ULTRAFAST OPTICS

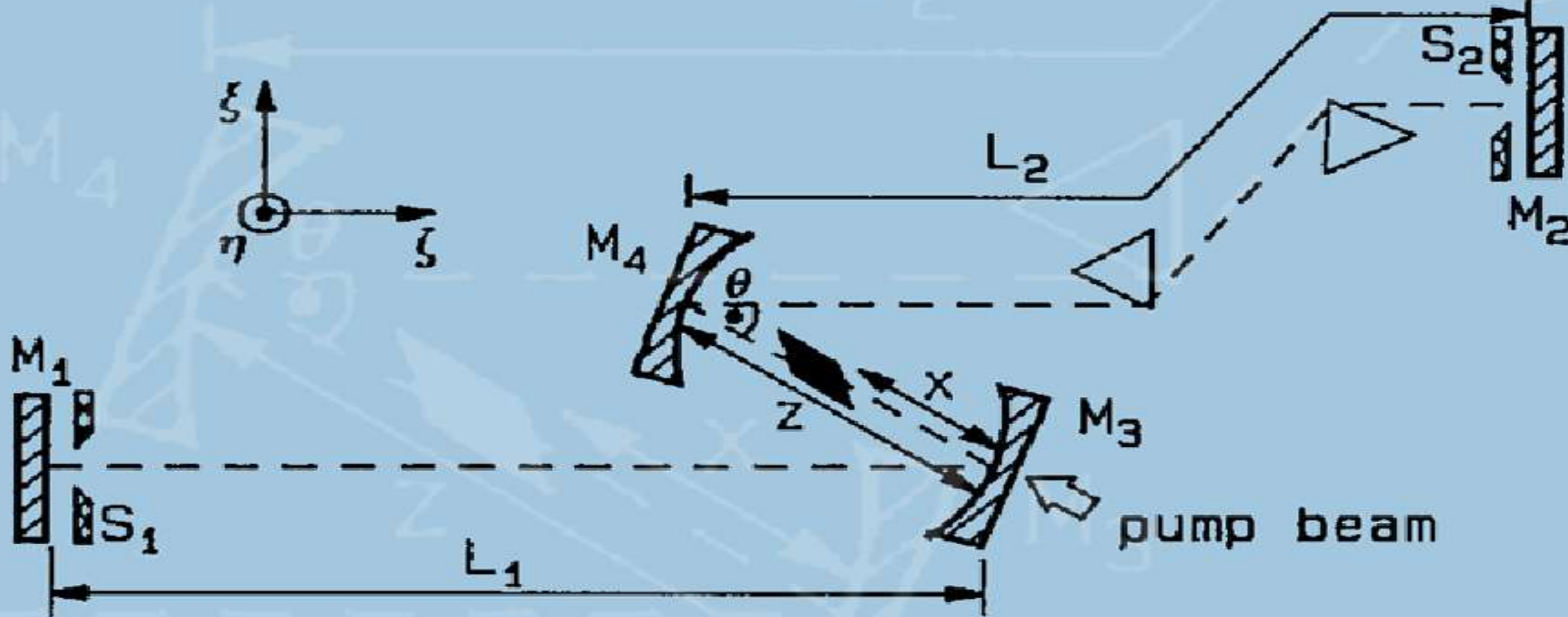


image from G. Cerullo et al., Opt. Lett. 19, 807 (1994), © OSA

by PIOTR WASYLCZYK

Lecture 3. Generation of Ultrashort Laser Pulses

The importance of bandwidth

Laser modes and mode-locking

Passive mode-locking and the saturable absorber

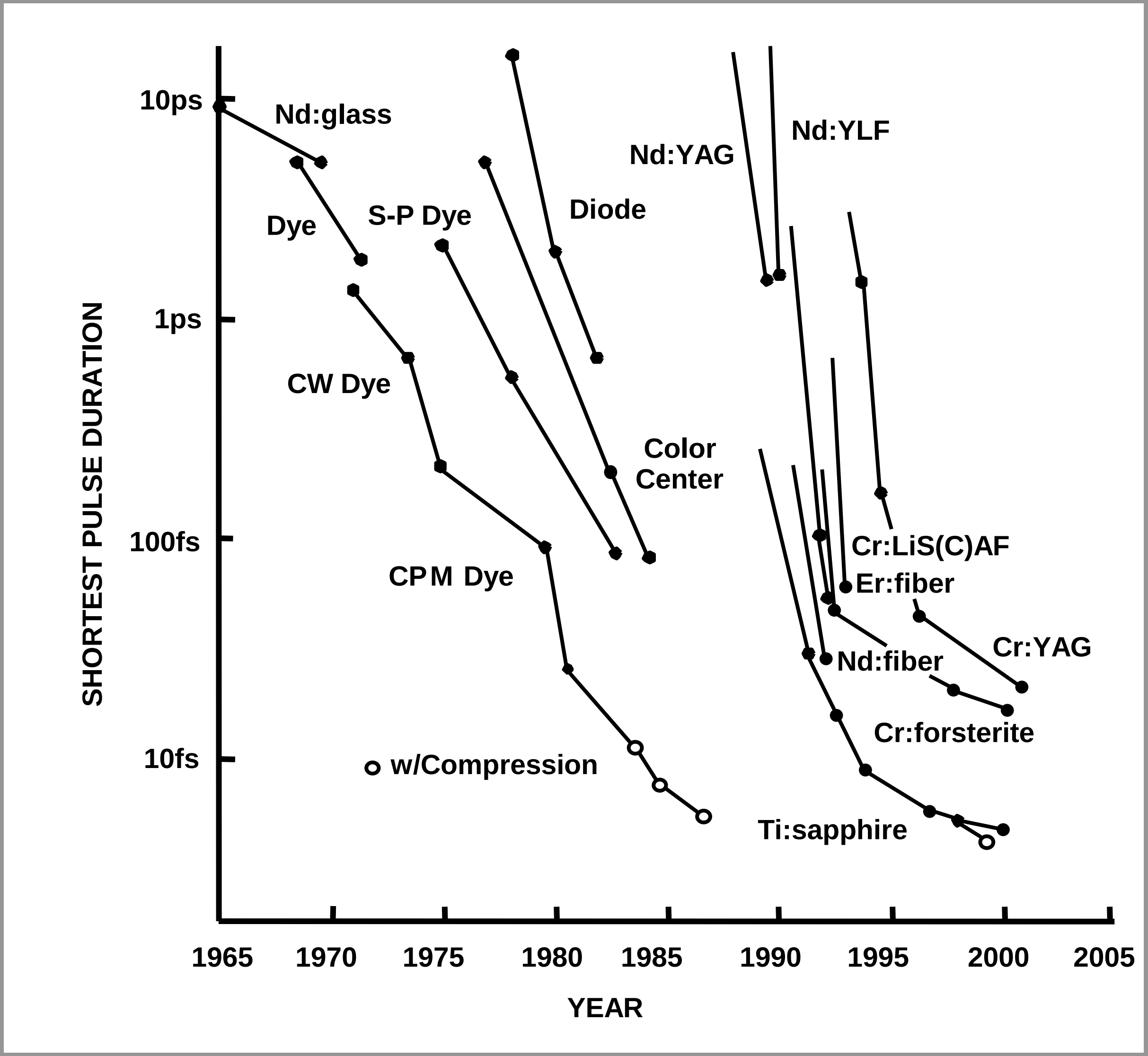
Kerr-lensing and Ti:Sapphire

Fiber mode-locking techniques

Limiting factors

Commercial lasers

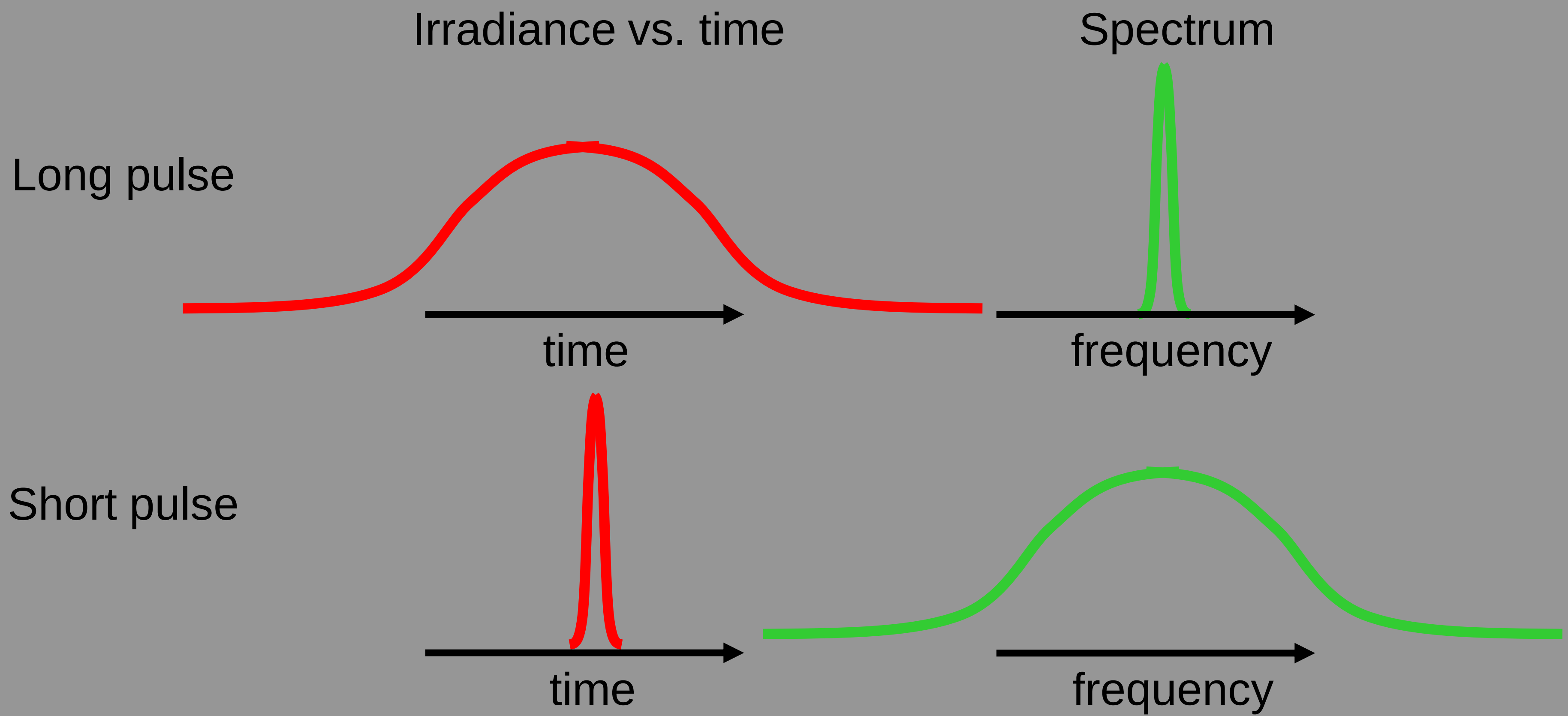
But first: the progress has been amazing!



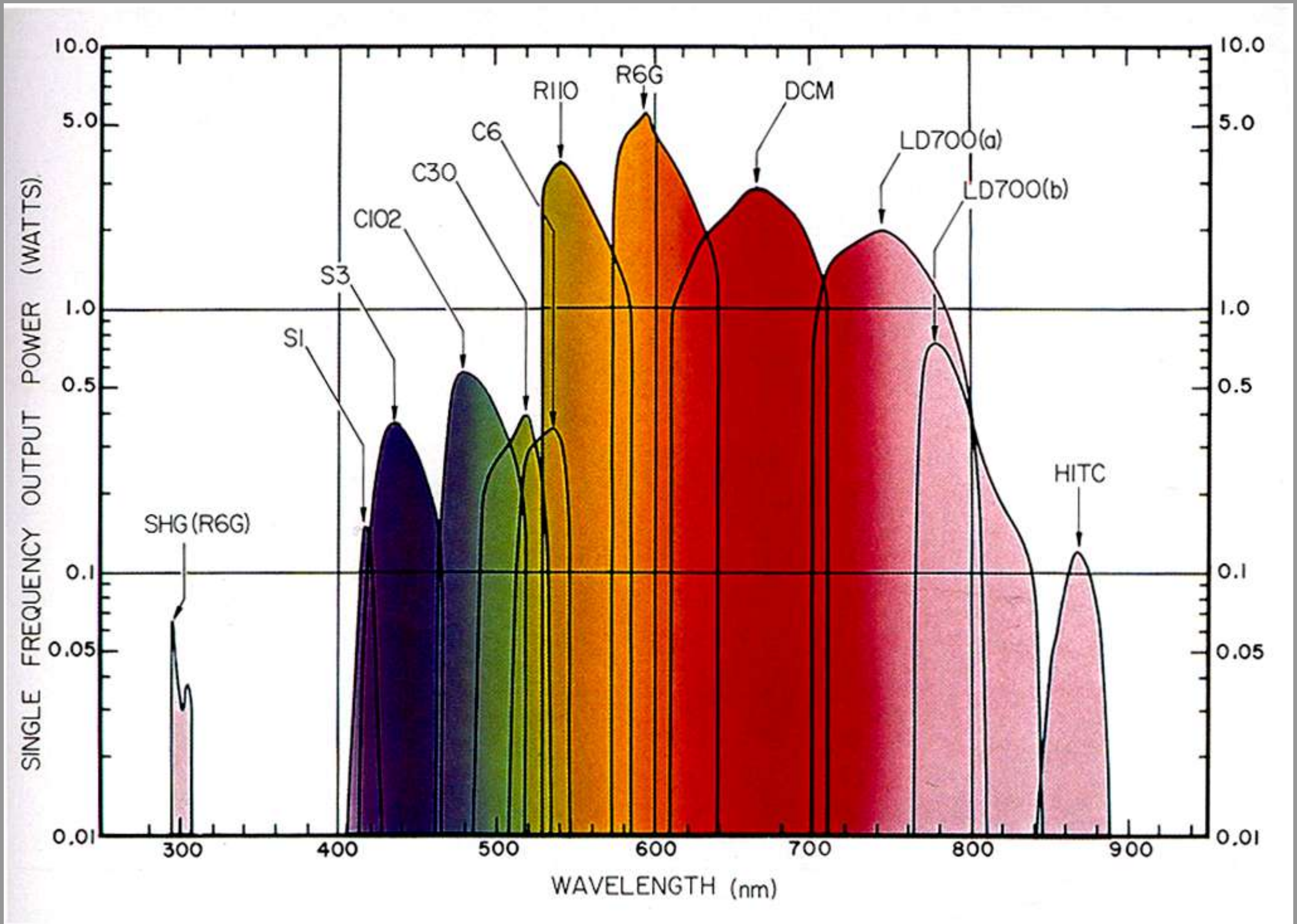
The shortest pulse vs. year (for different media)

Long vs. short pulses of light

The uncertainty principle says that the product of the temporal and spectral pulse widths is greater than ~1.

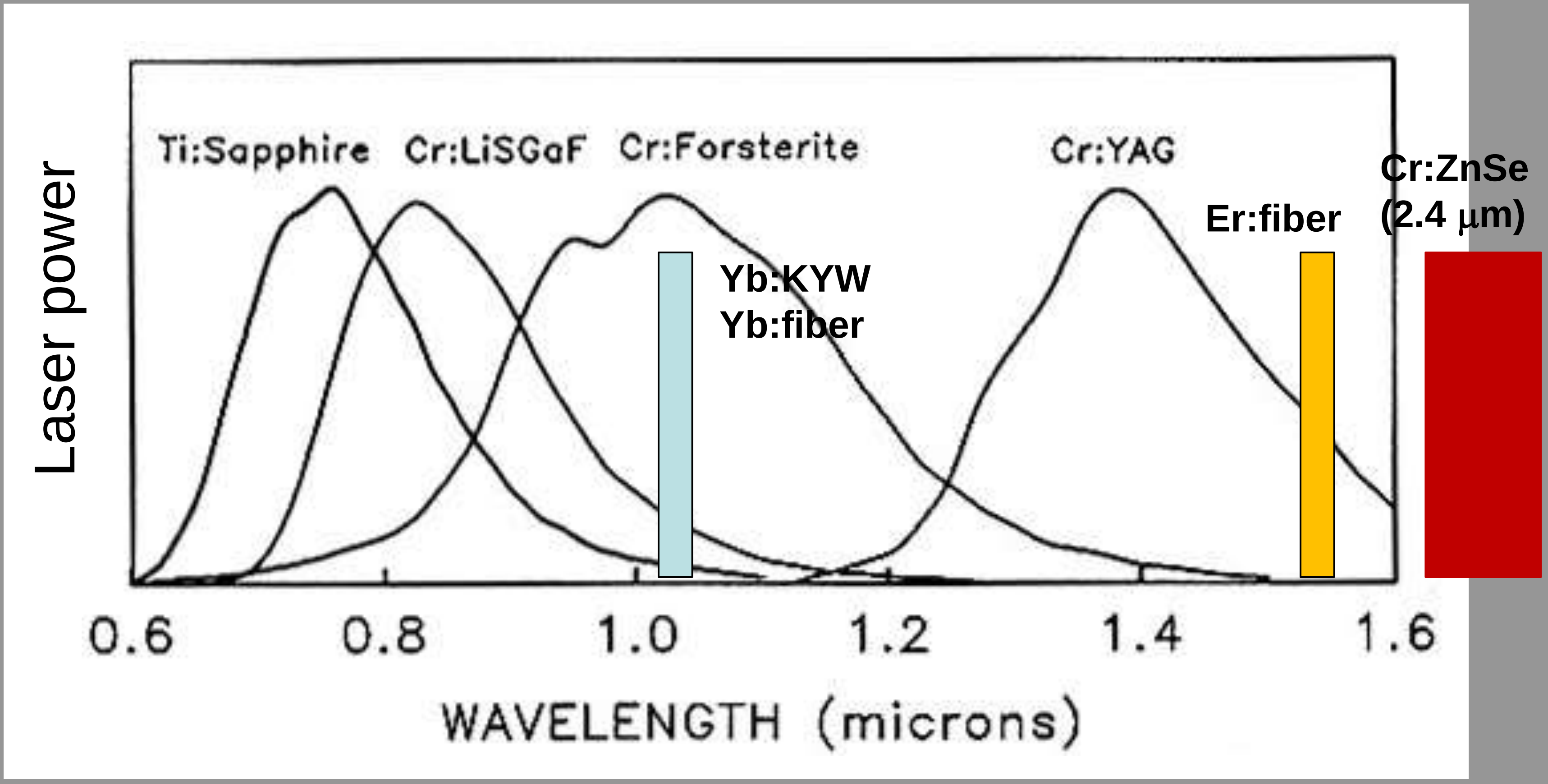


For many years, dyes have been the broadband media that have generated ultrashort laser pulses



Ultrafast solid-state laser media have replaced dyes around 1990's

Solid-state laser media have broad bandwidths and are convenient.



Light bulbs, lasers, and ultrashort pulses

But a light bulb is also broadband.

What exactly is required to make an ultrashort pulse?

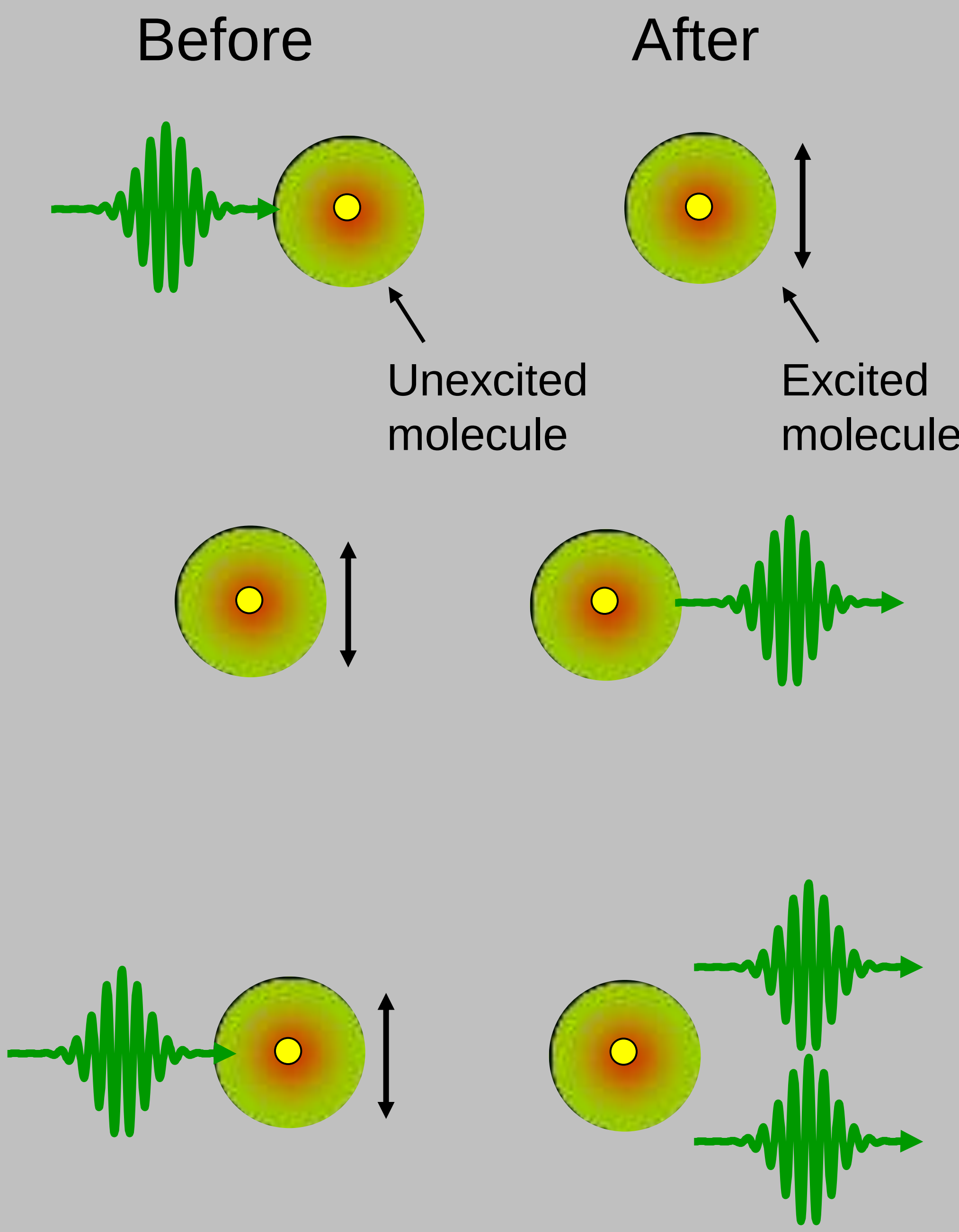
Answer: **A Mode-locked Laser**

Okay, what's a laser, what are modes, and what does it mean to lock them?

Absorption

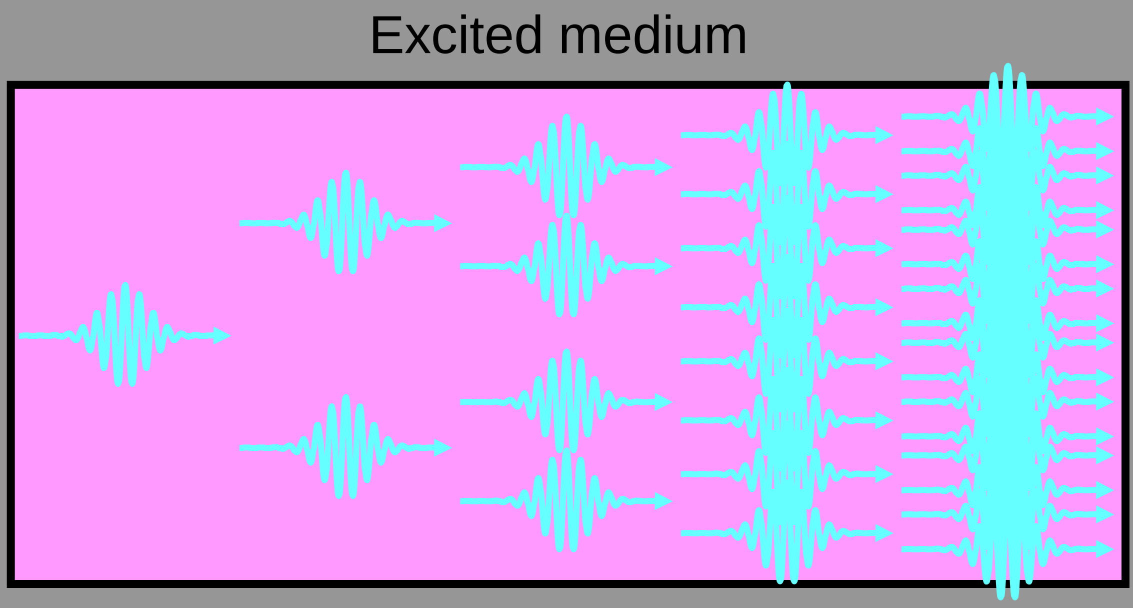
Spontaneous Emission

Stimulated Emission



Stimulated emission leads to a chain reaction and laser emission.

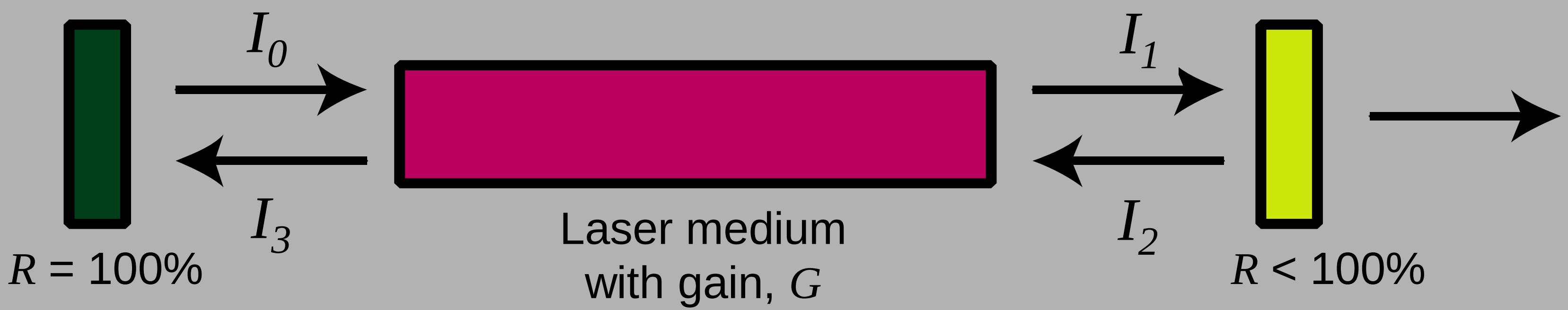
If a medium has many excited molecules, one photon can become many.



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.

The laser

A laser is a medium that stores energy, surrounded by two mirrors.
A partially reflecting output mirror lets some light out.



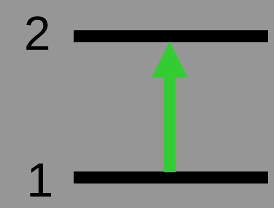
A laser will lase if the beam increases in intensity during a round trip: that is, if $I_3 \geq I_0$

Usually, additional **losses** in intensity occur, such as absorption, scattering, and reflections. In general, the laser will lase if, in a round trip:

Gain > Loss

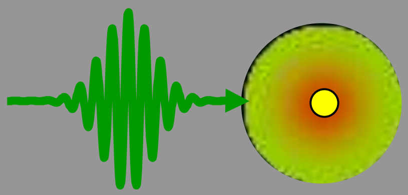
This called achieving **Threshold**.

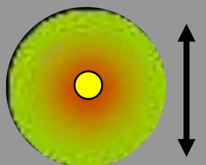
Calculating the gain: Einstein A and B coefficients



In 1916, Einstein considered the various transition rates between molecular states (say, 1 and 2) involving light of irradiance, I:

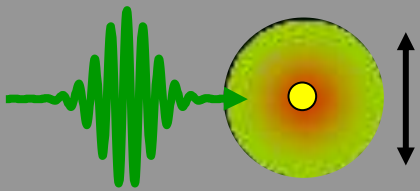
Absorption rate = $B\,N_1\,I$





Spontaneous emission rate = $A\,N_2$

Stimulated emission rate = $B\,N_2\,I$



Laser gain

Neglecting spontaneous emission:

$$\frac{dI}{dt} = \text{v}_g \frac{dI}{dz} \propto BN_2I - BN_1I$$

[Stimulated emission minus absorption]

$$\propto B\left[N_2 - N_1\right]I$$

The solution is:

Proportionality constant is the absorption/gain cross-section, σ

$$I(z) = I(0)\exp\left\{\sigma\left[N_2 - N_1\right]z\right\}$$

There can be exponential gain or loss in irradiance. Normally, $N_2 < N_1$, and there is loss (absorption). But if $N_2 > N_1$, there's gain, and we define the gain, G:

$$\boxed{G \equiv \exp\left\{\sigma\left[N_2 - N_1\right]z\right\}}$$

If $N_2 > N_1$: $g \equiv \left[N_2 - N_1\right]\sigma$

If $N_2 < N_1$: $\alpha \equiv \left[N_1 - N_2\right]\sigma$

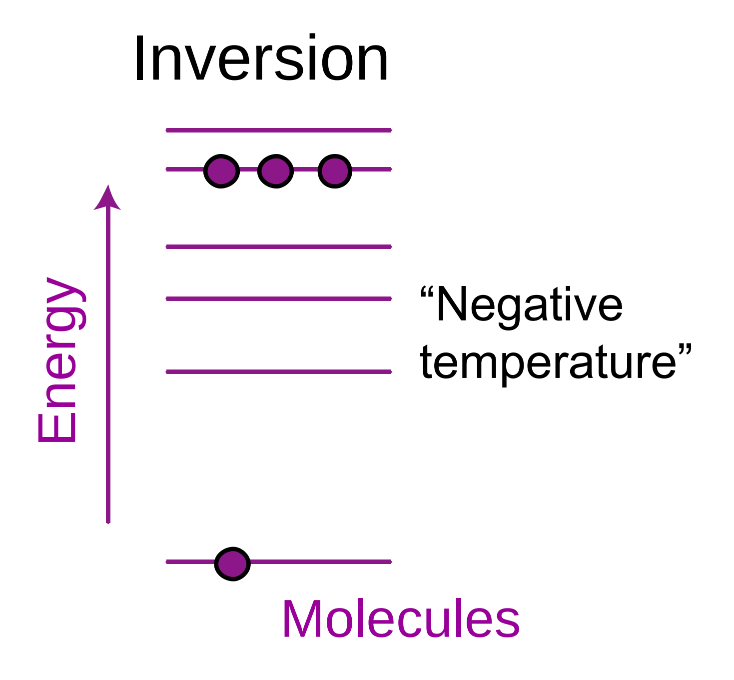
How to achieve laser threshold

In order to achieve threshold, $G > 1$, that is, stimulated emission must exceed absorption:

$$B\, N_2\, I \;>\; B\, N_1\, I$$

Or, equivalently,

$$\boxed{N_2 \;>\; N_1}$$

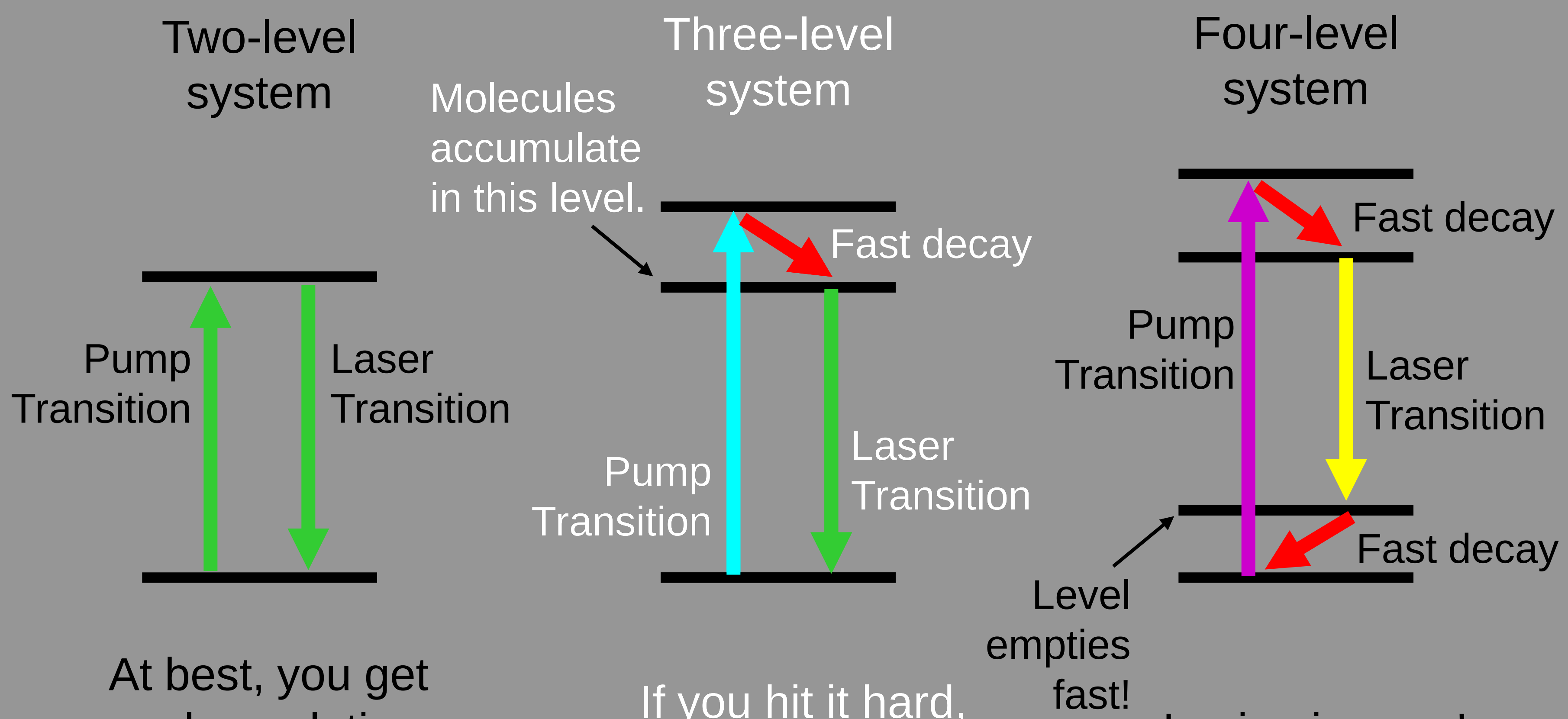


This condition is called **Inversion**.
It does not occur naturally.

In order to achieve inversion, we must hit (not heat) the laser medium very hard in some way and choose our medium correctly.

Two-, three-, and four-level systems

It took laser physicists a while to realize that four-level systems are best.



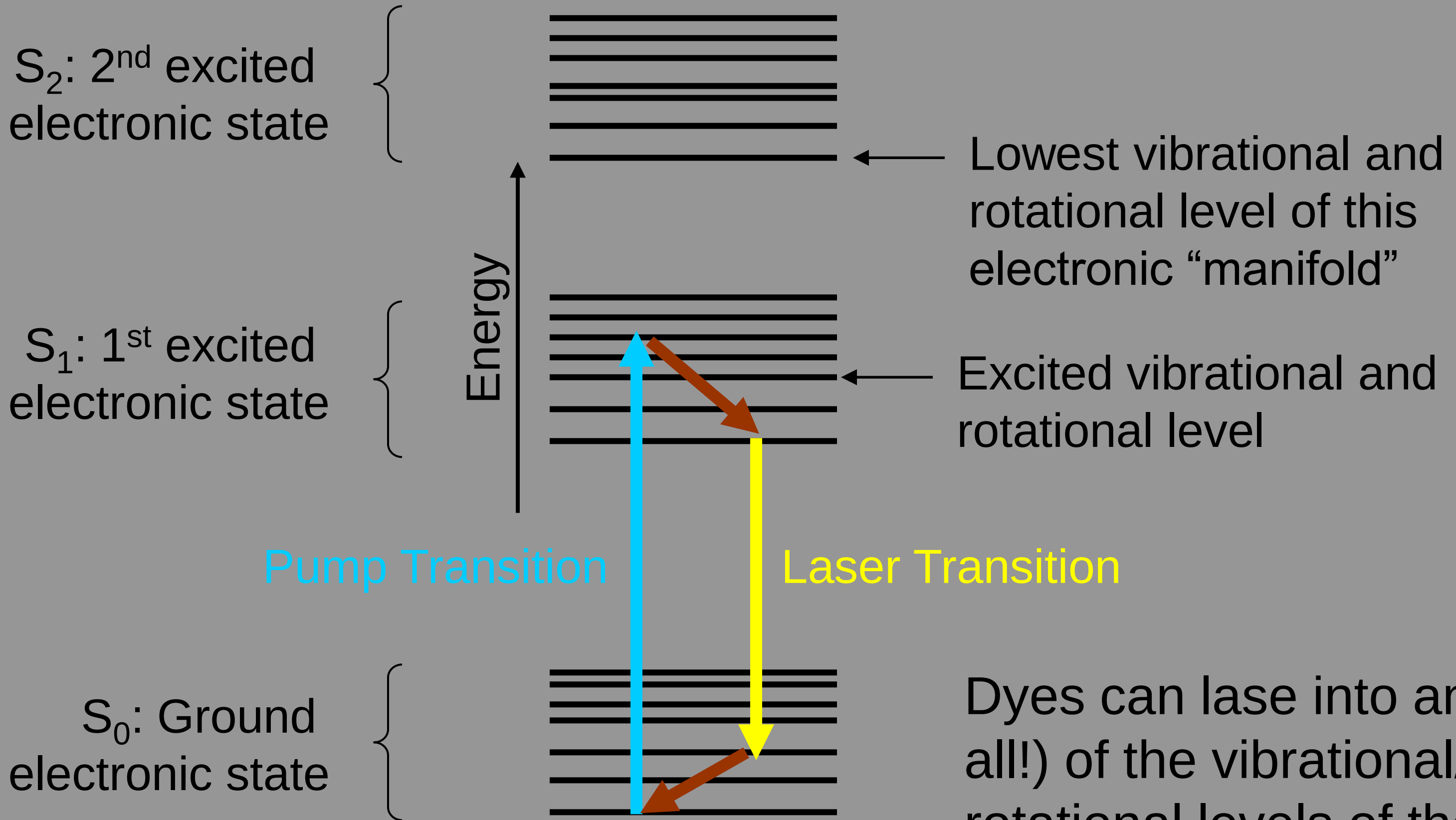
At best, you get equal populations. No lasing.

If you hit it hard, you get lasing.

Lasing is easy!

A dye’s energy levels

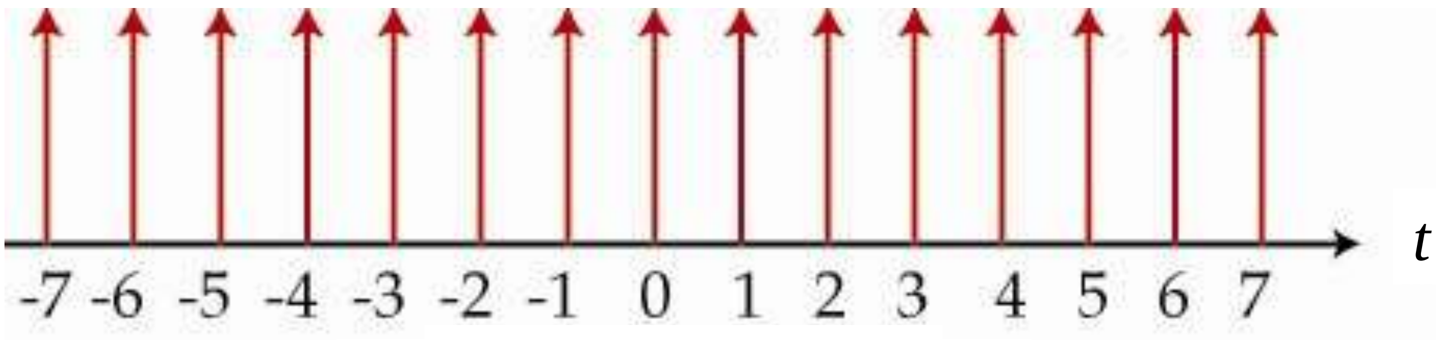
Dyes are big molecules, and they have complex energy level structure.



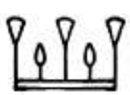
Dyes can lase into any (or all!) of the vibrational/ rotational levels of the S_0 state, and so can lase very broadband.

Lasers modes: The Shah function

The Shah function, $\text{III}(t)$, is an infinitely long train of equally spaced delta-functions.



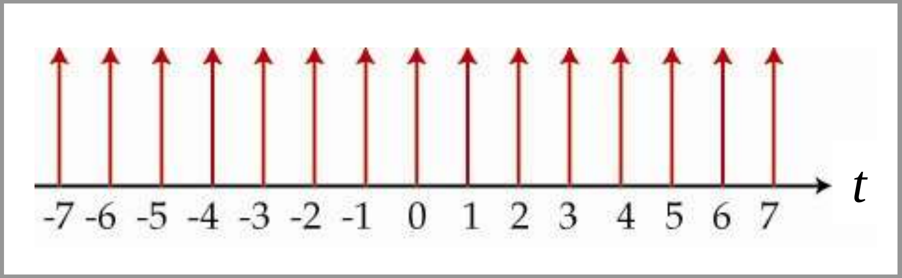
$$\text{III}(t) \equiv \sum_{m=-\infty}^{\infty} \delta(t-m)$$

The symbol III is pronounced *shah* after the Cyrillic character III, which is said to have been modeled on the Hebrew letter ש (shin) which, in turn, may derive from the Egyptian  a hieroglyph depicting papyrus plants along the Nile.

The Fourier transform of the Shah function

$$= \int_{-\infty}^{\infty} \sum_{m=-\infty}^{\infty} \delta(t-m)\exp(-i\omega t)dt$$

$\mathrm{III}(t)$



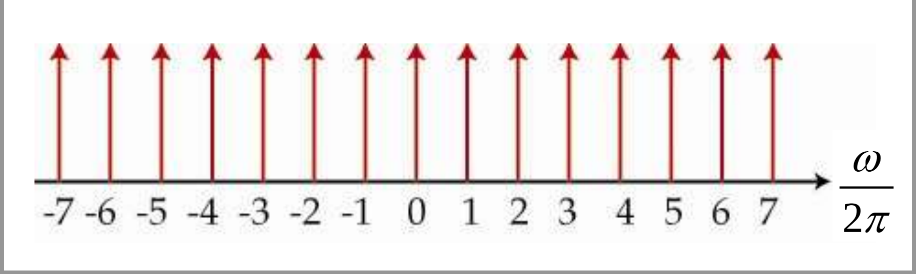
$$= \sum_{m=-\infty}^{\infty} \int_{-\infty}^{\infty} \delta(t-m)\exp(-i\omega t)dt$$

$$= \sum_{m=-\infty}^{\infty} \exp(-i\omega m)$$

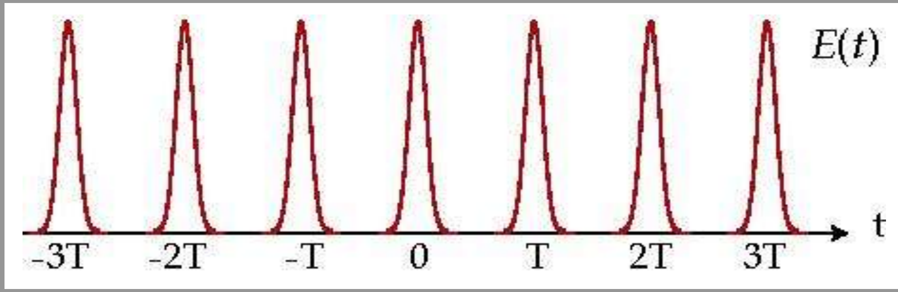
If $\omega = 2n\pi$, where n is an integer, every term is $\exp(-2mn\pi i) = 1$, and the sum diverges; otherwise, cancellation occurs. So:

$$\boxed{\mathcal{F}\{\mathrm{III}(t)\} \propto \mathrm{III}(\omega/2\pi)}$$

$\mathcal{F}\{\mathrm{III}(t)\}$



The Shah function and a pulse train



An infinite train of identical pulses (from a laser!) can be written:

Convolution

$$E(t) = \mathrm{III}(t/T) * f(t)$$

where $f(t)$ is the shape of each pulse and T is the time between pulses.

$$= \sum_{m=-\infty}^{\infty} \int_{-\infty}^{\infty} \delta(t'/T - m) f(t - t')\, dt'$$

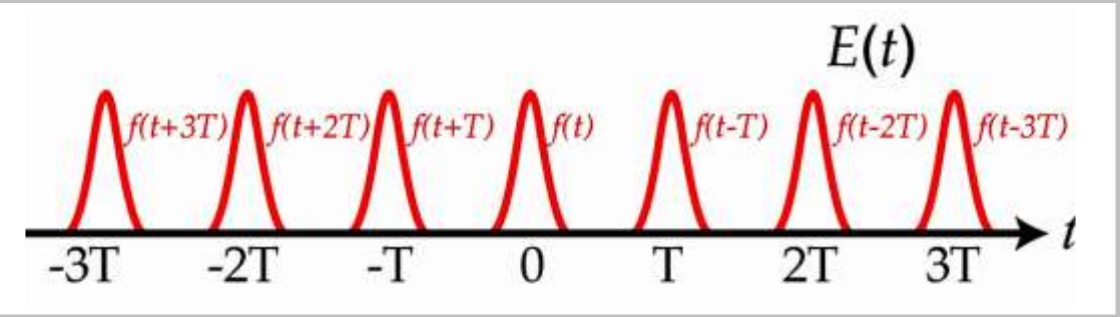
Set $t'/T = m$ or $t' = mT$

$$= \sum_{m=-\infty}^{\infty} f(t - mT)$$

The Fourier transform of an infinite train of pulses

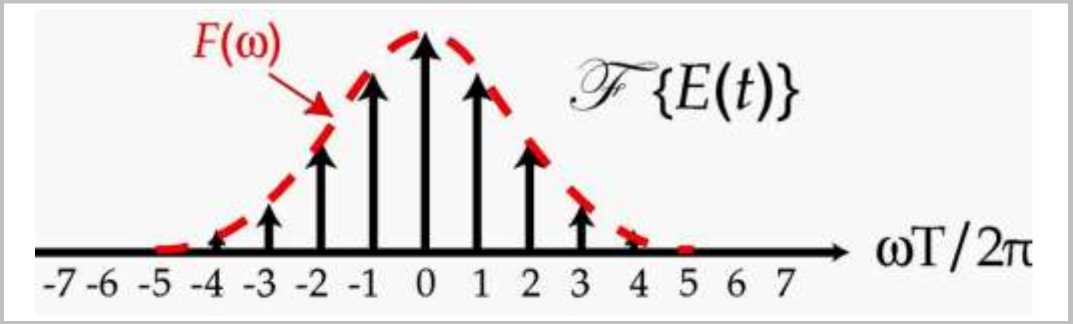
An infinite train of identical pulses can be written:

$$E(t) = \mathrm{III}(t/T) * f(t)$$



where *f(t)* represents a single pulse and *T* is the time between pulses. The Convolution Theorem states that the Fourier Transform of a convolution is the product of the Fourier Transforms. So:

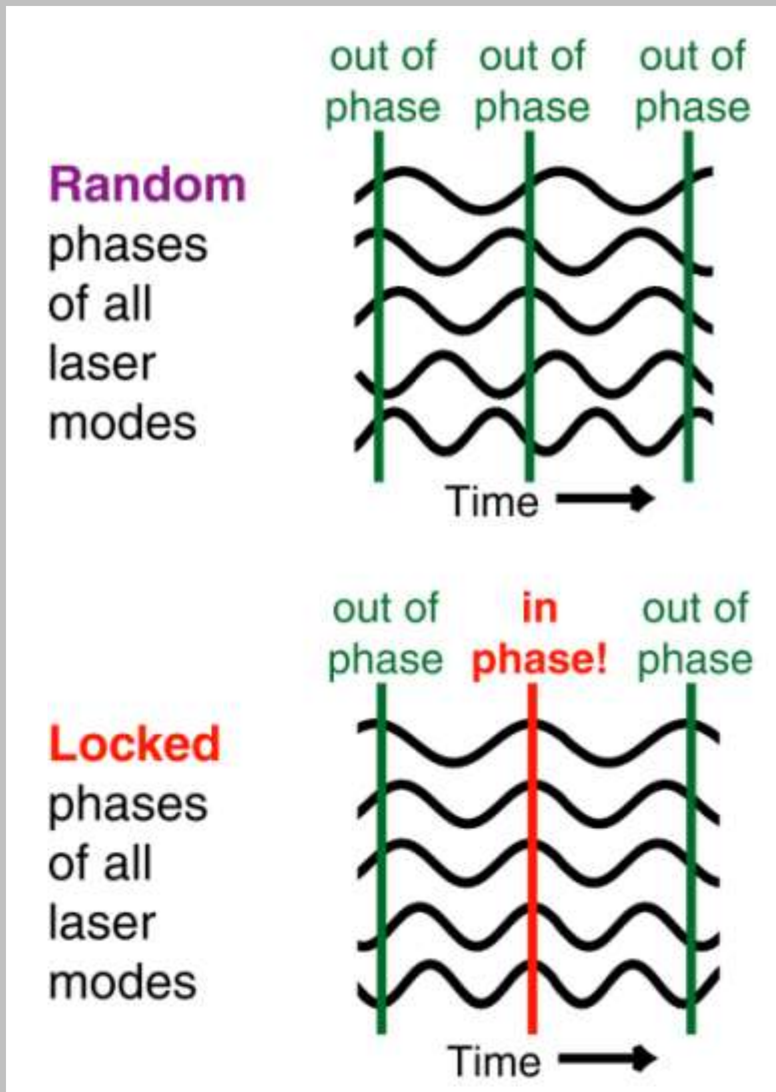
$$\tilde{E}(\omega) \propto \mathrm{III}(\omega T / 2\pi) F(\omega)$$

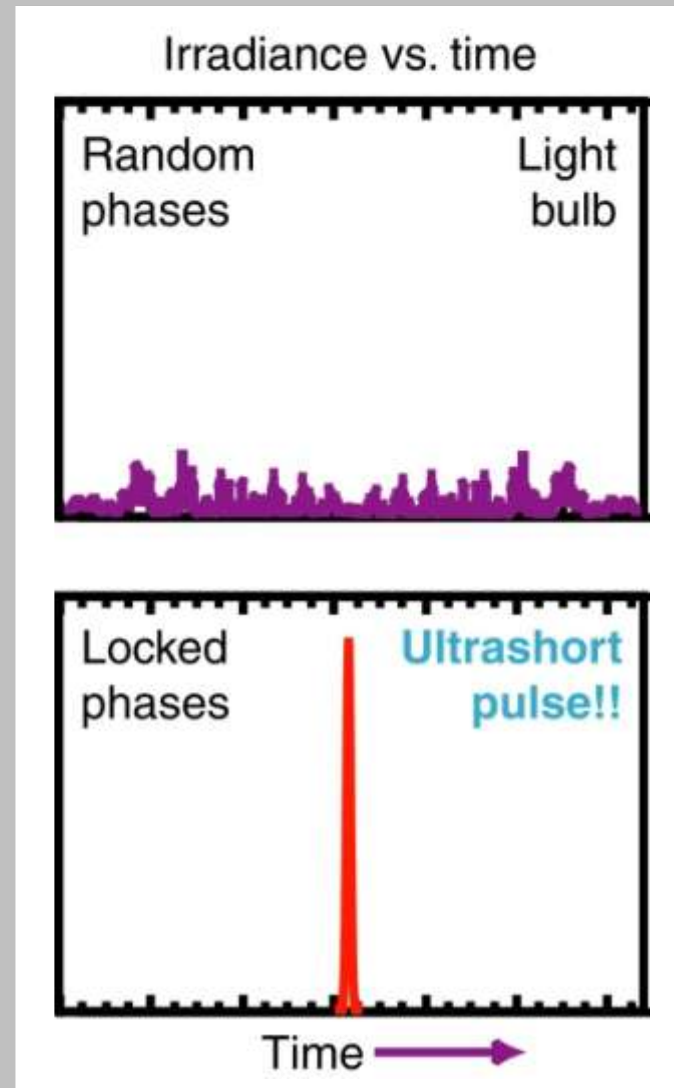


A train of pulses results from a single pulse bouncing back and forth inside a laser cavity of round-trip time T. The spacing between frequencies—called laser modes—is then $\delta\omega = 2\pi/T$ or $\boldsymbol{\delta\nu = 1/T}$.

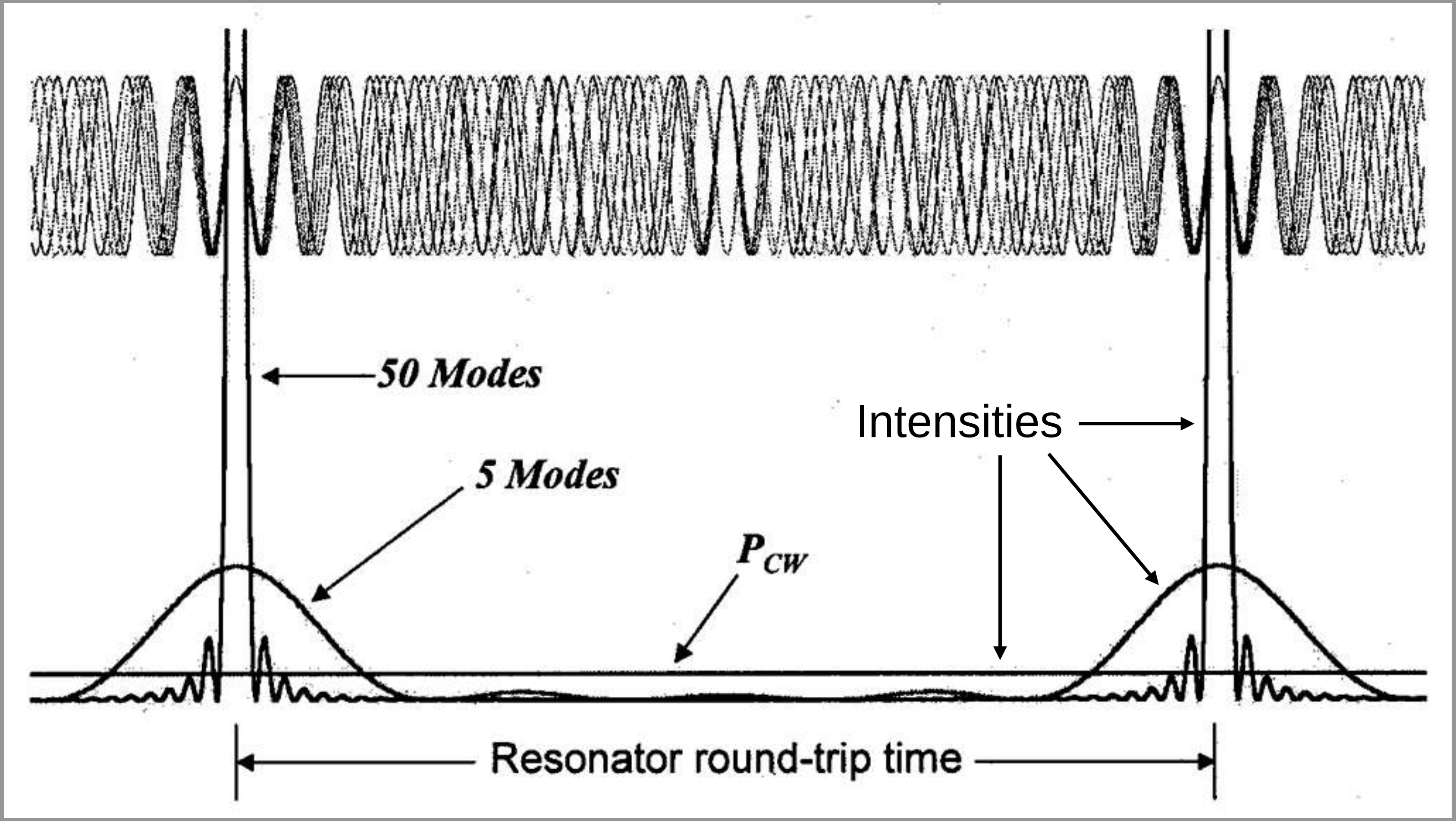
Generating short pulses = mode-locking

Locking the phases of the laser modes yields an ultrashort pulse.

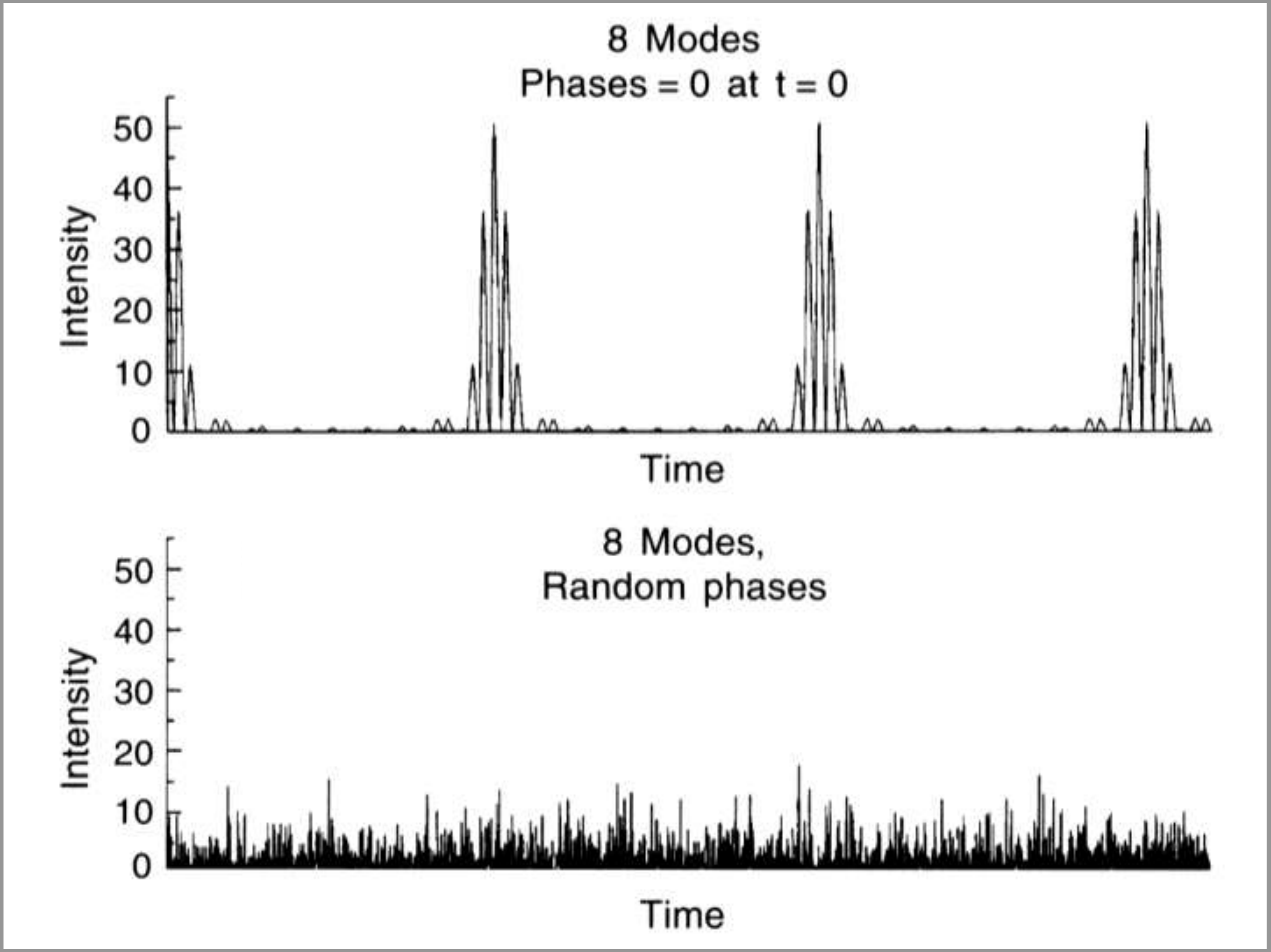




Locked modes



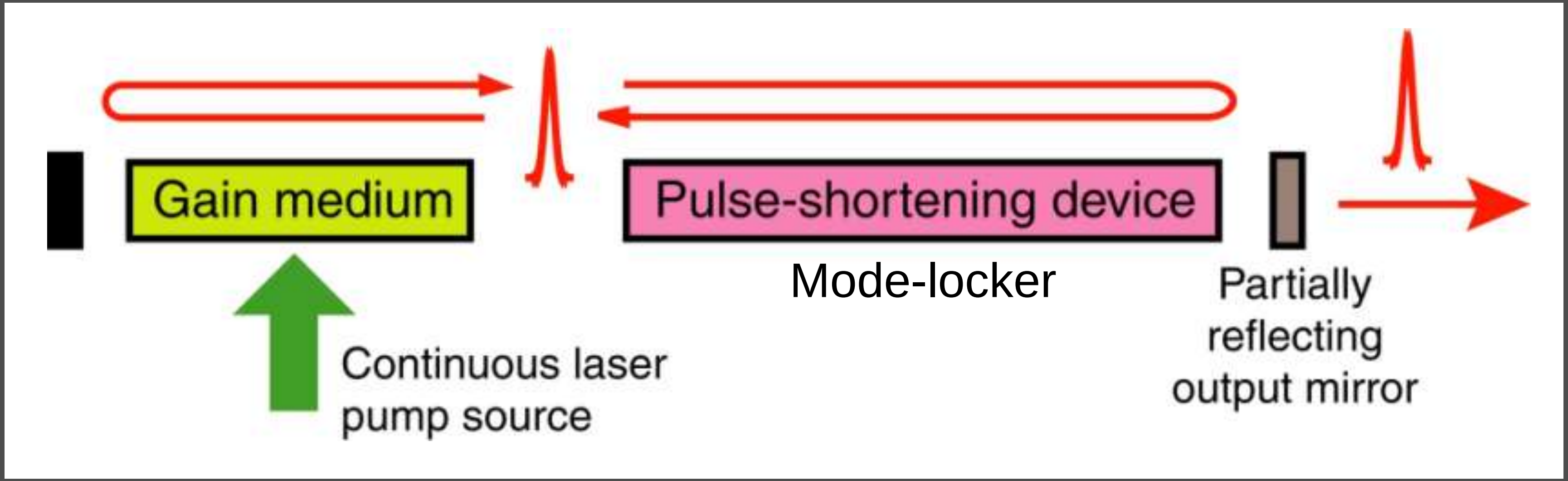
Numerical simulation of mode-locking



Ultrafast lasers often have thousands of modes.

A generic ultrashort-pulse laser

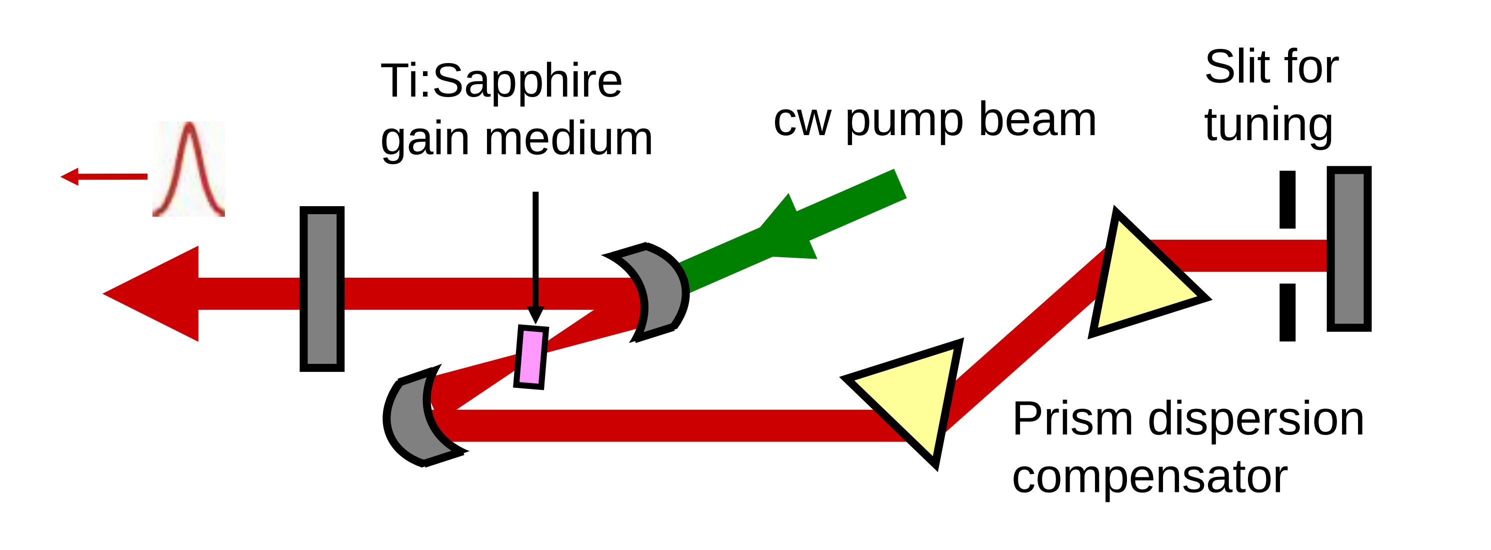
A generic ultrafast laser has a broadband gain medium, a pulse-shortening device, and two or more mirrors:

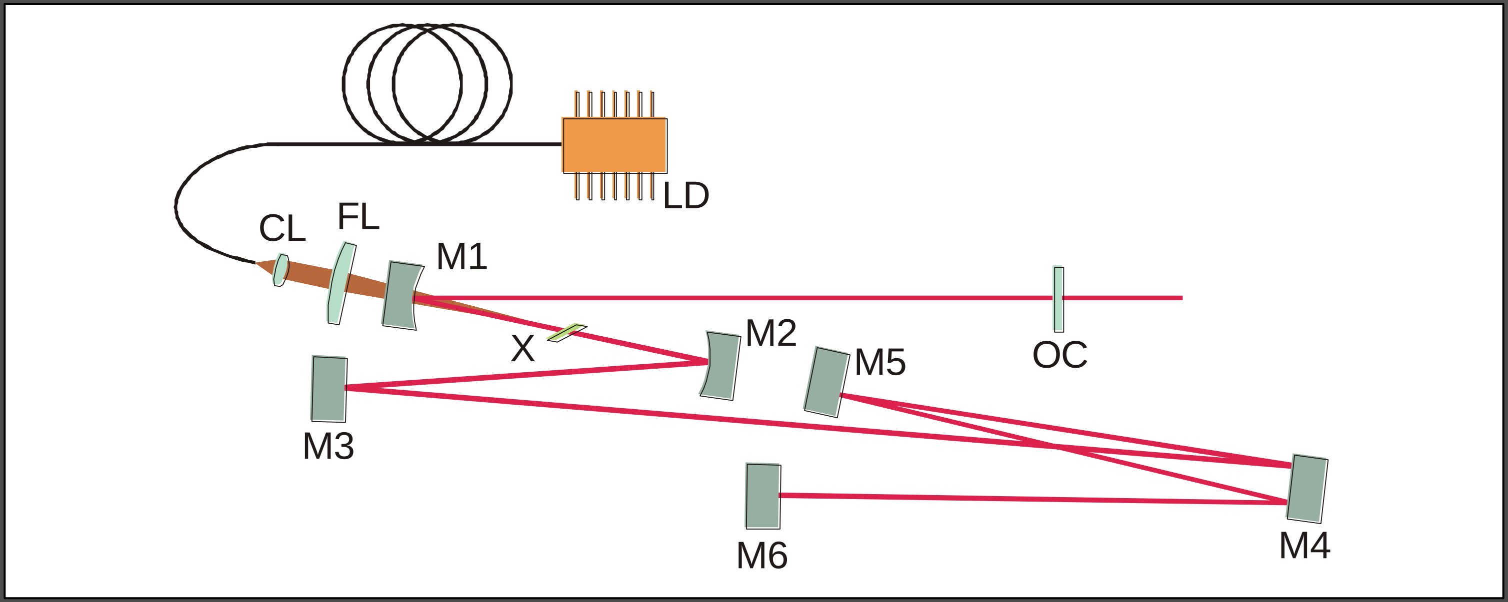


Many pulse-shortening devices have been proposed and used.

Fs lasers usually use prism pairs or chirped mirrors.

A real ultrashort-pulse laser



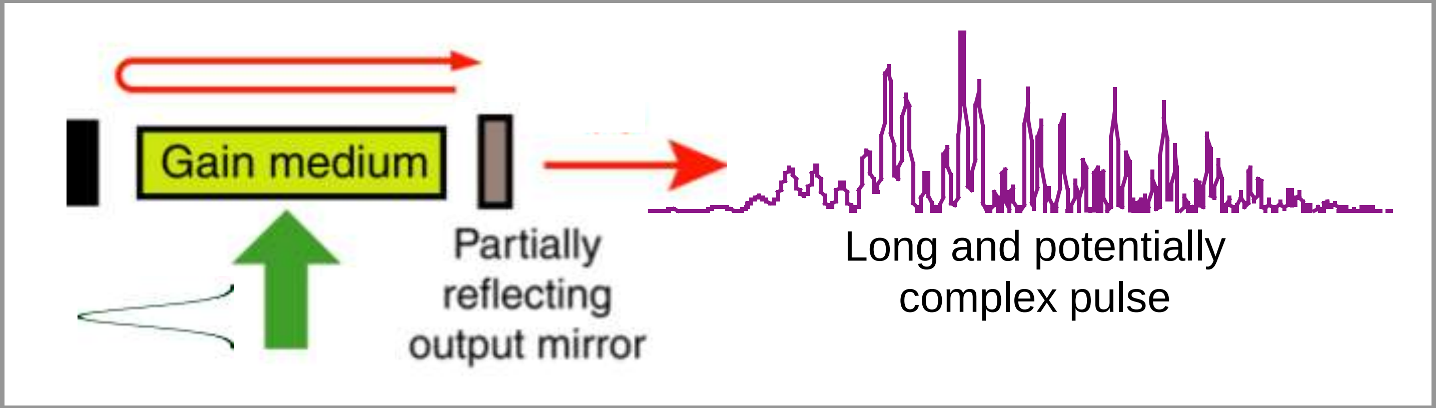


History: Pulsed Pumping

Pumping a laser medium with a short-pulse flash lamp yields a short pulse. Flash lamp pulses as short as ~1 μs exist.

Unfortunately, this yields a pulse as long as the excited-state lifetime of the laser medium, which can be considerably longer than the pump pulse.

Since solid-state laser media have lifetimes in the microsecond range, it yields pulses microseconds to milliseconds long.

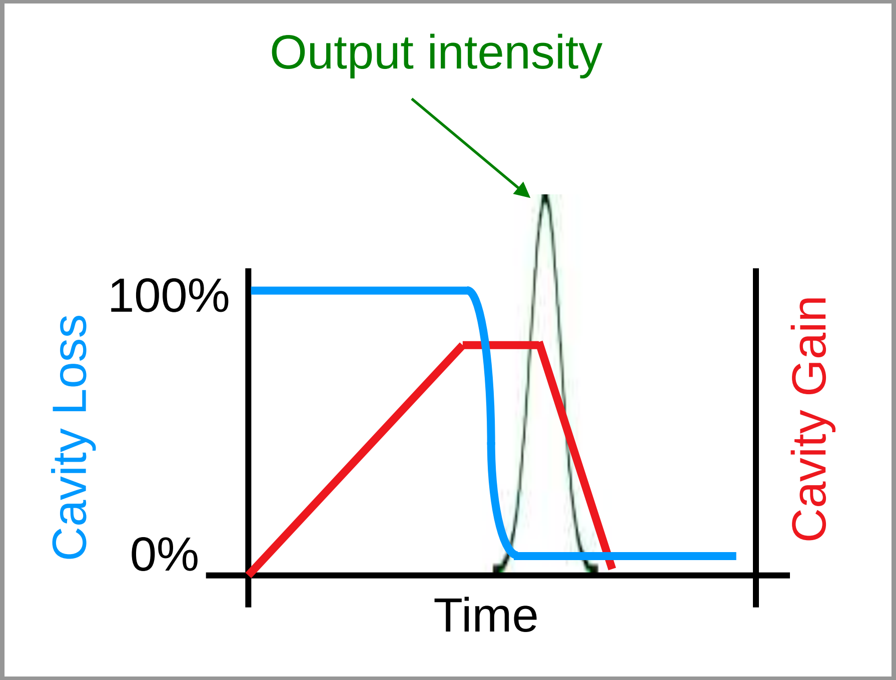


History (and some present designs): Q-switching

Q-switching involves:

Preventing the laser from lasing until the flash lamp is finished flashing, and

Abruptly allowing the laser to lase.



The pulse length is limited by how fast we can switch and the round-trip time of the laser and yields pulses 10 - 100 ns long.

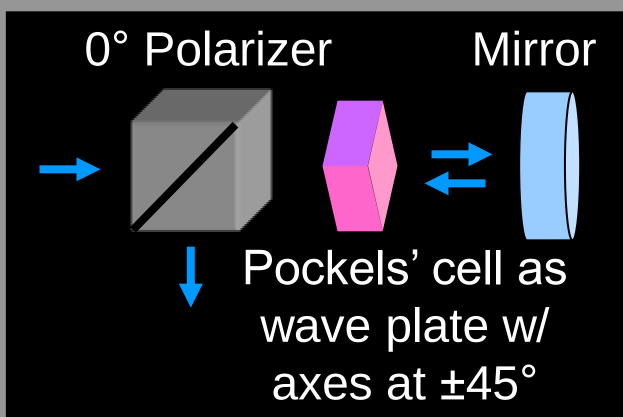
Q-Switching

How do we Q-switch a laser?

Q-switching involves preventing lasing until we're ready.

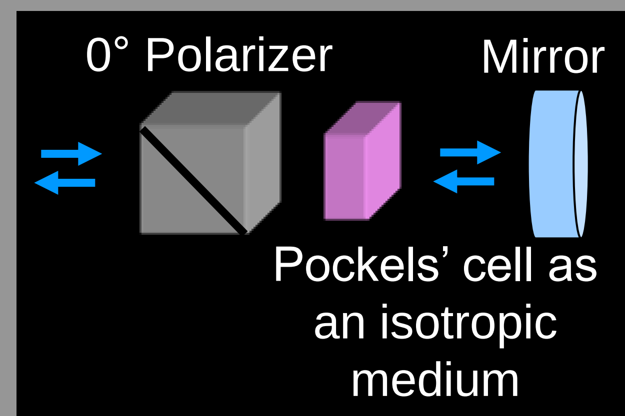
A Pockels' cell switches (in a few nanoseconds) from a quarter-wave plate to nothing.

Before switching



Light becomes circular on the first pass and then horizontal on the next and is then rejected by the polarizer.

After switching



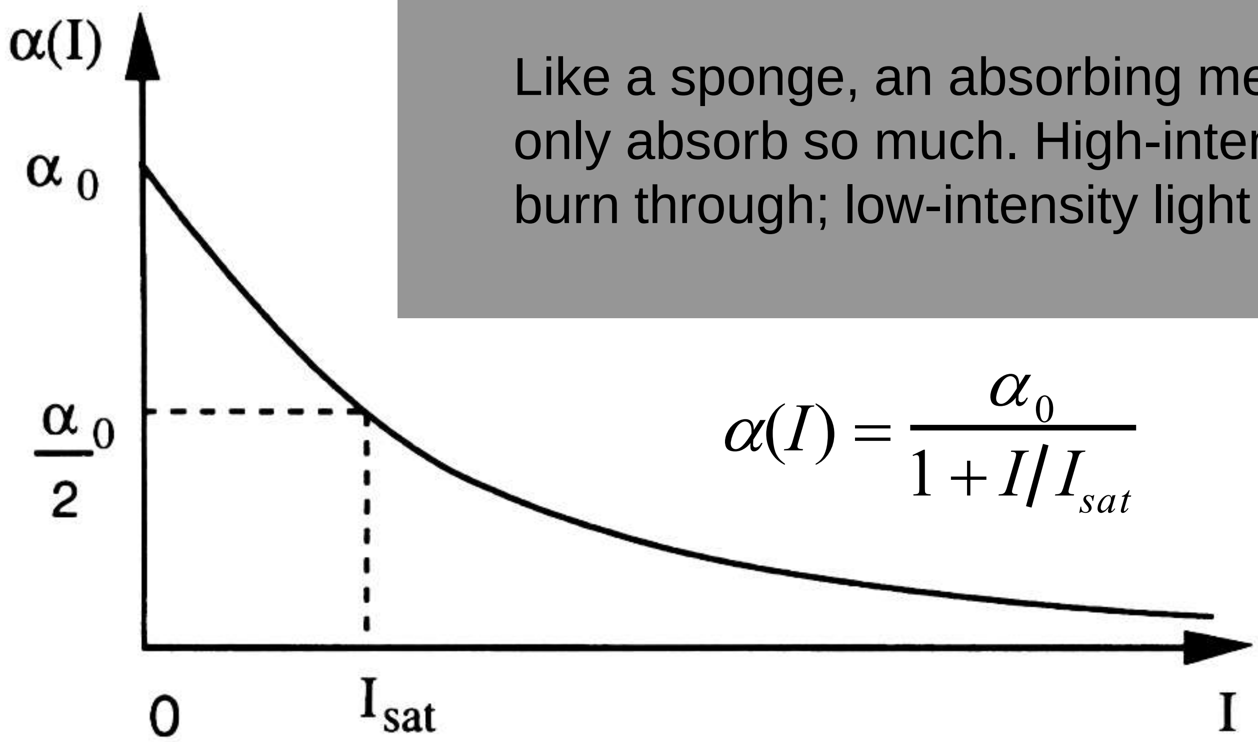
Light is unaffected by the Pockels' cell and hence is passed by the polarizer.

Passive mode-locking: the saturable absorber

$$\alpha = \left[N_0 - N_1\right]\sigma$$

For a two-level system

$$= \frac{N}{1 + I / I_{sat}}\sigma$$



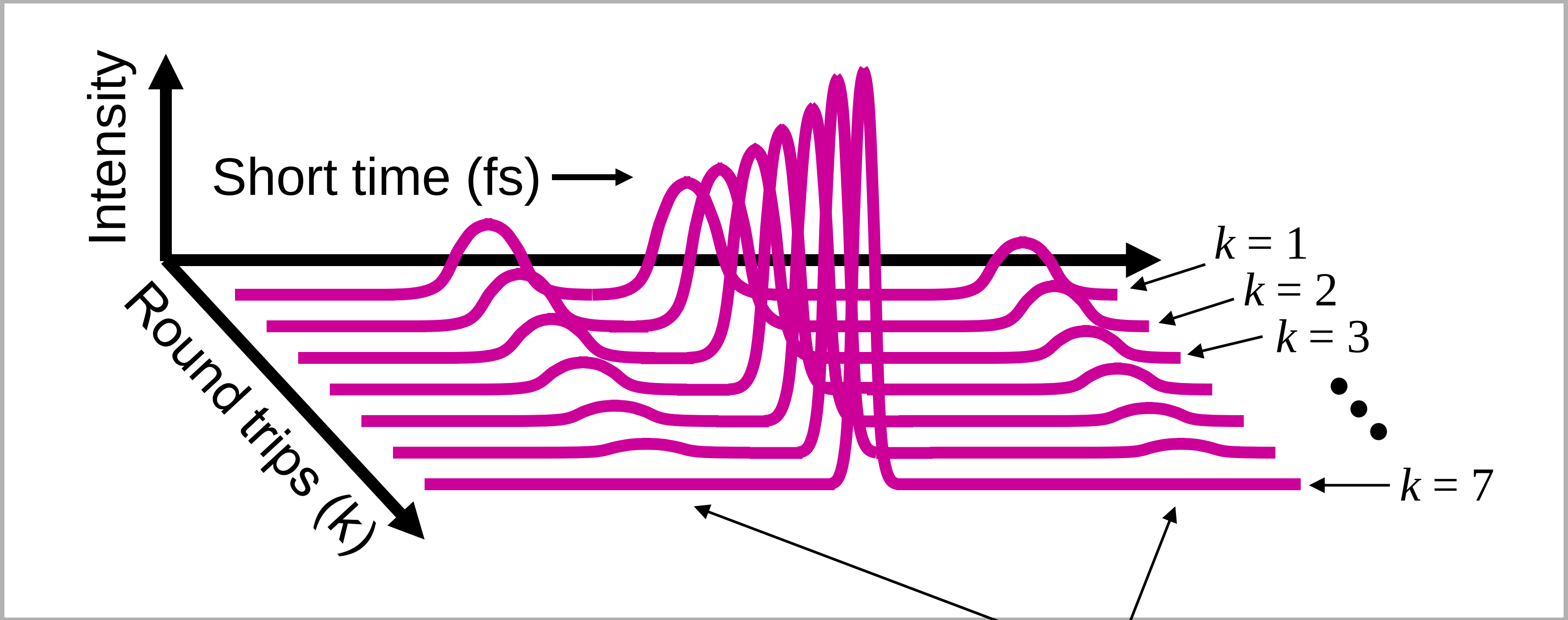
$$\alpha(I) = \frac{\alpha_0}{1 + I/I_{sat}}$$

Like a sponge, an absorbing medium can only absorb so much. High-intensity spikes burn through; low-intensity light is absorbed.

$$\alpha_0 = N\sigma$$

The effect of a saturable absorber

Pulse evolution in time



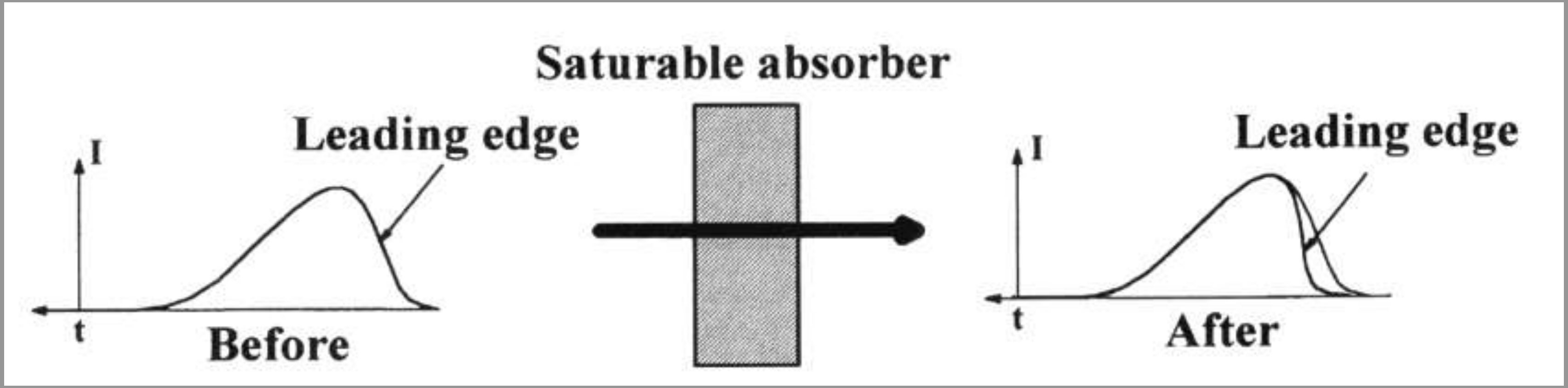
Notice that the weak pulses are suppressed,
and the strong pulse shortens and is amplified.

After many round trips, even a slightly saturable absorber can yield a very short pulse.

Passive mode-locking with a slow saturable absorber

What if the absorber responds slowly (more slowly than the pulse)?

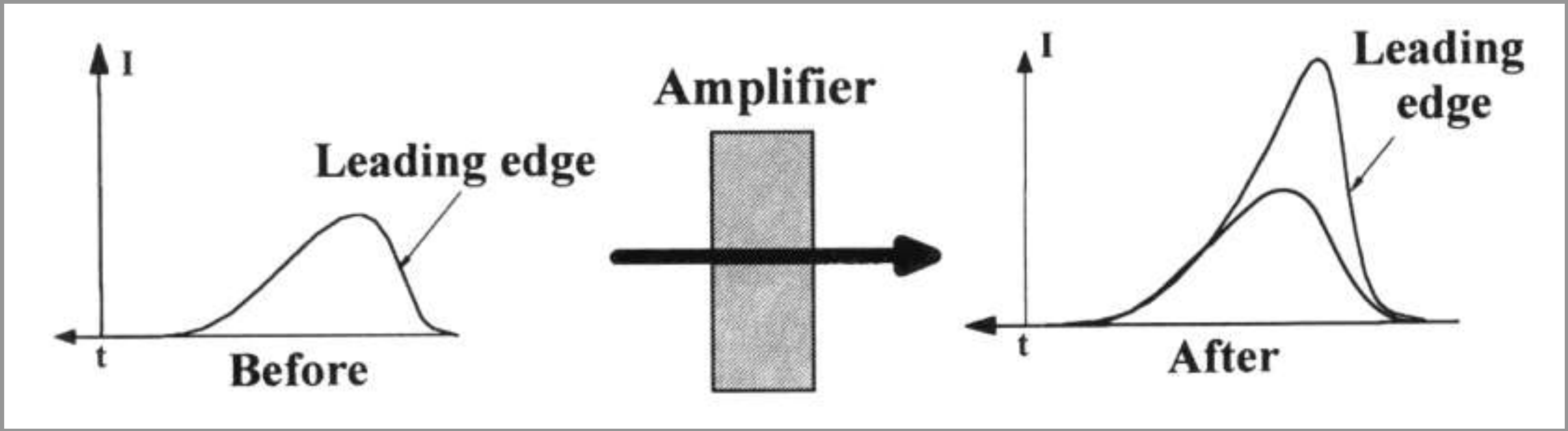
Then only the leading edge will experience pulse shortening.



This is the most common situation, unless the pulse is many ps long.

Gain saturation shortens the pulse trailing edge.

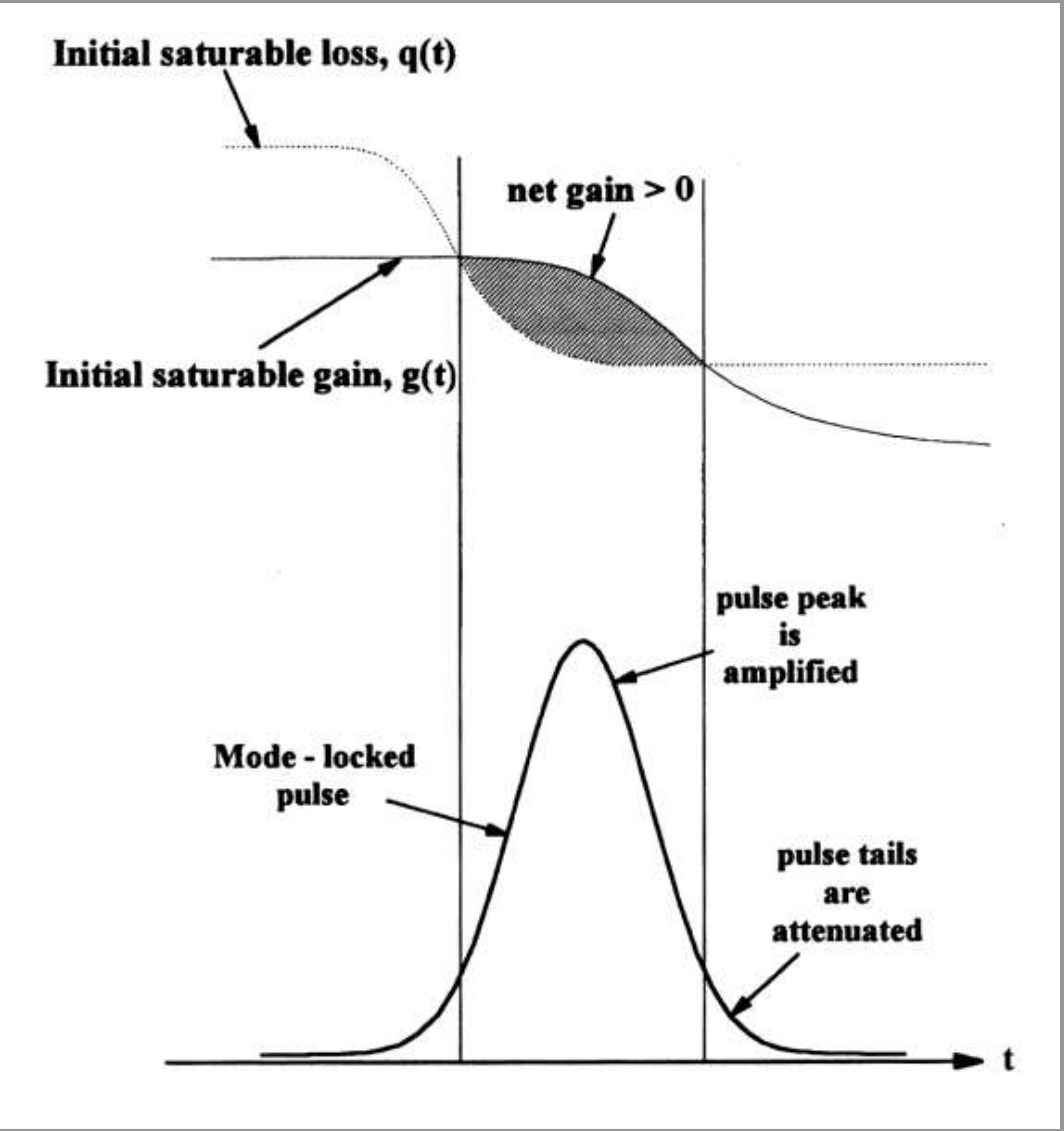
The intense spike uses up the laser gain-medium energy, reducing the gain available for the trailing edge of the pulse (and for later pulses).



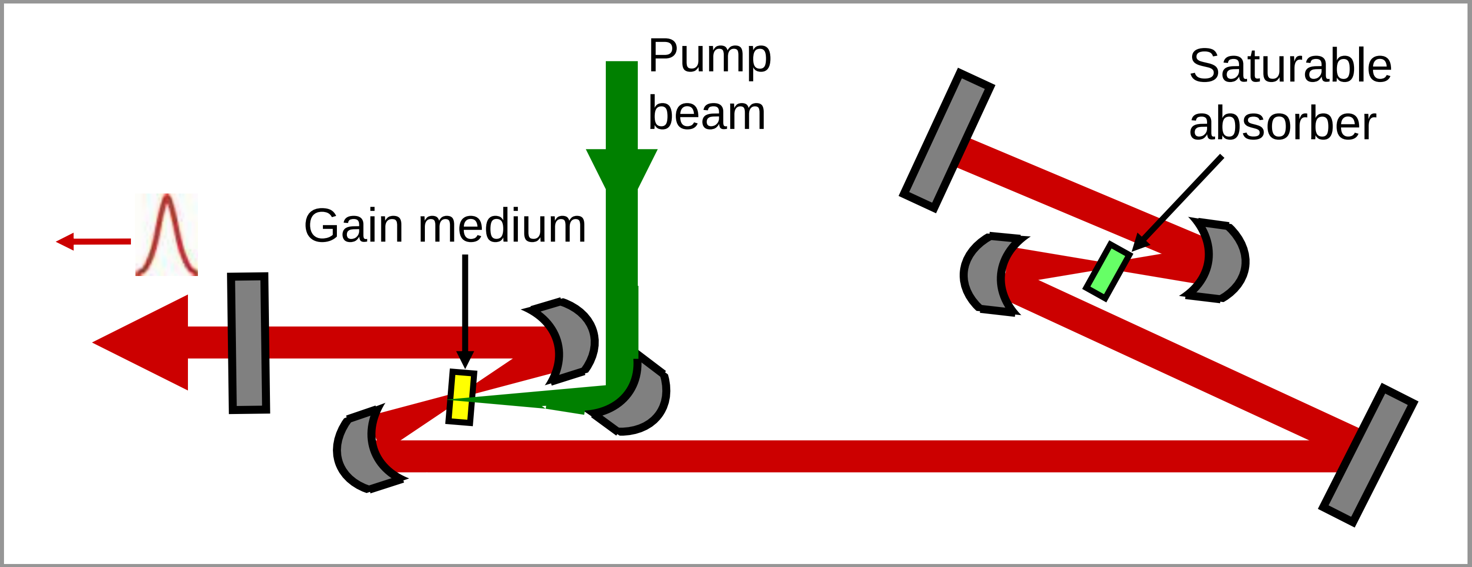
Saturable gain and loss

Lasers lase when the gain exceeds the loss.

The combination of saturable absorption and saturable gain yields short pulses even when the absorber is slower than the pulse.



The Passively Mode-locked Dye Laser



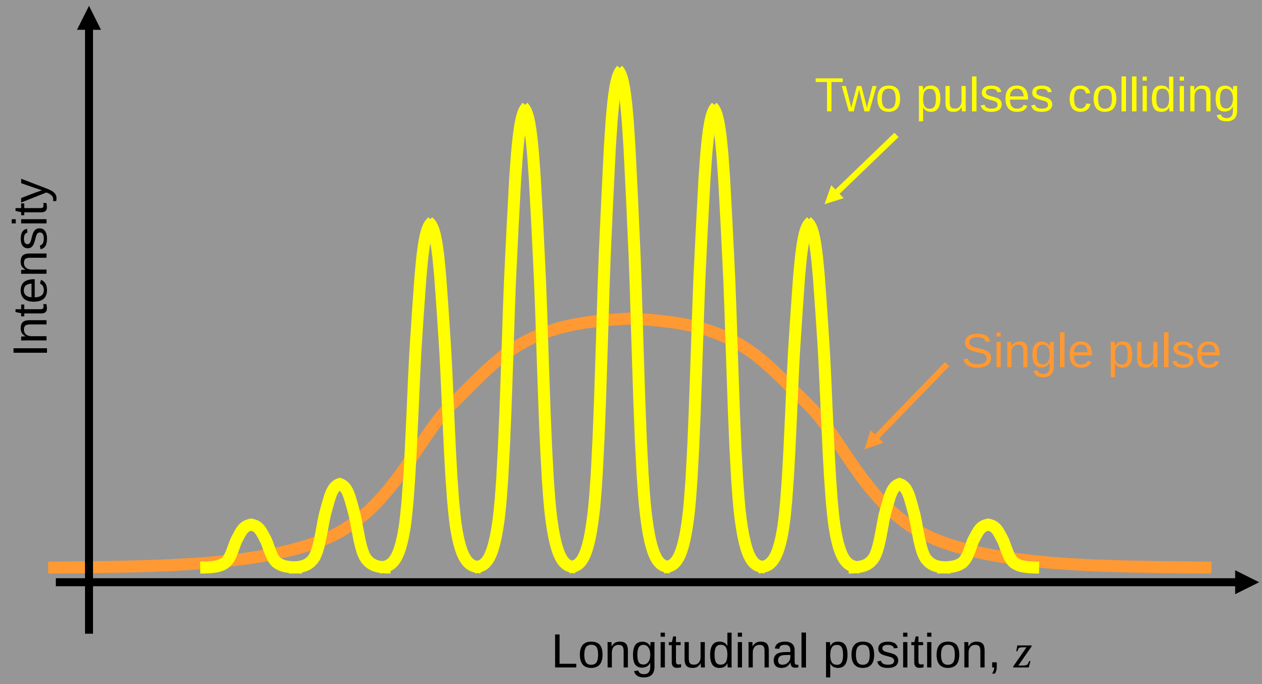
Passively mode-locked dye lasers yield pulses as short as a few hundred fs.

They're limited by our ability to saturate the absorber.

Some common dyes and their corresponding saturable absorbers

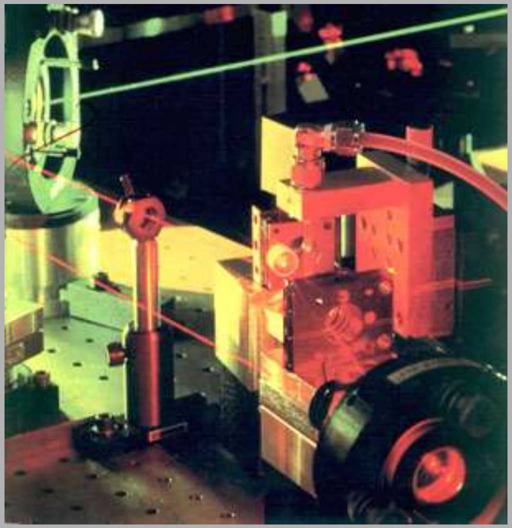
Gain dye	Saturable absorber	Wavelength in nm
Rh6G	DODCI, DDI	575–620
Kiton Red	DQOCI	600–655
DCM	DODCI, DTDCI	620–660
Pyridine 1	DTDCI, DDI	670–740
LD 700	DTDCI, DDI, IR 140	700–800
Pyridine 2	IR 140, HITC	690–770
Styryl 9M	DDI, IR 140	780–860

Colliding pulses have a higher peak intensity.

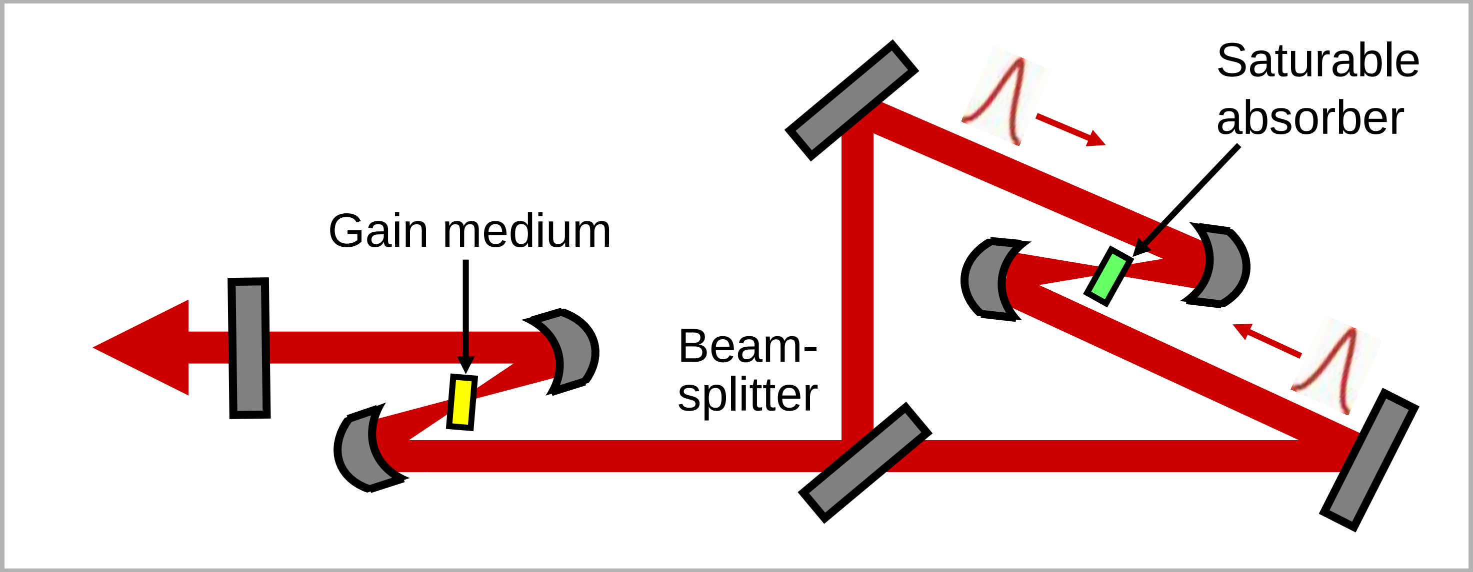


And higher intensity in the saturable absorber is what CPM lasers require.

The colliding-pulse mode-locked (CPM) laser



A Sagnac interferometer is ideal for creating colliding pulses.

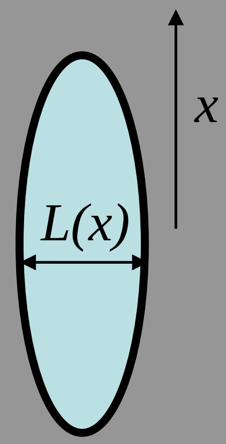


CPM dye lasers produce even shorter pulses: ~30 fs.

A lens and a lens

A lens is a lens because the phase delay seen by a beam varies with x:

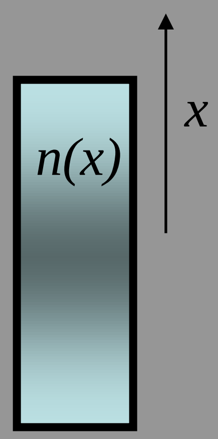
$$\phi(x) = n\,k\,L(x)$$



In both cases, a quadratic variation of the phase with x yields a lens.

Now what if L is constant, but n varies with x:

$$\phi(x) = n(x)\,k\,L$$



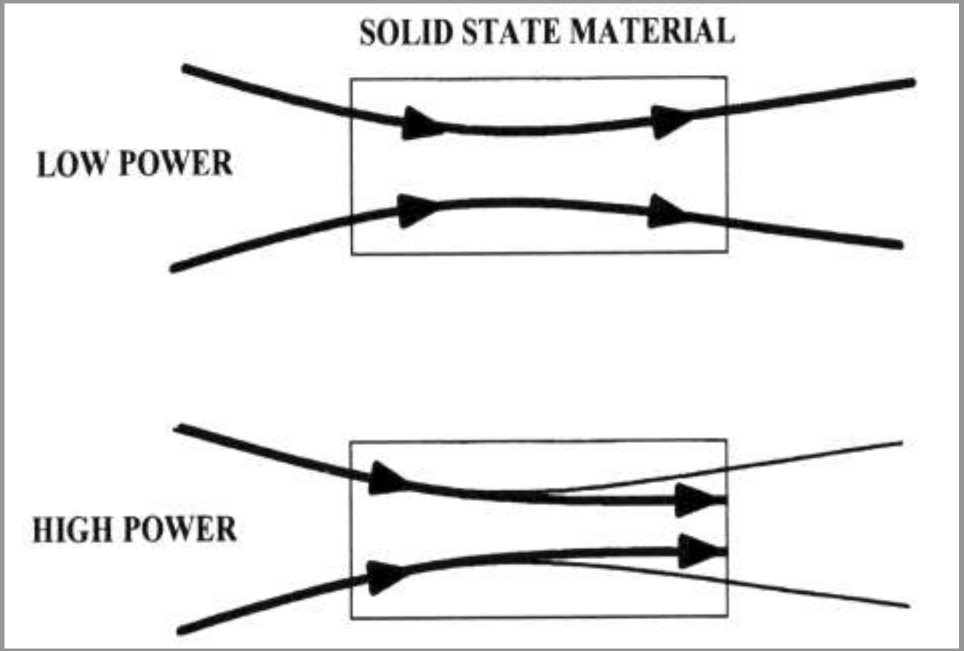
Kerr-lens mode-locking

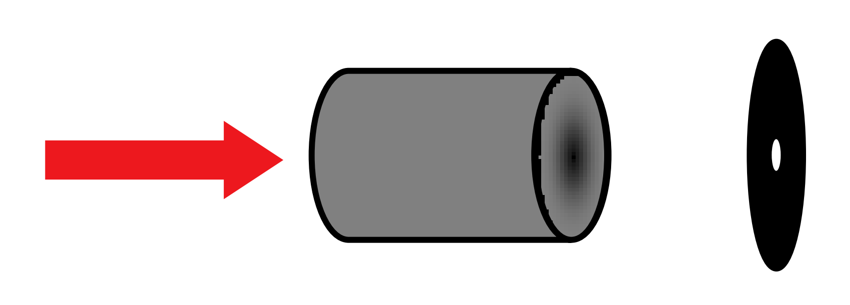
A medium's refractive index depends on the intensity.

$$n(I) = n_0 + n_2 I$$

If the pulse is more intense in the center, it induces a lens.

Placing an aperture at the focus favors a short pulse.



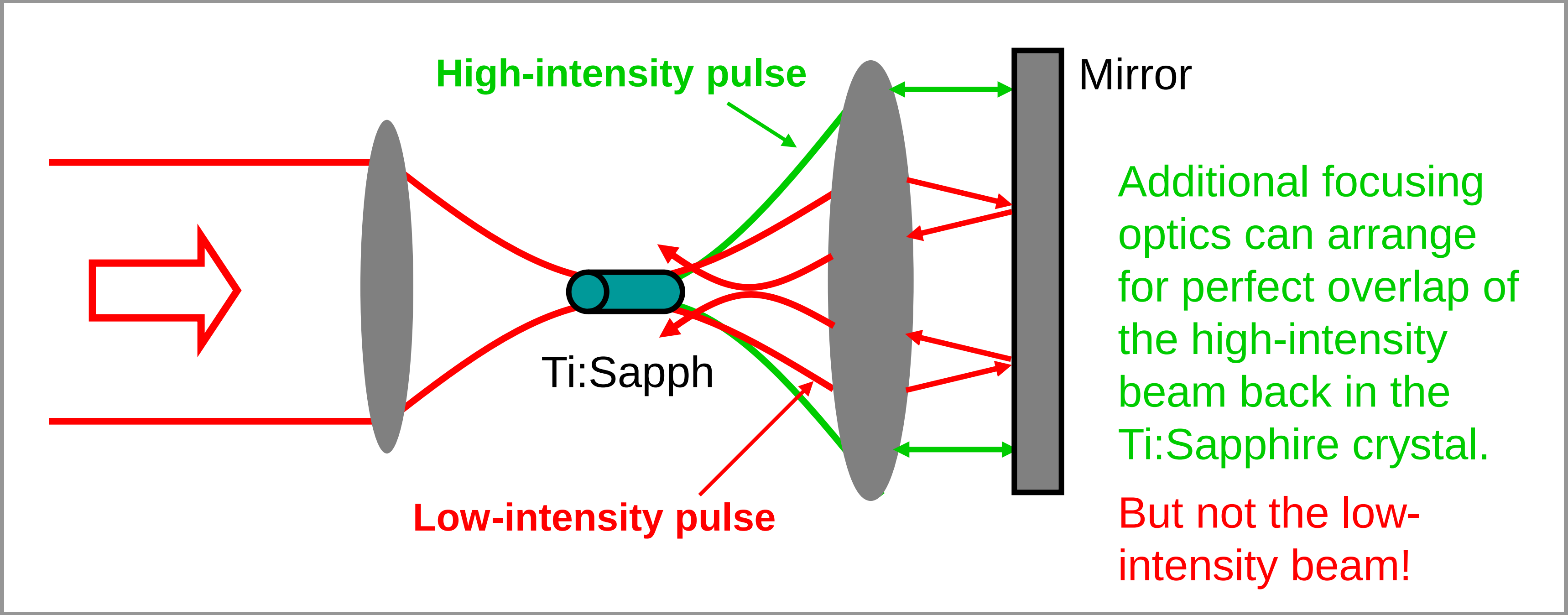


Losses are too high for a low-intensity cw mode to lase, but not for high-intensity fs pulse.

Kerr-lensing is the mode-locking mechanism of the Ti:Sapphire laser.

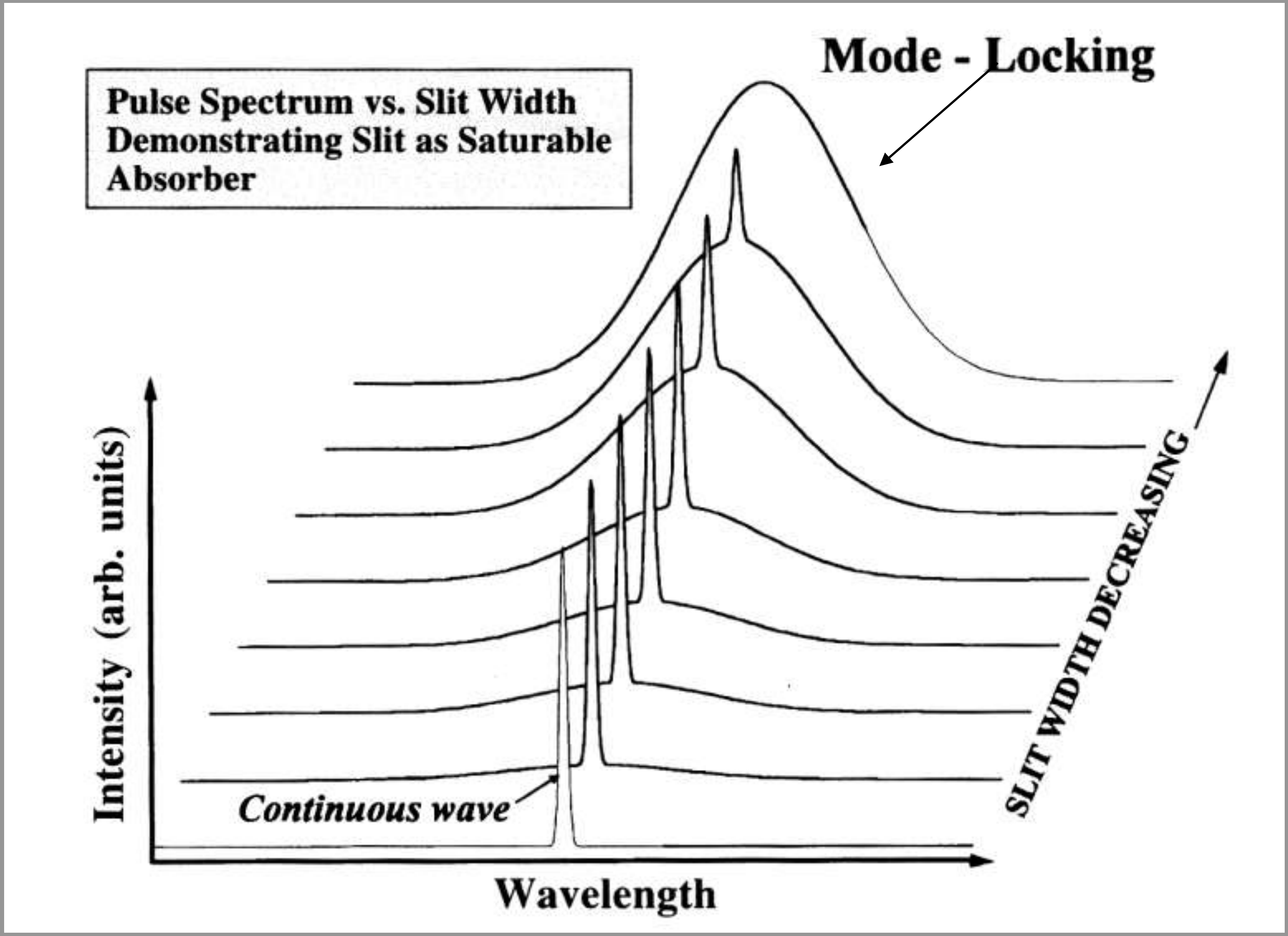
Kerr-lensing is a type of saturable absorber.

If a pulse experiences additional focusing due to high intensity and the nonlinear refractive index, and we align the laser for this extra focusing, then a high-intensity beam will have better overlap with the gain medium.



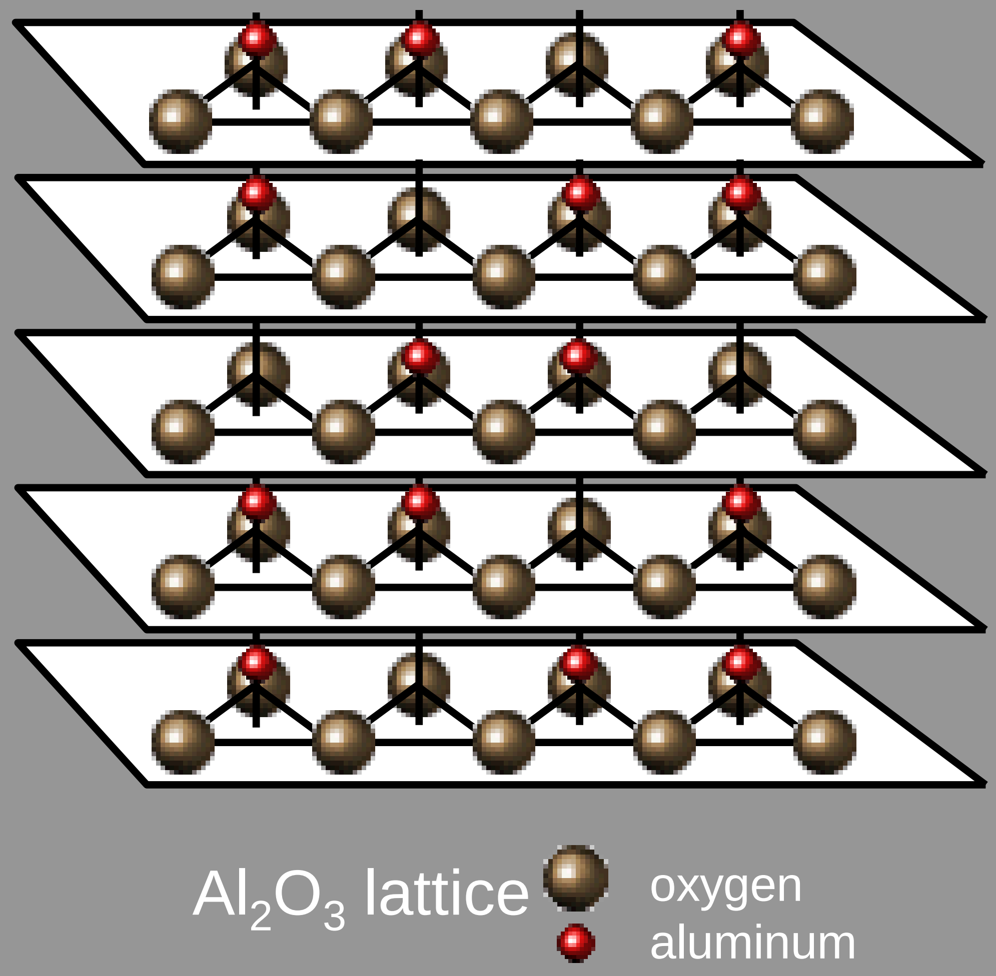
This is a type of saturable absorption.

Modeling Kerr-lens mode-locking



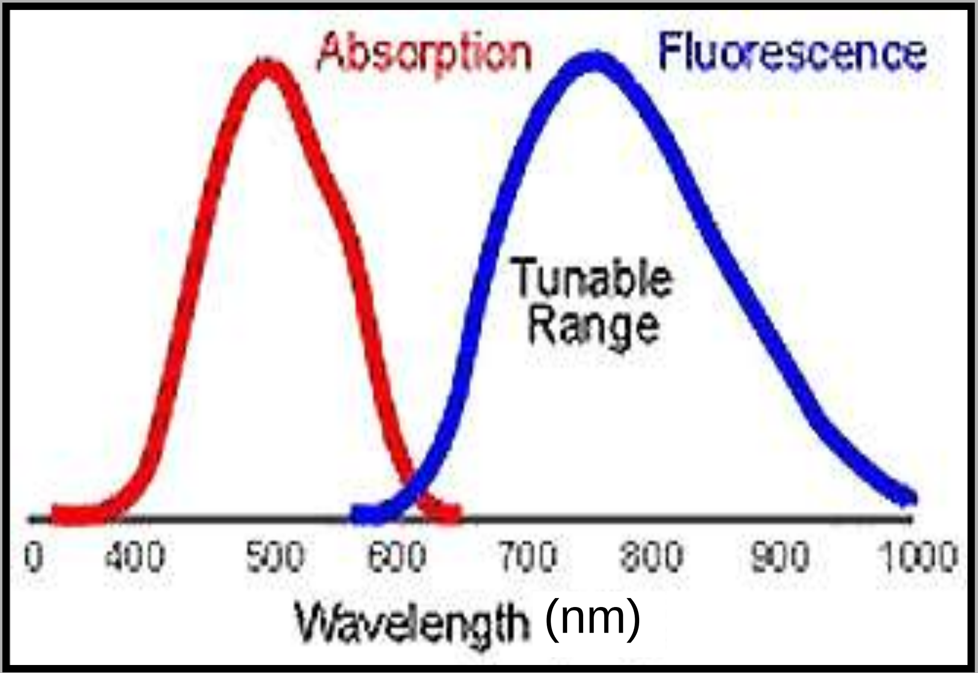
Titanium Sapphire (Ti:Sapphire)

Ti:Sapphire is currently the workhorse laser of the ultrafast community, emitting pulses as short as a few fs and average power in excess of a Watt.



Titanium Sapphire

Absorption and emission spectra of Ti:Sapphire



It can be pumped with:
- CW Argon laser (~450-515 nm)
- CW doubled-Nd laser (532 nm)
- blue laser diodes (~400 nm)

Upper level lifetime:
3.2 μsec

Ti:Sapphire lases from ~700 nm to ~1000 nm.

Mechanisms that limit pulse shortening

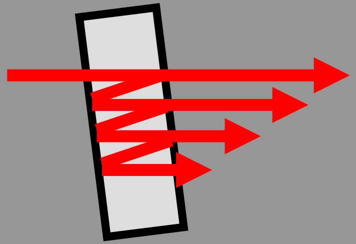
The universe conspires to lengthen pulses.

Gain narrowing:

$G(\omega) = \exp(-a\omega^2)$, then after N passes, the spectrum will narrow by $G^N(\omega) = \exp(-Na\omega^2)$, which is narrower by $N^{1/2}$

Etalon effects:

This yields multiple pulses, spreading the energy over time, weakening the pulses.



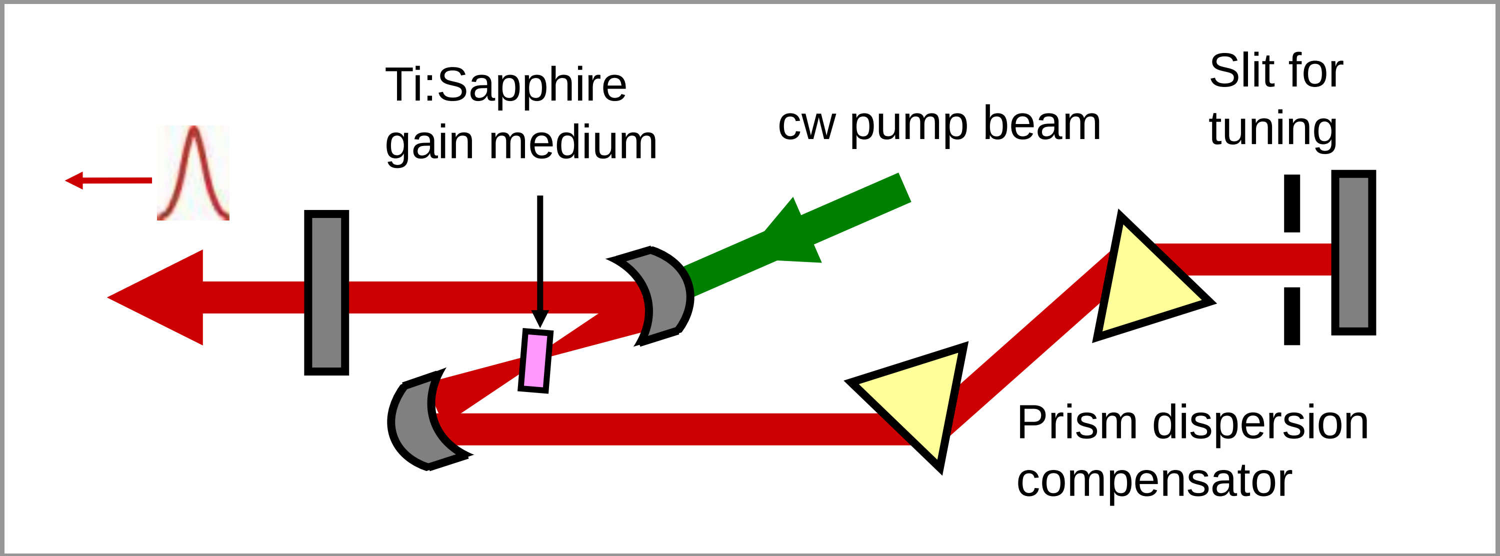
Group-velocity dispersion:

GVD spreads the pulse in time. And everything has GVD…

All fs lasers incorporate dispersion-compensating components.

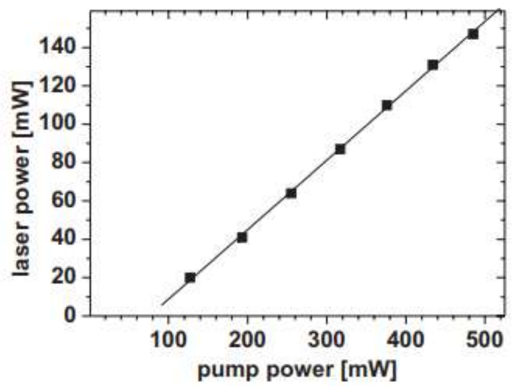
The Ti:Sapphire laser including dispersion compensation

Adding two prisms compensates for dispersion in the Ti:Sapphire crystal and mirrors.

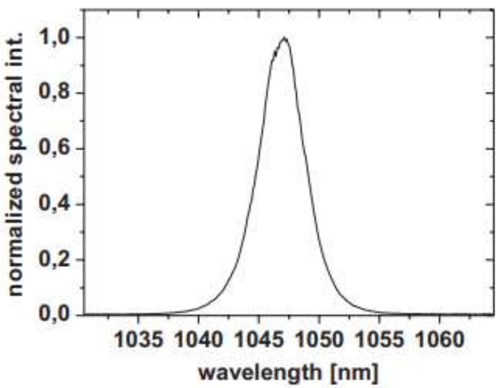


This is currently the workhorse laser of the ultrafast optics community.

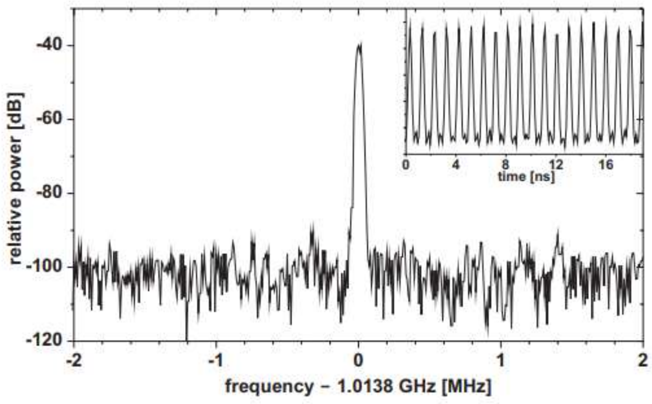
Fs oscillator characterization



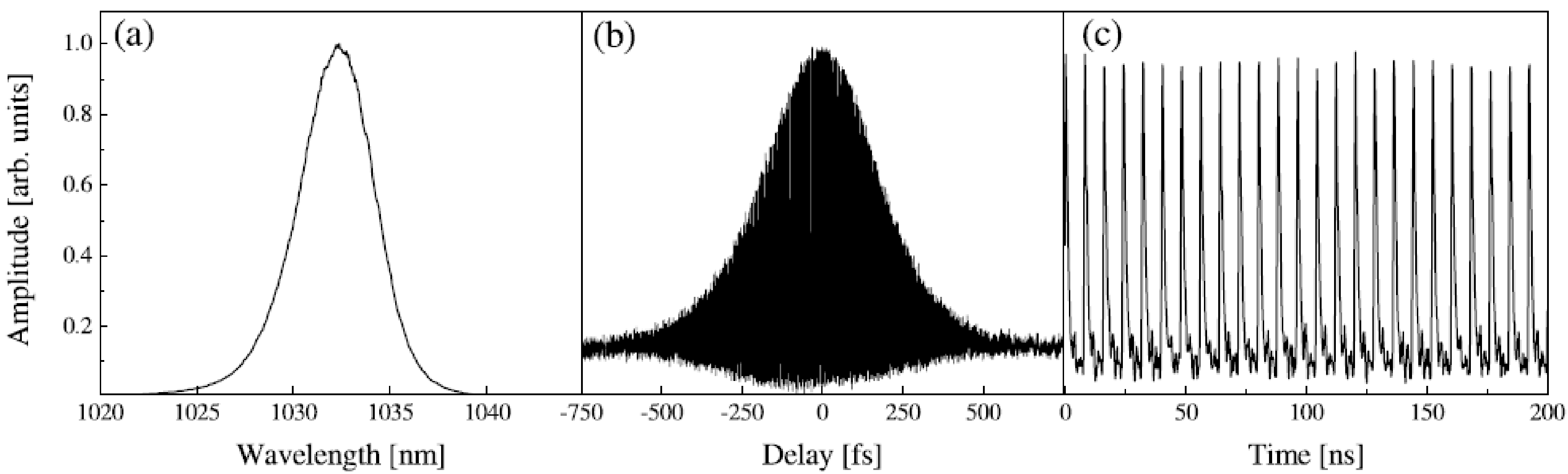
Slope efficiency



Spectrum



„Microwave" spectrum



Spectrum

Autocorrelation

Pulse train

Commercial fs lasers

Ti:Sapphire

Coherent:

Mira (<35 fs pulse length, 1 W ave power),

Chameleon (Hands-free, ~100 fs pulse length),

Spectra-Physics:

Tsunami (<35 fs pulse length, 1 W ave power)

Mai Tai (Hands-free, ~100 fs pulse length)

Very-short-pulse commercial fs lasers

Ti:Sapphire

KM Labs

< 20 fs and < $20K

Femtolasers

As short as 8 fs!

Ytterbium Tungstate (Yb:KGW)

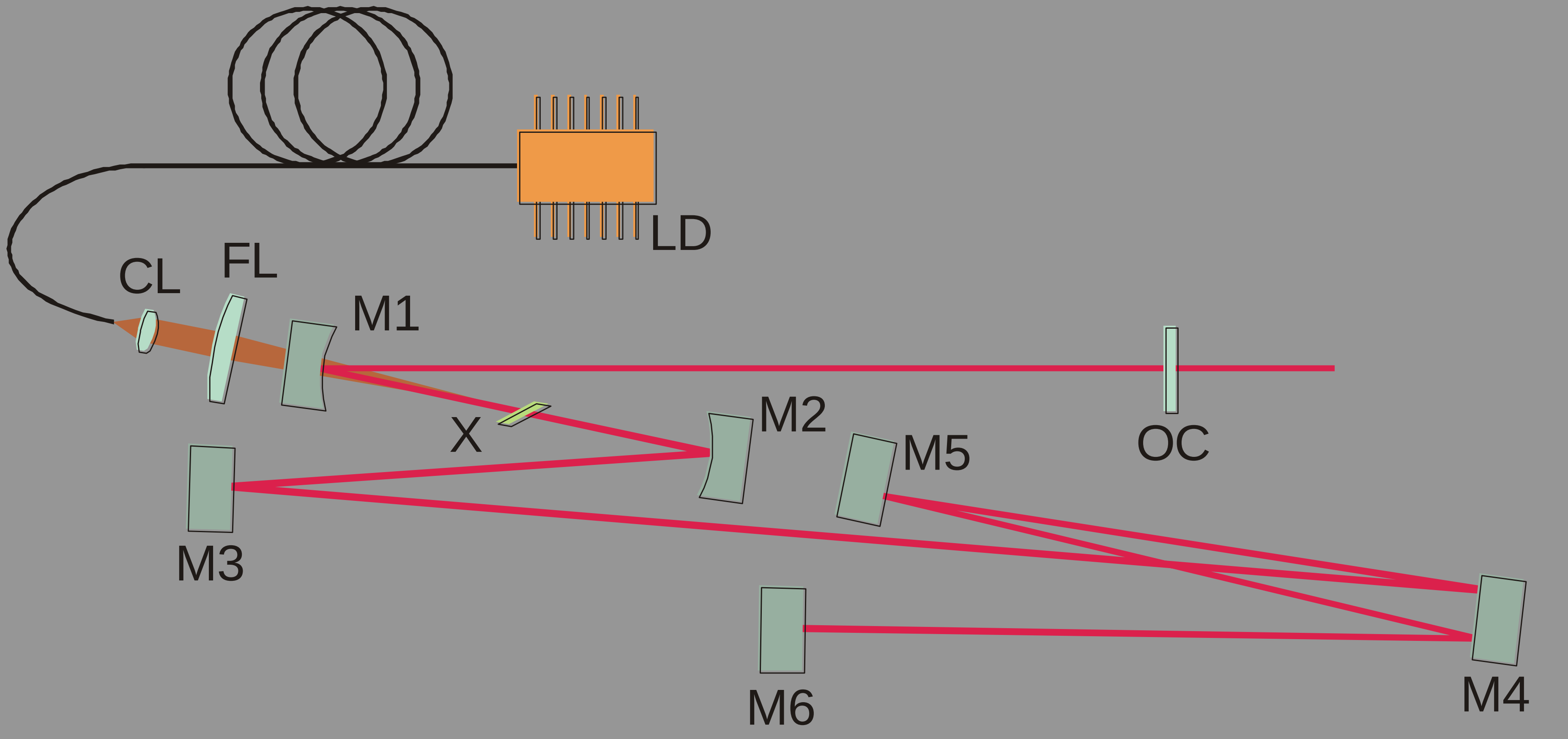
Amplitude Systemes

Ytterbium doped laser materials can be directly diode-pumped, eliminating the need for an intermediate (green) pump laser used in Ti:Sapphire lasers.

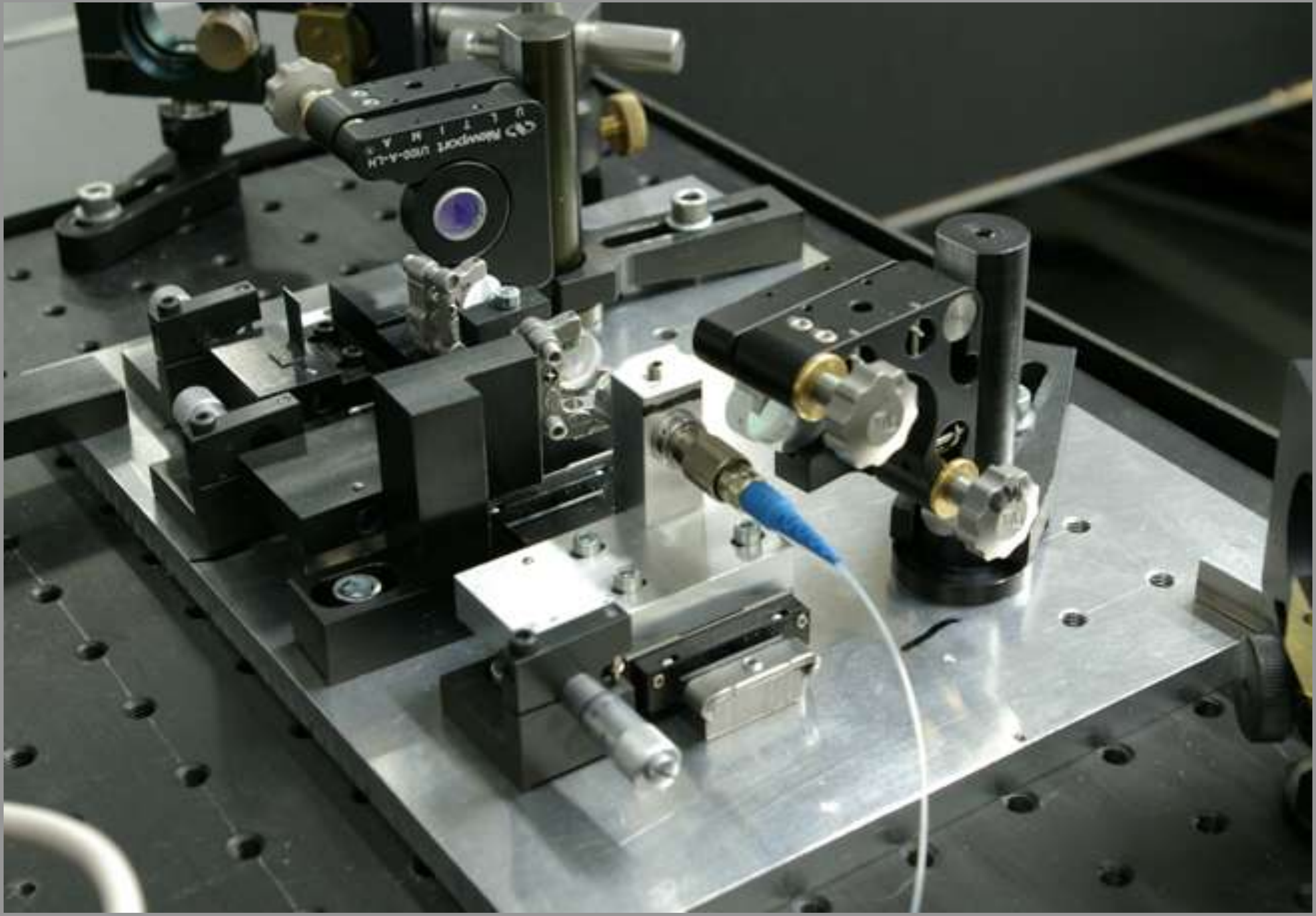
They also offer other attractive properties, such as a very high thermal efficiency and high average power.

Model	**t-Pulse 20**	**t-Pulse 100**	**t-Pulse 200**
Pulse energy (nJ)	20	100	**200**
Average power (W)	1	1	2
Repetition rate (MHz)	50	10	10

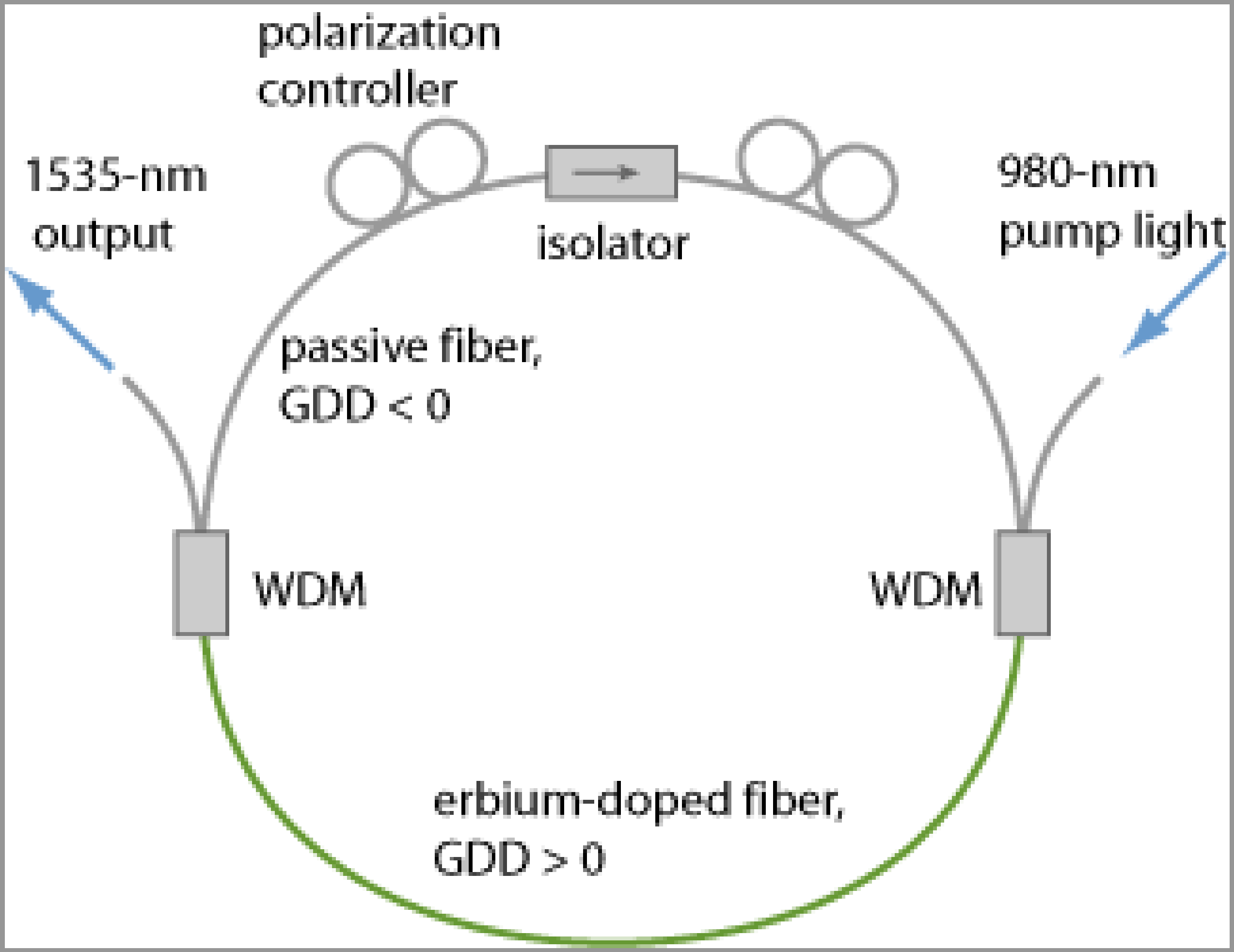
Yb:KYW femtosecond oscillator



1 GHz repetition rate Yb:KYW laser



Femtosecond fiber lasers - ideas



Nonlinear polarization rotation

Nonlinear optical loop mirror (NALM)

Commercial fs fiber lasers

Erbium

Menlo Systems

150 fs; 150 mW

IMRA America

Frequency-doubled

Wavelength	780 nm
Average Power	50 mW
Pulse width	< 250 fs
Repetition rate:	50 MHz
Stability:	+/- 2%

Commercial fs fiber lasers

Lasers

1030 nm Industry Grade Femtosecond Oscillator

This is not a usual laser. This is the superhero of laser oscillators. It has special superpowers that make it stand out from the crowd. Super-short yet ultra-fast. Small in size but very stable and robust. The earth may tremble but the laser will operate as usual. Same power, same pulse and no degradation over many years. Meet Fluence Oscillator – the first SESAM-free and truly-all-fiber 1030 nm ultrafast laser.

This oscillator was specifically developed to be the rock-solid heart of the Fluence Jasper amplified system. It is build upon the Fluence truly-all-fibre technology, with no degradable components inside and no SESAM. The oscillator is equipped with a special self-starting solution ensuring the laser mode-locks every time. This feature together with the low size and power consumption makes the Fluence Oscillator perfect for OEM applications.

Type of output	Fiber connector
Pulse duration	Chirped pulse (compression option available <200 fs)
Maximum average power	>20 mW
Pulse energy	>1 nJ
Polarization	Linear, vertical
Central wavelength	1030 ± 5 nm
Optional wavelength outputs	515 nm
Repetition rate	20 MHz (other on request)