} & I_{2\omega} \propto I_{\omega} \\ & \Rightarrow I_{4\omega} \propto I_{2\omega} \propto I_{\omega} \end{aligned}}$$

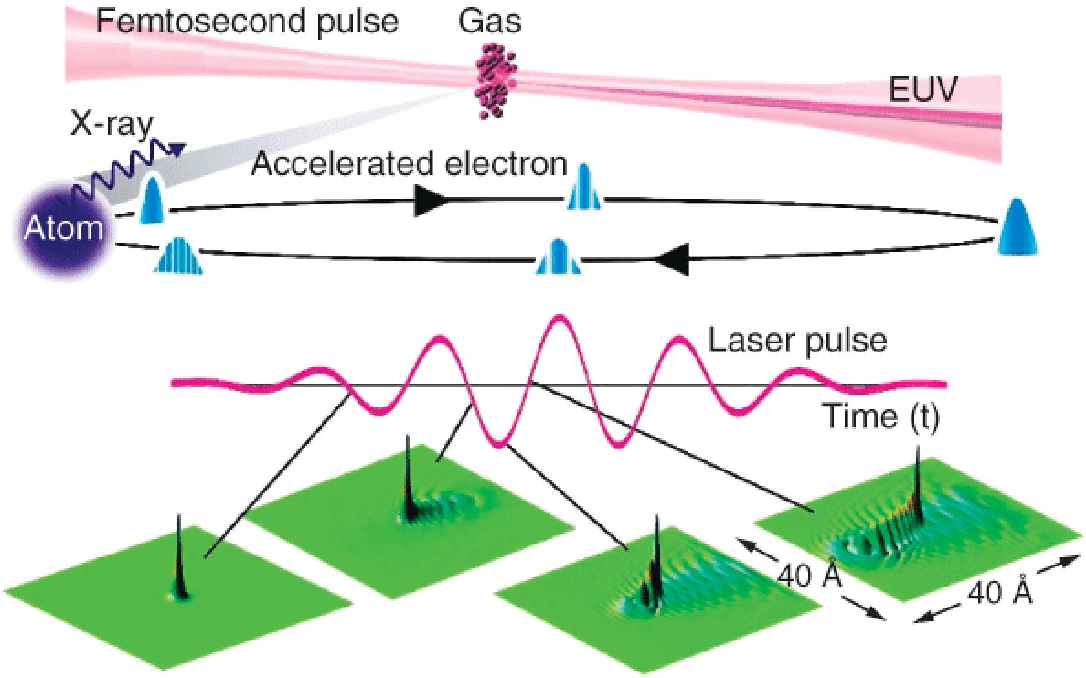


saturation

linear

Frequency conversion: High order harmonics generation

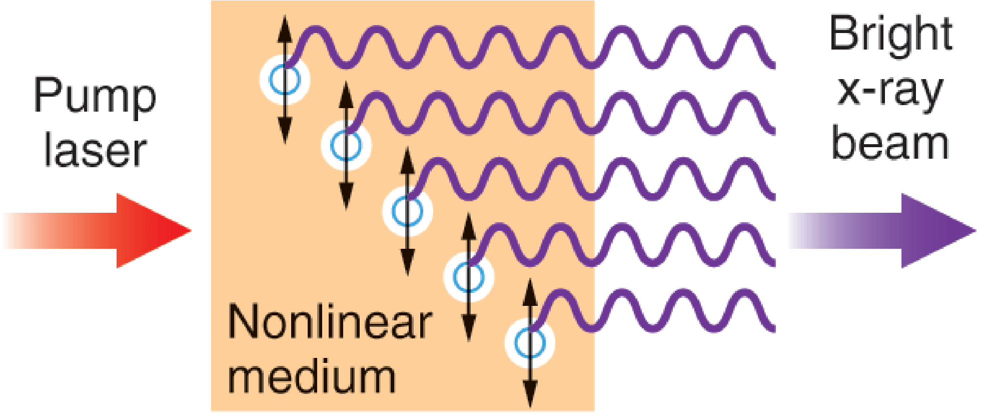
- Atoms as the nonlinear media
- Emission due to multiple photon absorption of electrons bounded to an atom
- Carry over the spatial coherence of the driving laser
- Of short pulse duration comparable or shorter than the drive laser up to attoseconds
- Currently at ~10 nm.

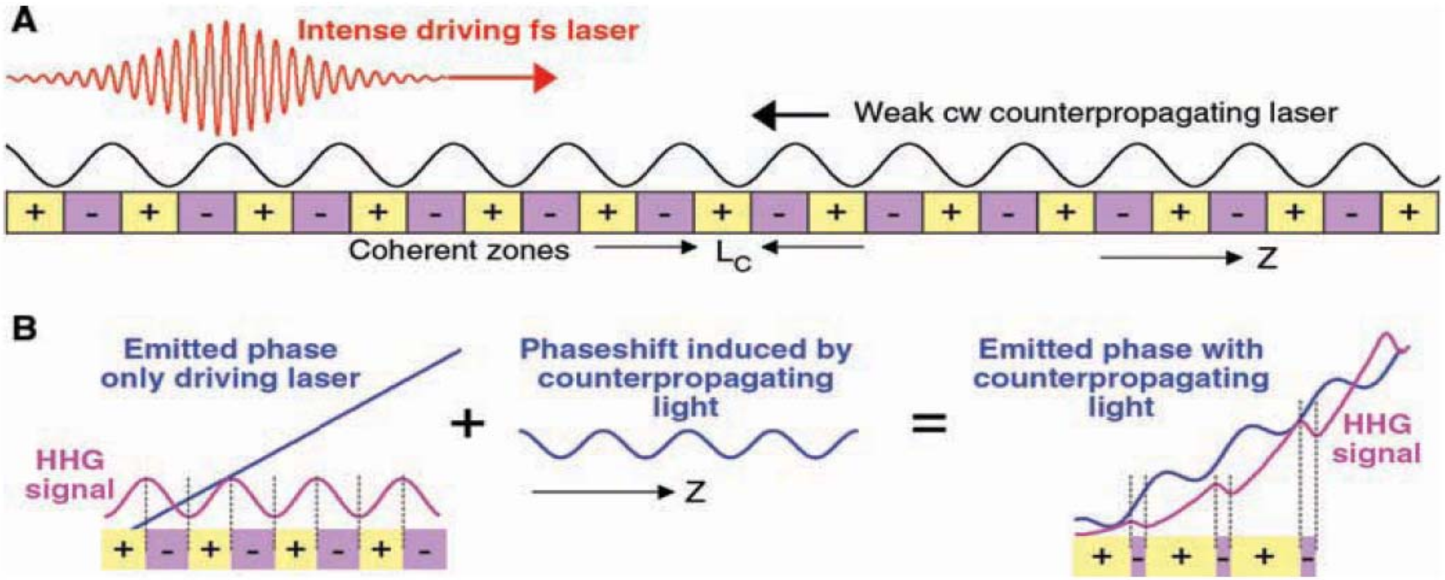


H. Kaptyn et al., 'Harnessing Attosecond Science in the Quest for Coherent X-rays,' Science 317, 775 (2007).

High order harmonics generation: phase matching

- Phase mismatching due to group velocity difference or continuous signal emission or group velocity mismatch
- Can be accomplished by modulating the interaction via modulated laser propagation or counter propagating beams

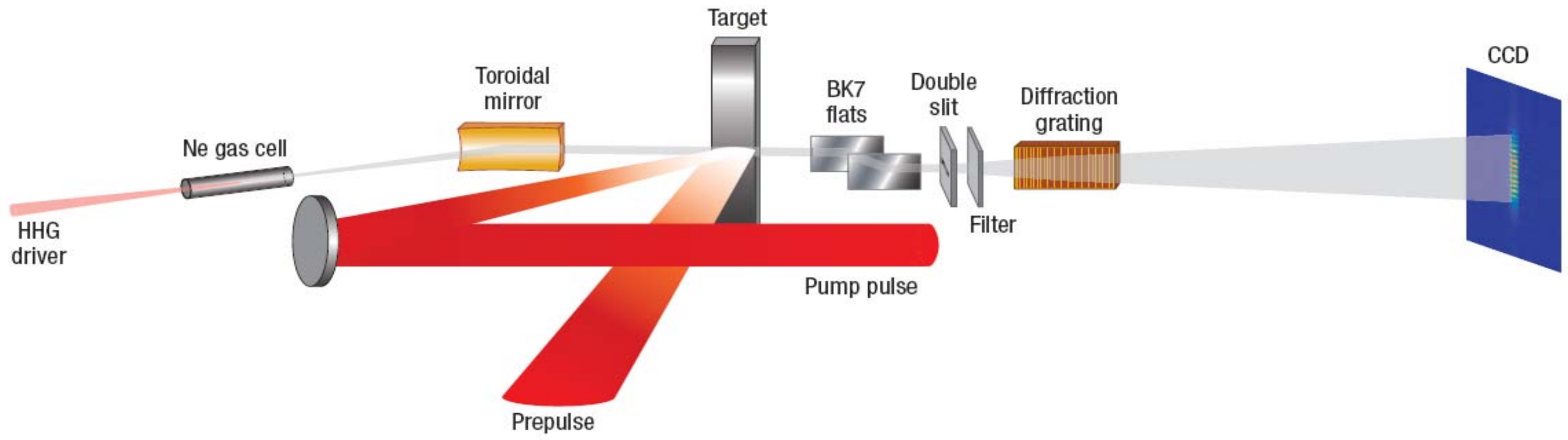




H. Kaptyn et al., 'Harnessing Attosecond Science in the Quest for Coherent X-rays,' Science 317, 775 (2007).

Short wavelength lasers

- Plasma base soft-x-ray lasers
  - Still a traditional laser based on population inversion, but in hot dense plasma to accommodate the high energy difference between atomic levels, wavelength from 1 nm to 100 nm.
  - Can be pumped by laser, discharge, and bombs
  - Challenges: tunability and capability for shorter wavelengths, stabilities
  - J. Hecht, “The history of X-ray lasers,” Optics & Photonics News 19, 26 (2008); Y. Wang et al., Nature Photonics 2, 94 (2008)



Short wavelength lasers

- X-ray Free electron lasers: 0.1 nm, high brightness, high transverse coherence, etc.
- Design with cavity going on
- Many projects going on