2. The Generation of Ultrashort Laser Pulses

The importance of bandwidth

More than just a light bulb

Laser modes and mode-locking

Making shorter and shorter pulses

- Pulse-pumping
- Q-switching and distributed-feedback lasers
- Passive mode-locking and the saturable absorber
- Kerr-lensing and Ti:Sapphire
- Active mode-locking
- Other mode-locking techniques

Limiting factors

Commercial lasers

But a light bulb is also broadband.

What else is required to make an ultrashort pulse?

Answer: **"Mode-locking"**

Okay, what are modes and what does it mean to lock them?

Mode locking

- Mode locking is a **dynamic steady-state process**, differs previous the three pulse-generation
- **Pulsed laser** action is attained by **coupling together** the modes of a laser and **locking phase** to each other
- A laser can oscillate on many **longitudinal modes**, with **frequencies** that are equally separated by the **Fabry-Perot** intermodal spacing $\nu_F = c/2d$
- Although these modes normally **oscillate independently** (**free-running modes**), external means can be used to **couple** them and lock their phase together
- The modes can be regarded as the components of a **Fourier-series expansion** of a periodic function of time of period $T_F = 1/\ \nu_F = 2d/c$, which constitute a **periodic pulse train**.

- Each of laser modes is approximated by a uniform plane wave propagating with a velocity $c = c_0/n$

$$U(z,t) = \sum_q A_q \exp\left[j2\pi\nu_q\left(t - \frac{z}{c}\right)\right], \qquad (15.4\text{-}25)$$

$$\nu_q = \nu_0 + q\nu_F, \qquad q = 0, \pm 1, \pm 2, \ldots \qquad (15.4\text{-}26)$$

- For convenience, we assume that the $q = 0$ mode **coincides with** the **central frequency** ν_0 of the **atomic lineshape**

- Since the **modes interact with** different groups of atoms in an **inhomogeneously broadened medium**, their phases $\arg\{A_q\}$ are random and statistically independent

- Substituting (15.4-26) into (15.4-25) =>

$$U(z,t) = \mathcal{A}\left(t - \frac{z}{c}\right) \exp\left[j2\pi\nu_0\left(t - \frac{z}{c}\right)\right], \qquad (15.4\text{-}27)$$

- Complex envelope

$$\mathcal{A}(t) = \sum_q A_q \exp\left(\frac{jq2\pi t}{T_F}\right) \qquad (15.4\text{-}28)$$

$$T_F = \frac{1}{\nu_F} = \frac{2d}{c}. \qquad (15.4\text{-}29)$$

- If the **magnitudes** and **phases** of the **complex coefficients** A_q are properly chosen, ***A***(t) may be made to take the form of periodic narrow pulses

- Consider M modes ($M = 2S+1$), $A_q = A$, $q = 0, \pm1, \ldots, \pm S$

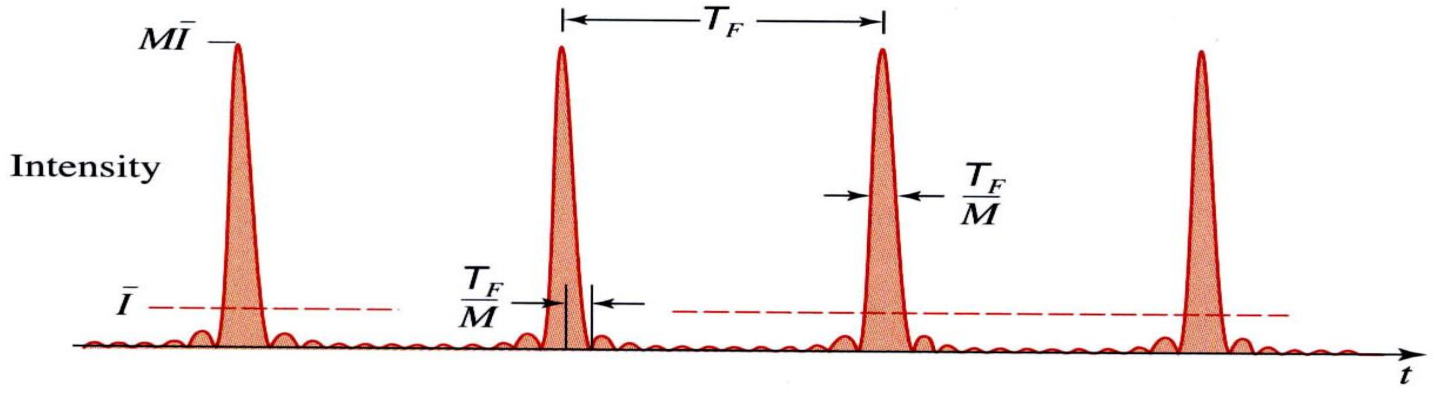
$$\mathcal{A}(t) = A\sum_{q=-S}^{S}\exp\left(\frac{jq2\pi t}{T_F}\right) = A\sum_{q=-S}^{S}x^q = A\frac{x^{S+1}-x^{-S}}{x-1} = A\frac{x^{S+\frac{1}{2}}-x^{-S-\frac{1}{2}}}{x^{\frac{1}{2}}-x^{-\frac{1}{2}}}, \quad (15.4\text{-}30)$$

$x = \exp(j2\pi t/T_F)$

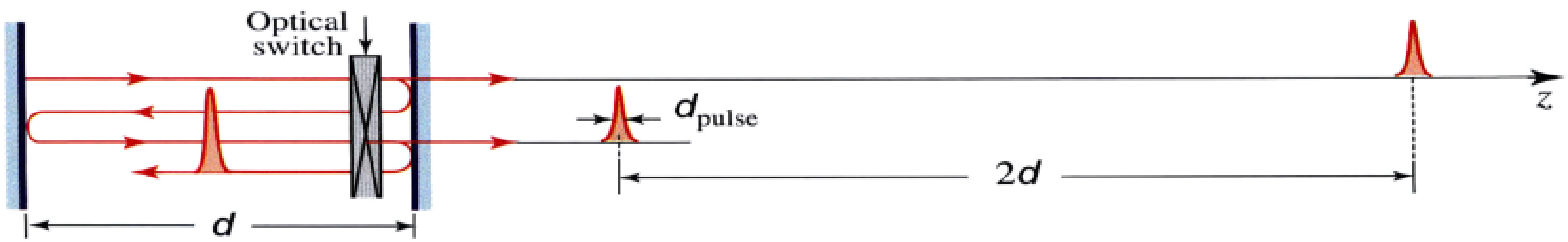
$$\mathcal{A}(t) = A\frac{\sin(M\pi t/T_F)}{\sin(\pi t/T_F)}. \quad (15.4\text{-}31)$$

- The optical intensity =

$$I(t,z) = |A|^2\frac{\sin^2[M\pi(t-z/c)/T_F]}{\sin^2[\pi(t-z/c)/T_F]}, \quad (15.4\text{-}32)$$



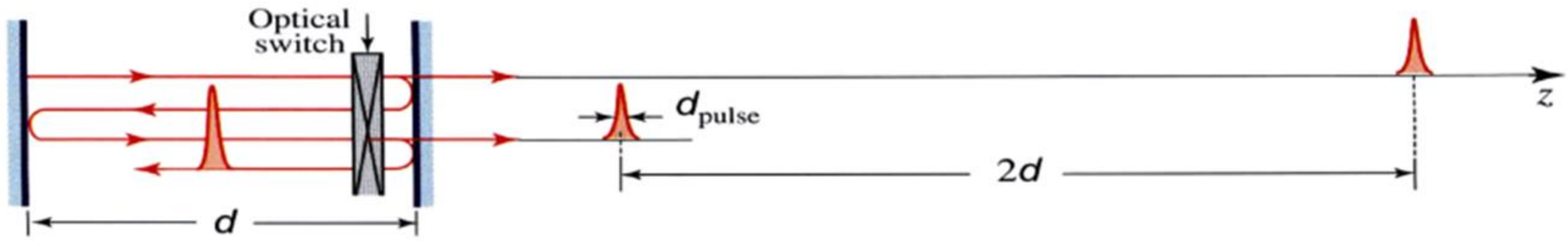
- The shape is **dependent** on the **number of modes** M
- If $M \approx \Delta\nu/\nu_F$, $\tau_{pulse} = T_F/\boldsymbol{M} \approx 1/\Delta\nu$
- Because $\Delta\nu$ can be **quite large**, very narrow mode-locked laser pulses can generated
- The ratio between the **peak** and **mean intensities** is equal to the number of modes M (also quite large)
- The period of the pulse train ($T_F = 2d/c$) is just the time for a single round trip of reflection within the resonator



- The light in a **mode-locked laser** can be regarded as

  A single narrow pulse of photons reflecting back and forth between the mirrors of the resonator

  The transmitted pulses are separated by the distance 2*d* and have a spatial width $\boldsymbol{d}_{\text{pulse}} = c\boldsymbol{\tau}_{\text{pulse}} = 2d/\boldsymbol{M}$



- A particular example : Nd^{3+}:glass laser

  Operating at $\lambda_0 = 1.05\ \mu m$, refractive index $n = 1.5$ and linewidth $\Delta\nu = 7$ THz

  Thus , pulse duration $\tau_{pulse} = 1/\Delta\nu \approx 140$ fs and pulse length $d_{pulse} \approx 42\ \mu m$

  If the length of the resonator $d = 15$ cm, the mode separation $\nu_F = c/2d = 1$ GHz

  $M = \Delta\nu/\nu_F = 7000$ modes, the peak intensity is 7000 times greater than the average intensity

- In media with broad linewidths

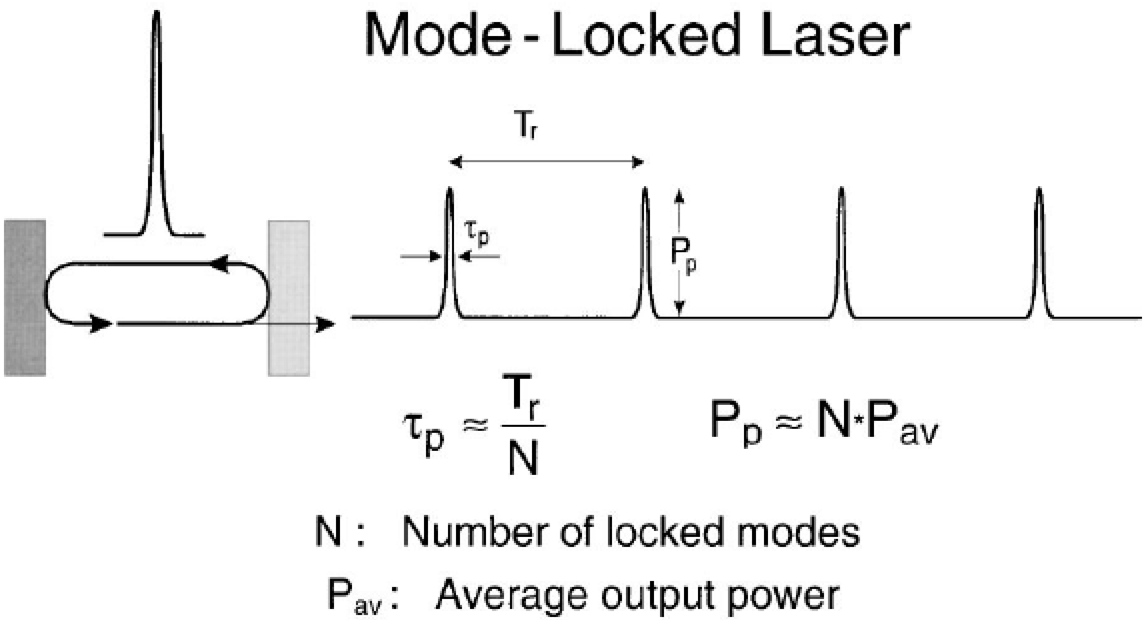
  Mode locking is generally more advantageous than Q-switching for obtaining short pulses

- Gas lasers generally have narrow atomic linewidths, so that ultrashort pulses cannot be obtained by mode locking

Table 15.4-1 Characteristic properties of a mode-locked pulse train.

Temporal period	$T_F = \frac{2d}{c}$	Pulse duration	$\tau_{pulse} = \frac{T_F}{M} = \frac{1}{\Delta\nu}$
Spatial period	$2d$	Pulse length	$d_{pulse} = \frac{2d}{M}$
Mean intensity	$\bar{I}$	Peak intensity	$I_p = M\bar{I}$

Mode-locked laser

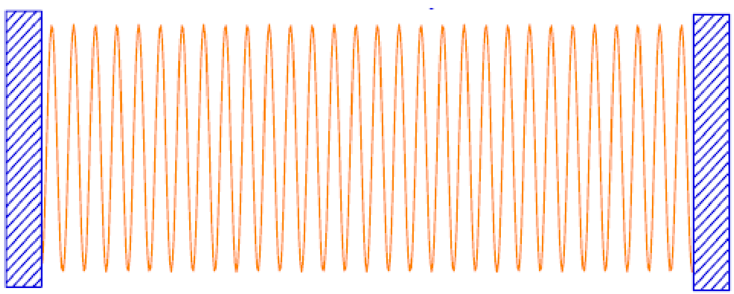


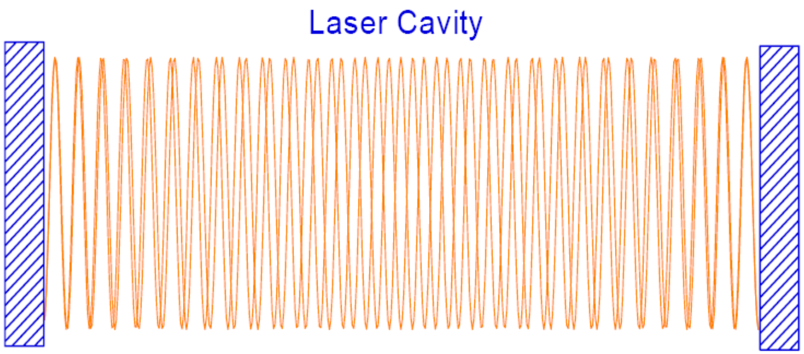
➢Radiation power as a function of time at the output of a stationary mode-locked laser

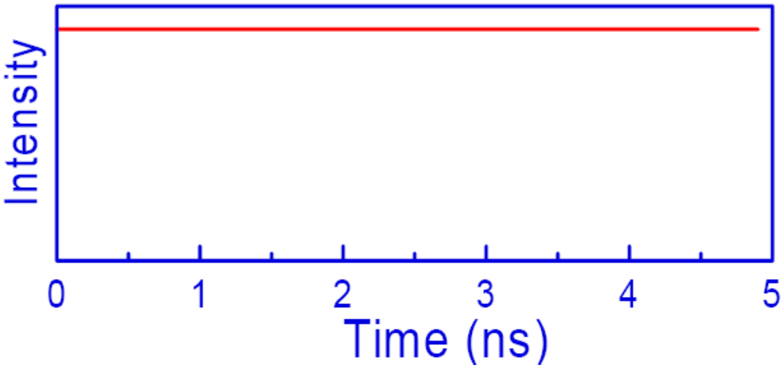
Mode Locking with one and two oscillation frequency

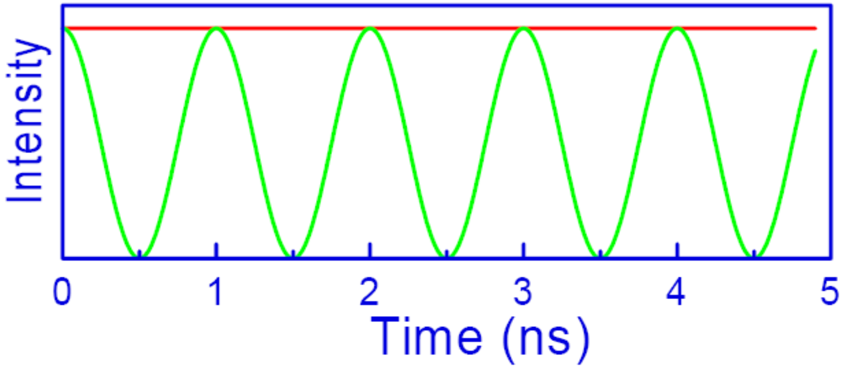
$$\vec{E}(t) = E_0\, e^{i N \omega t}$$

$$\vec{E}(t) = E_0\, e^{i N \omega t} + E_0\, e^{i (N-1) \omega t}$$

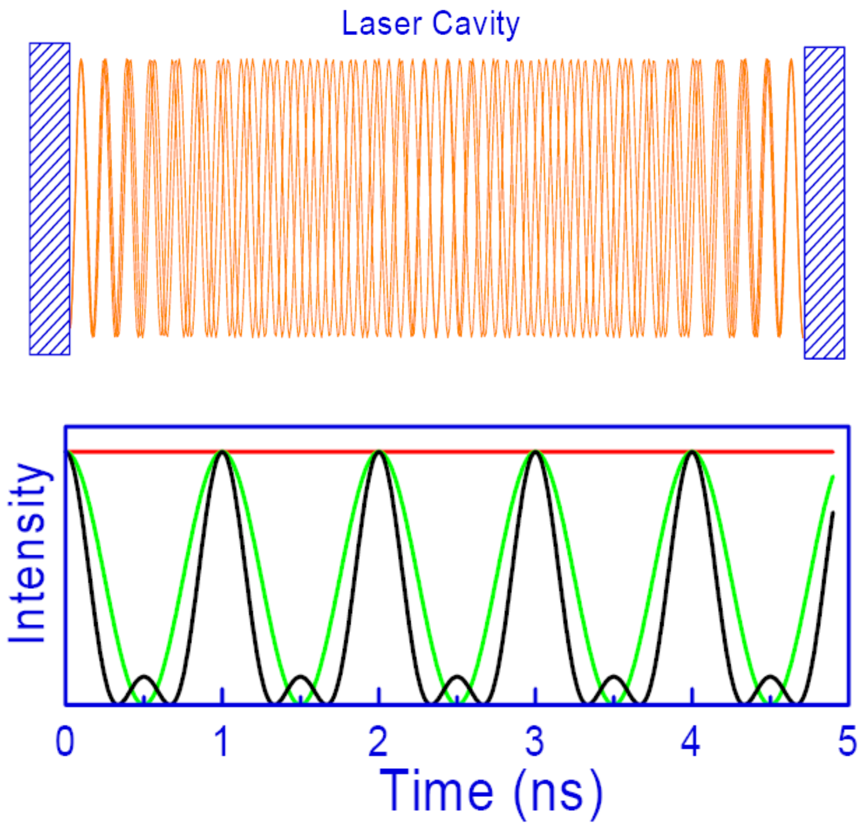


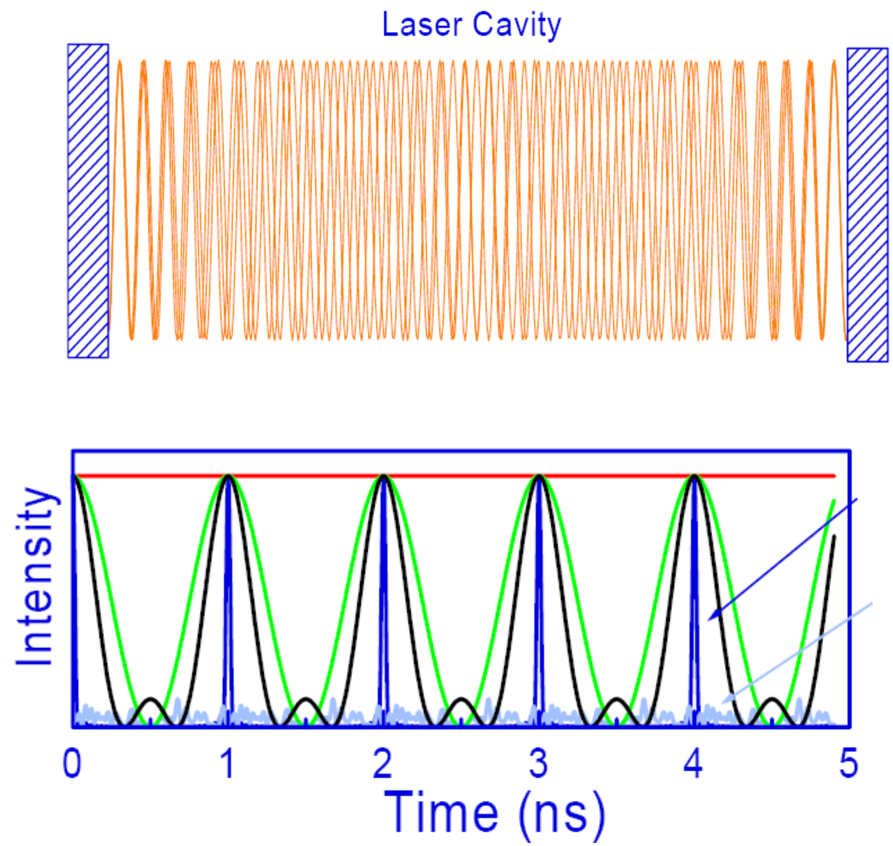






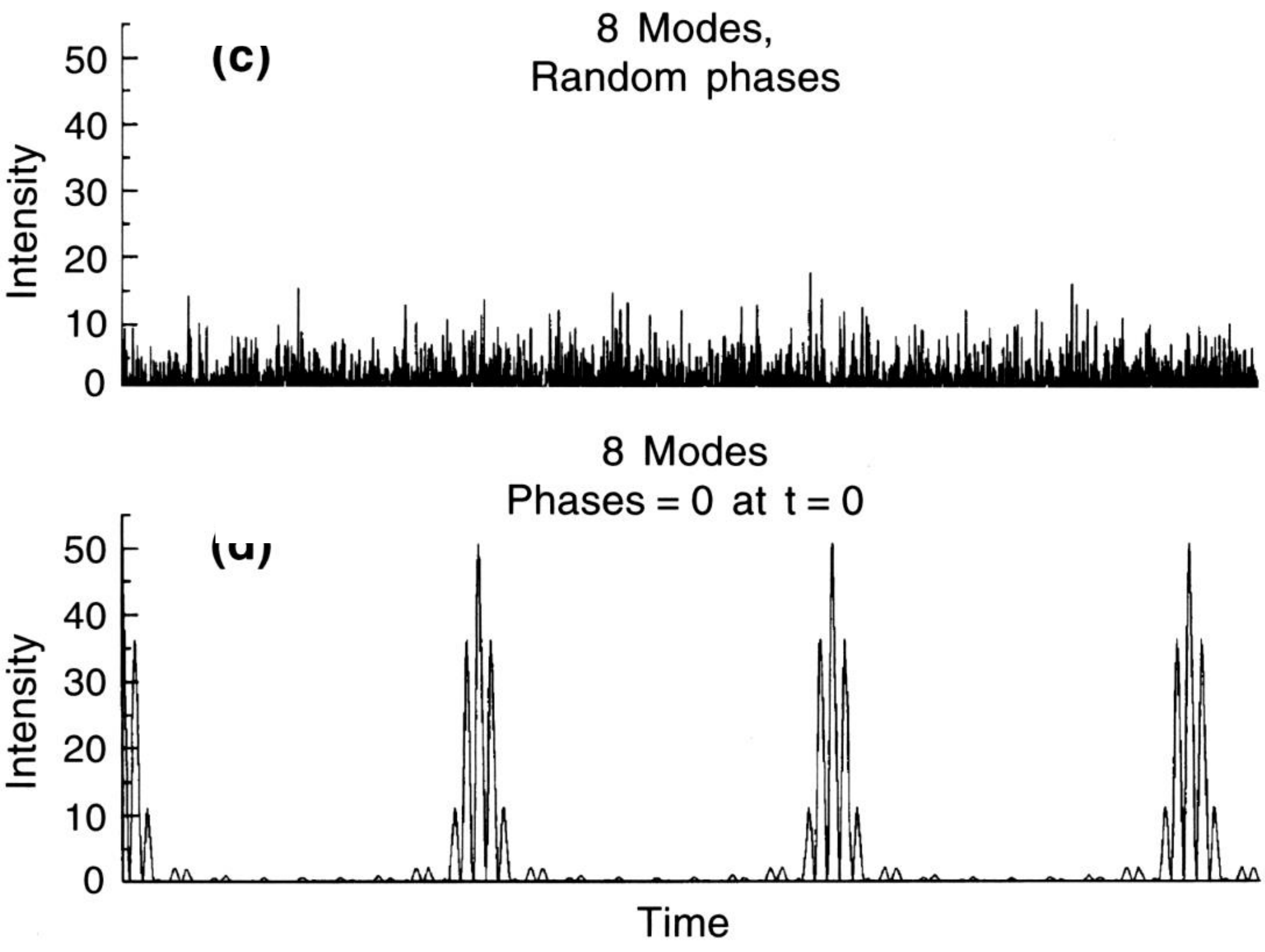
$$\vec{E}(t) = E_0\, e^{i(N+1)\omega t} + E_0\, e^{iN\omega t} + E_0\, e^{i(N-1)\omega t}$$





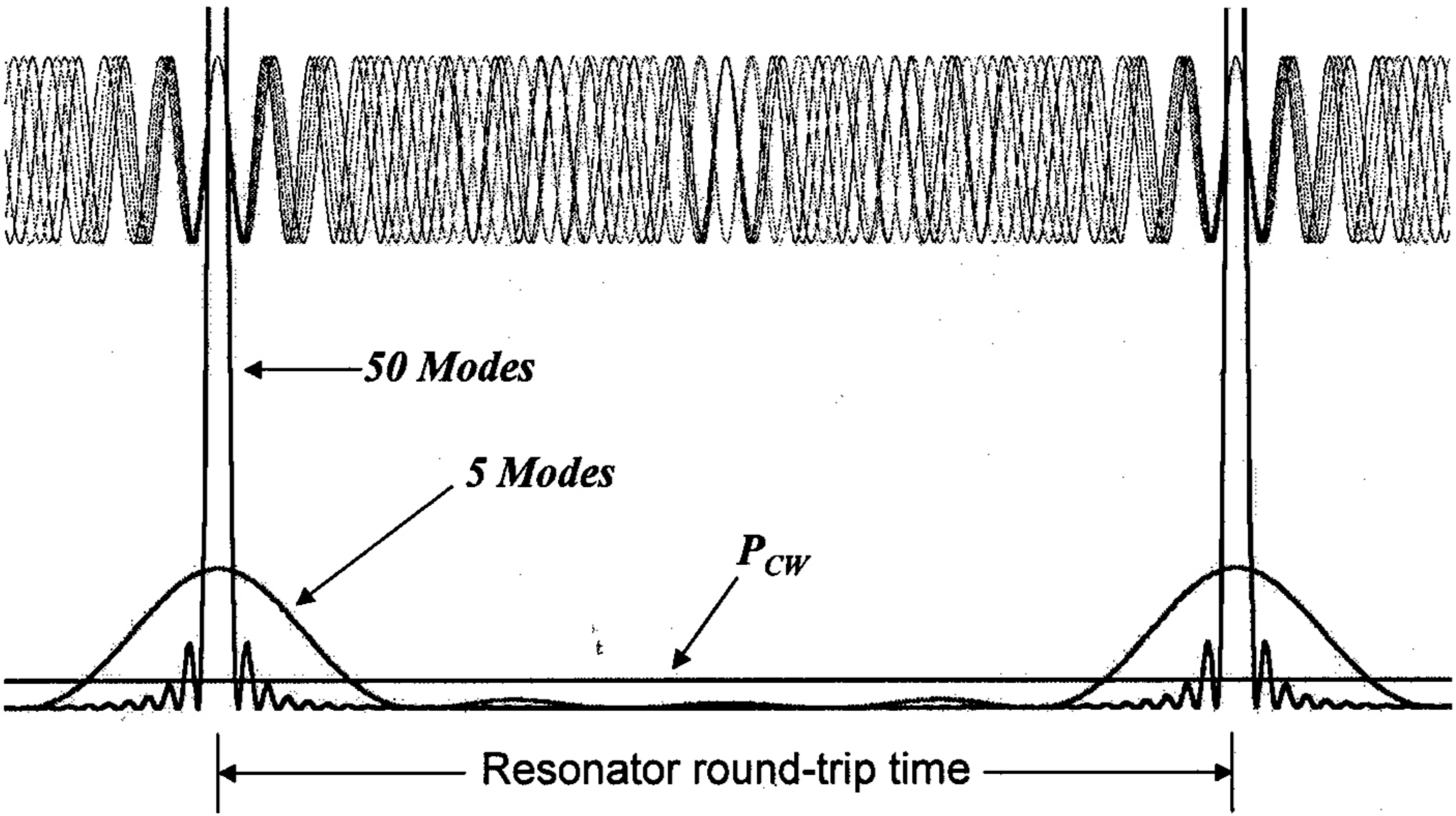
Ultrashort pulse can be generate as number of modes M increase

Numerical simulation of mode-locking



Ultrafast lasers often have thousands of modes.

Locked modes

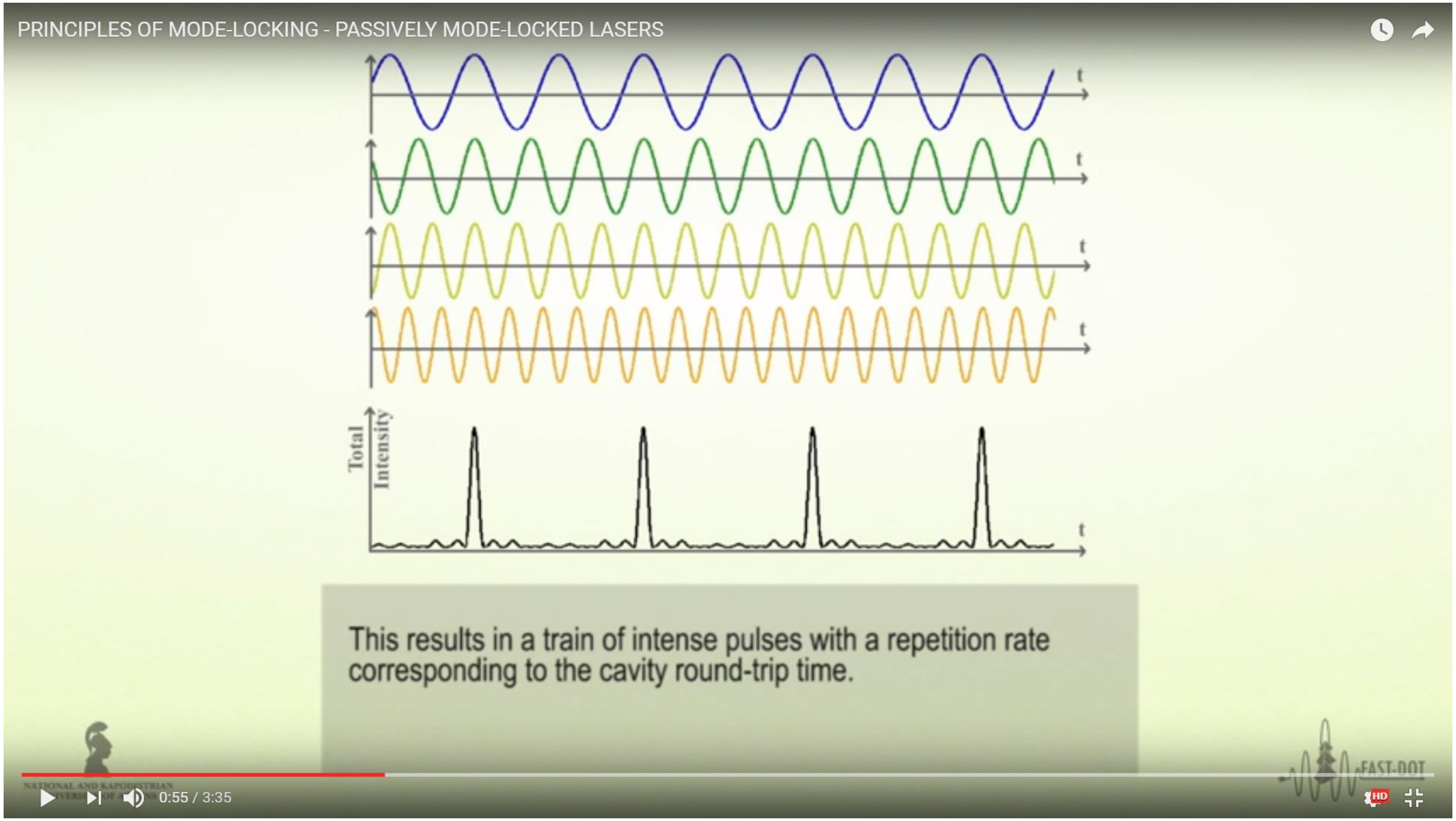


M. Didomenico, J. Appl. Phys. Lett. **35**, 2870 (1964); L. Hargrove *et al.*, Appl. Phys. Lett **5**, 4 (1964)

Video of mode locking

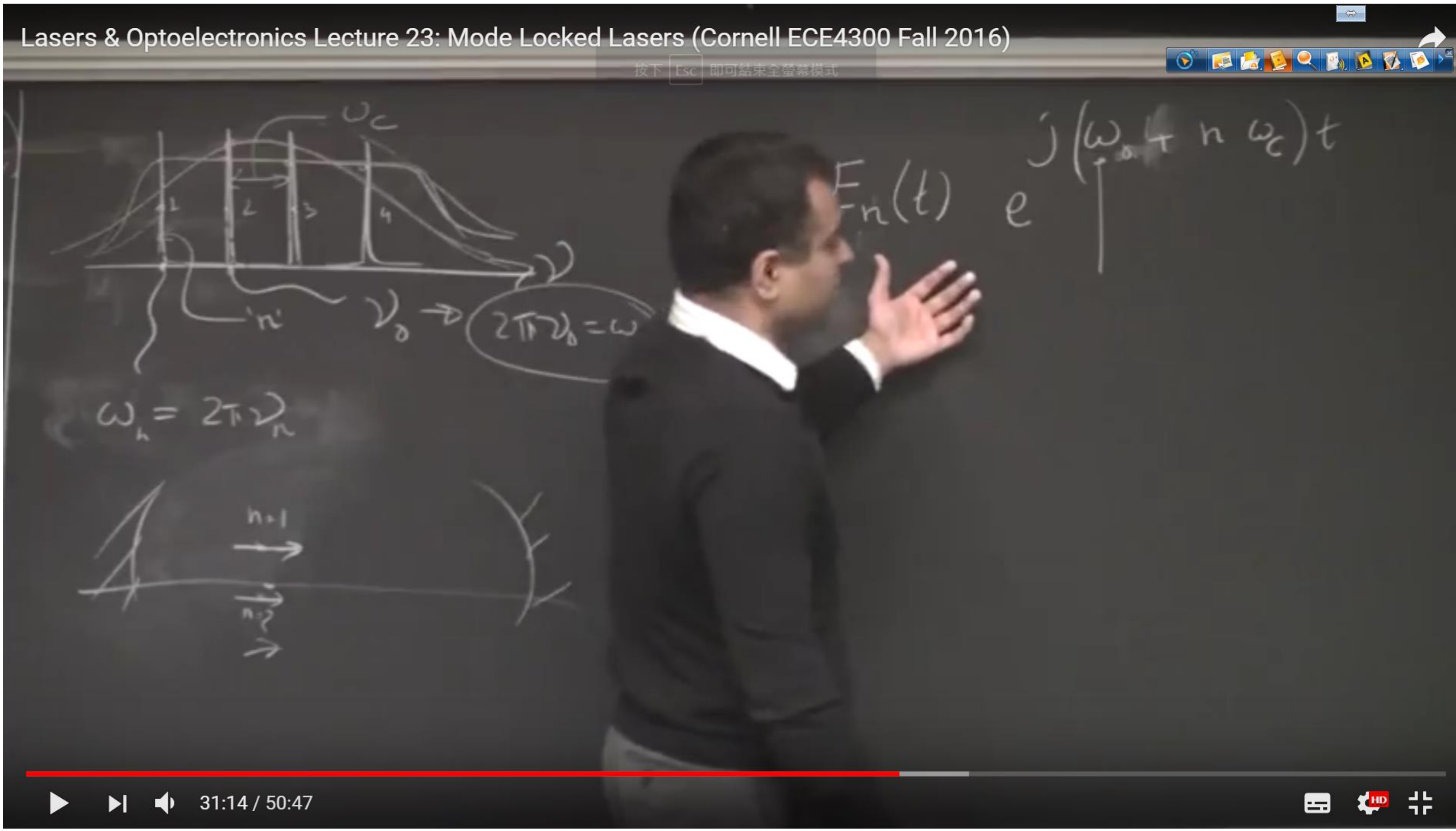
Linking

➢ https://www.youtube.com/watch?v=efxFduO2Yl8



Lecture of mode locking

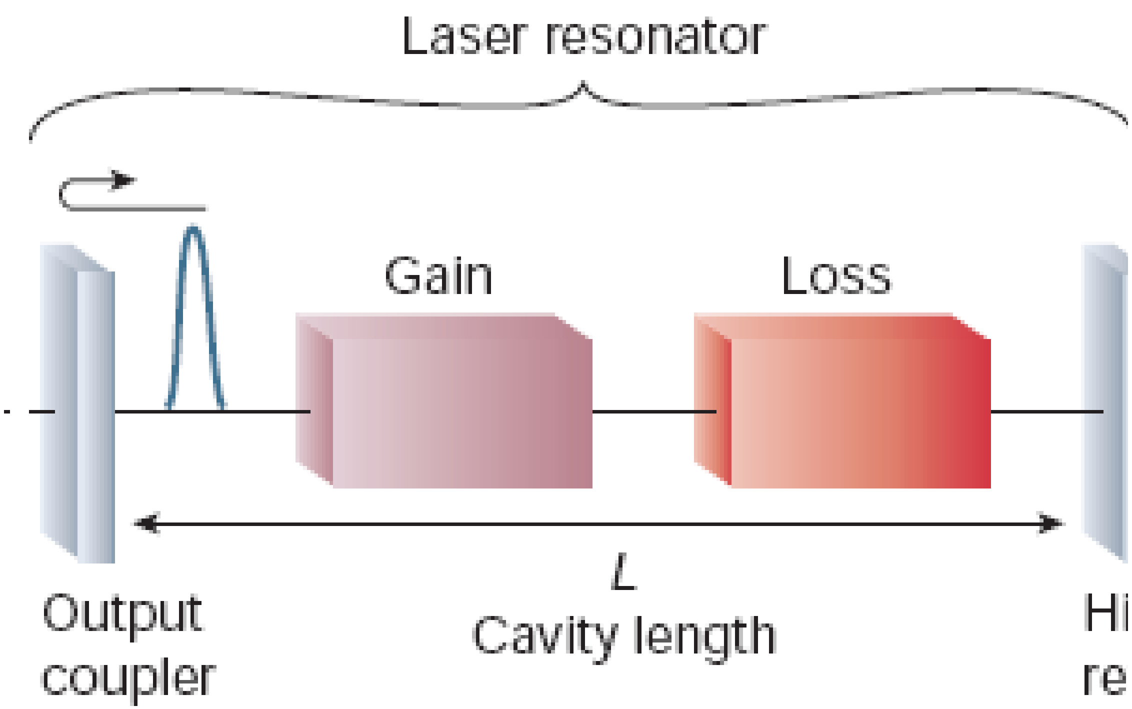
- https://www.youtube.com/watch?v=Jf-hQzVsLJ8

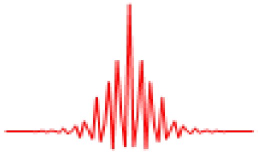


How to generate ultrafaser laser

- Mode locking method:
  - Active mode locking
    - Electro-optical modulator
    - Acoustic-optical modulator
  - Passive mode locking
    - Saturable absorber
    - Semiconductor saturable absorber mirror (SESAM)
    - Kerr lens mode locking
    - Nonlinear mirror mode locking

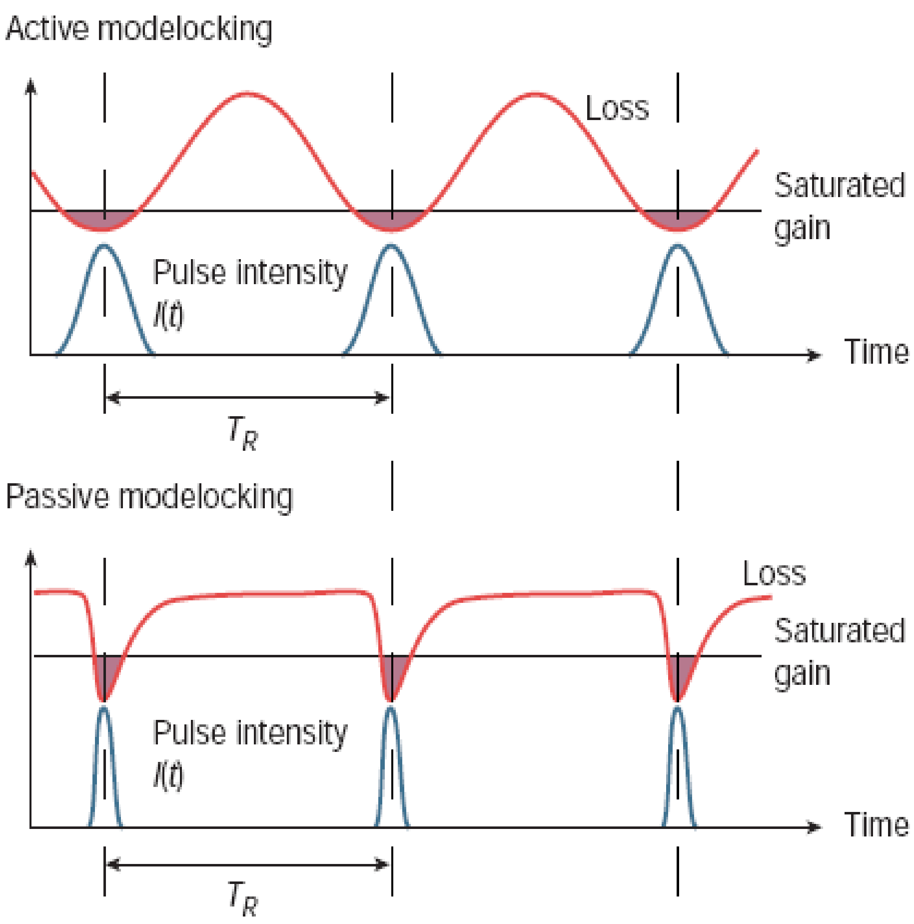
A generic ultrafast laser has a broadband gain medium,a loss modulator device, and two or more mirrors:





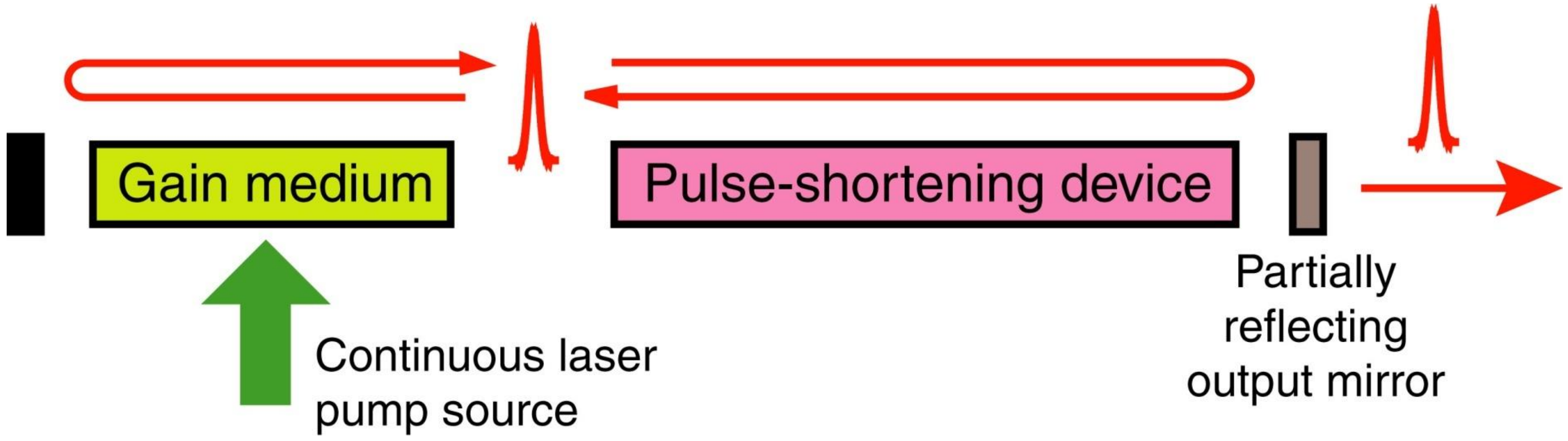
Active and Passive Mode Locking

- The acoustic-optical or electro-optical modulator => periodic sinusoidal loss modulation => equal the cavity round trip time
- A saturable absorber => to obtain a self-amplitude modulation of the light inside the laser cavity.
- Loss modulation => Relatively large for low intensities but significantly smaller for a short pulse with high intensity.
- The high intensity @ the peak of pulse => saturates the absorber more strongly than its low intensity wings => pulse shaping effect



A generic ultrashort-pulse laser

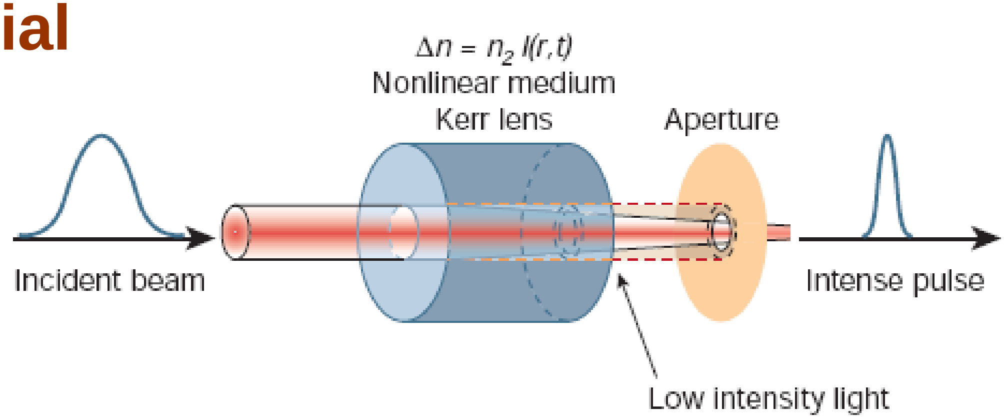
- A generic ultrafast laser has a broadband gain medium, a pulse-shortening device, and two or more mirrors:



Many pulse-shortening devices have been proposed and used.

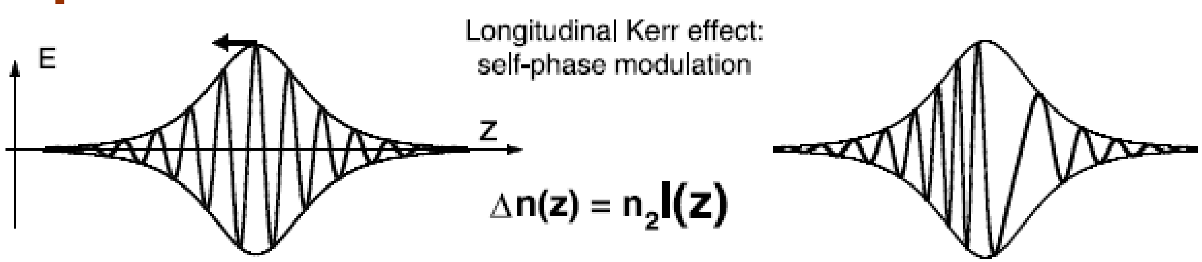
Kerr lens mode locking

Spatial



Self-focusing and aperture => high intensity pulse for low loss

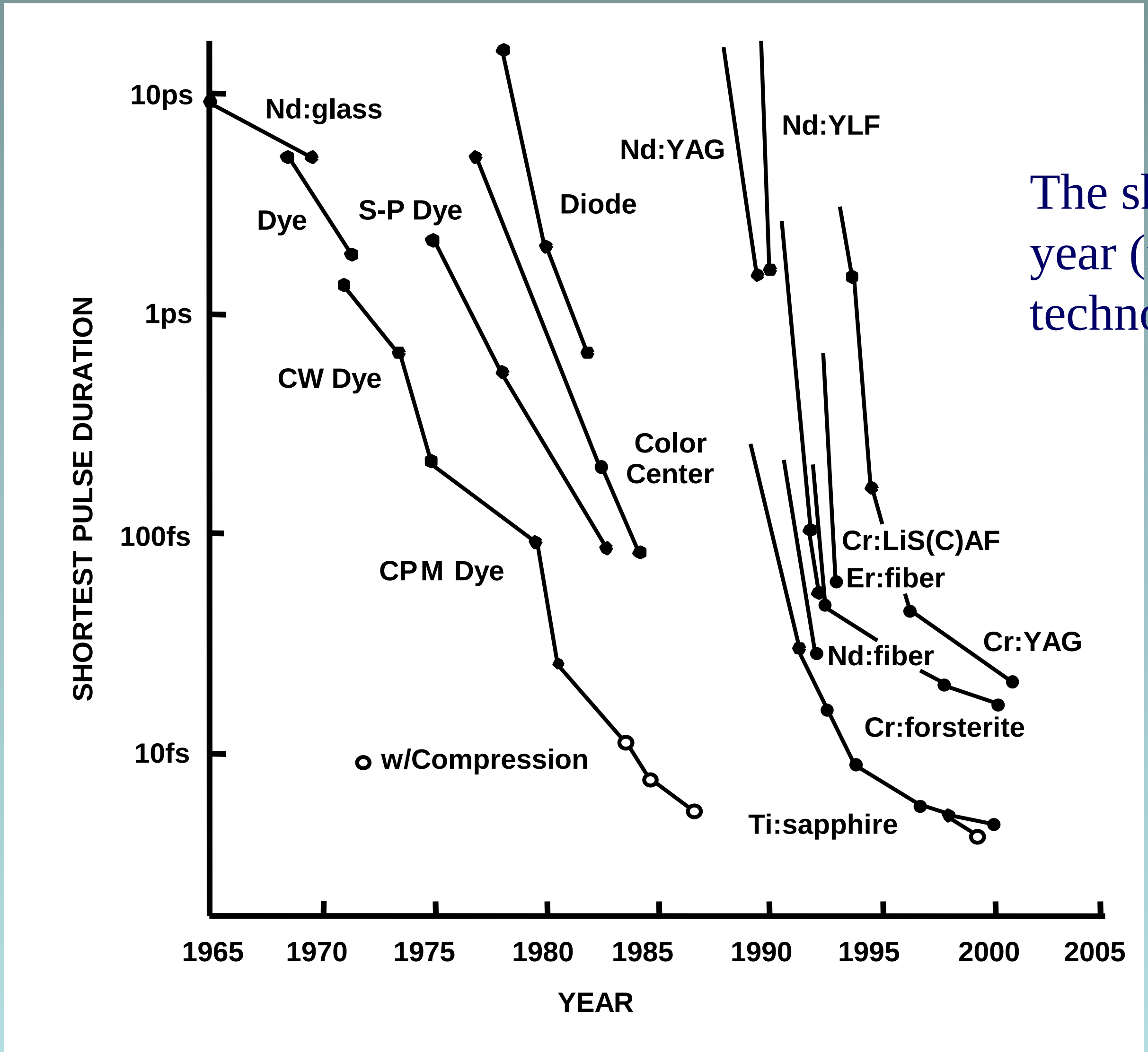
Temporal



λ increase @ leading edge

Self-phase modulation (SPM) and negative group velocity dispersion (GVD)=> pulse shaping effect

But first: the progress has been amazing!



The shortest pulse vs. year (for different technologies)

Erich Ippen, MIT

Continuous vs. ultrashort pulses of light

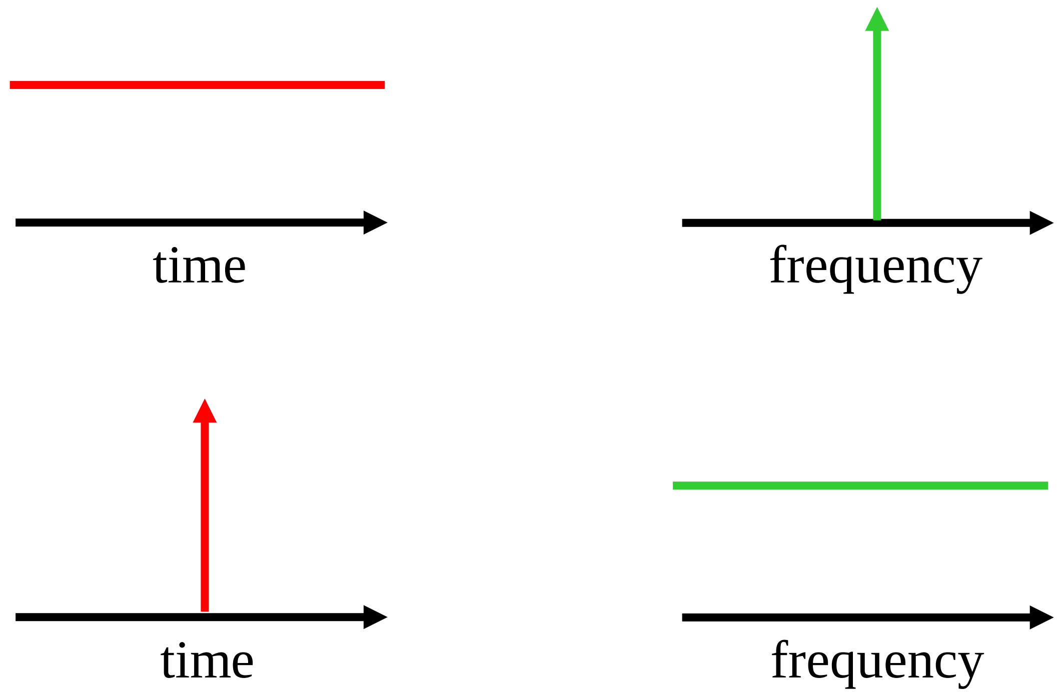
- A constant and a delta-function are a Fourier-Transform pair.

Irradiance vs. time

Spectrum

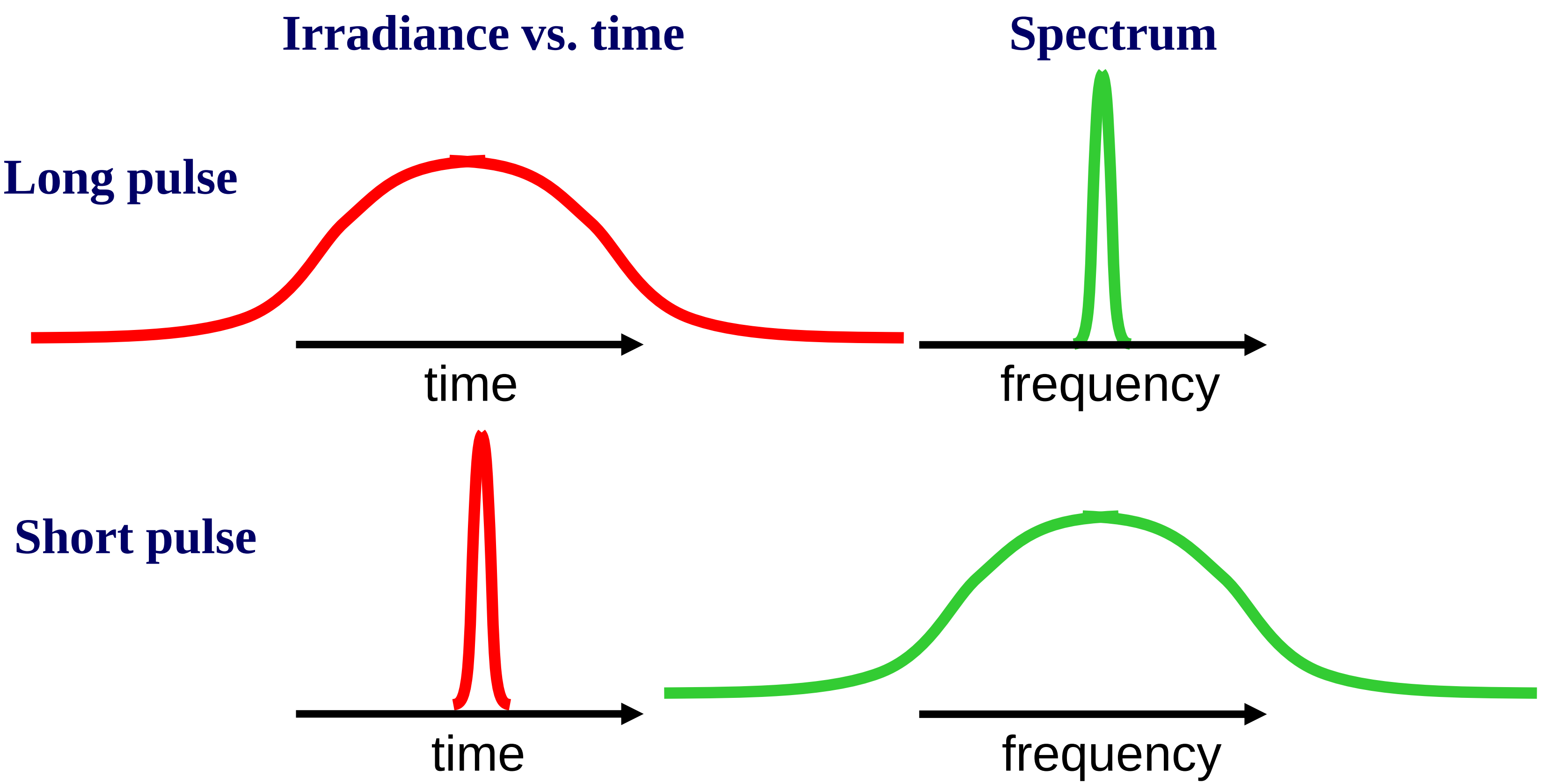
Continuous beam:

Ultrashort pulse:

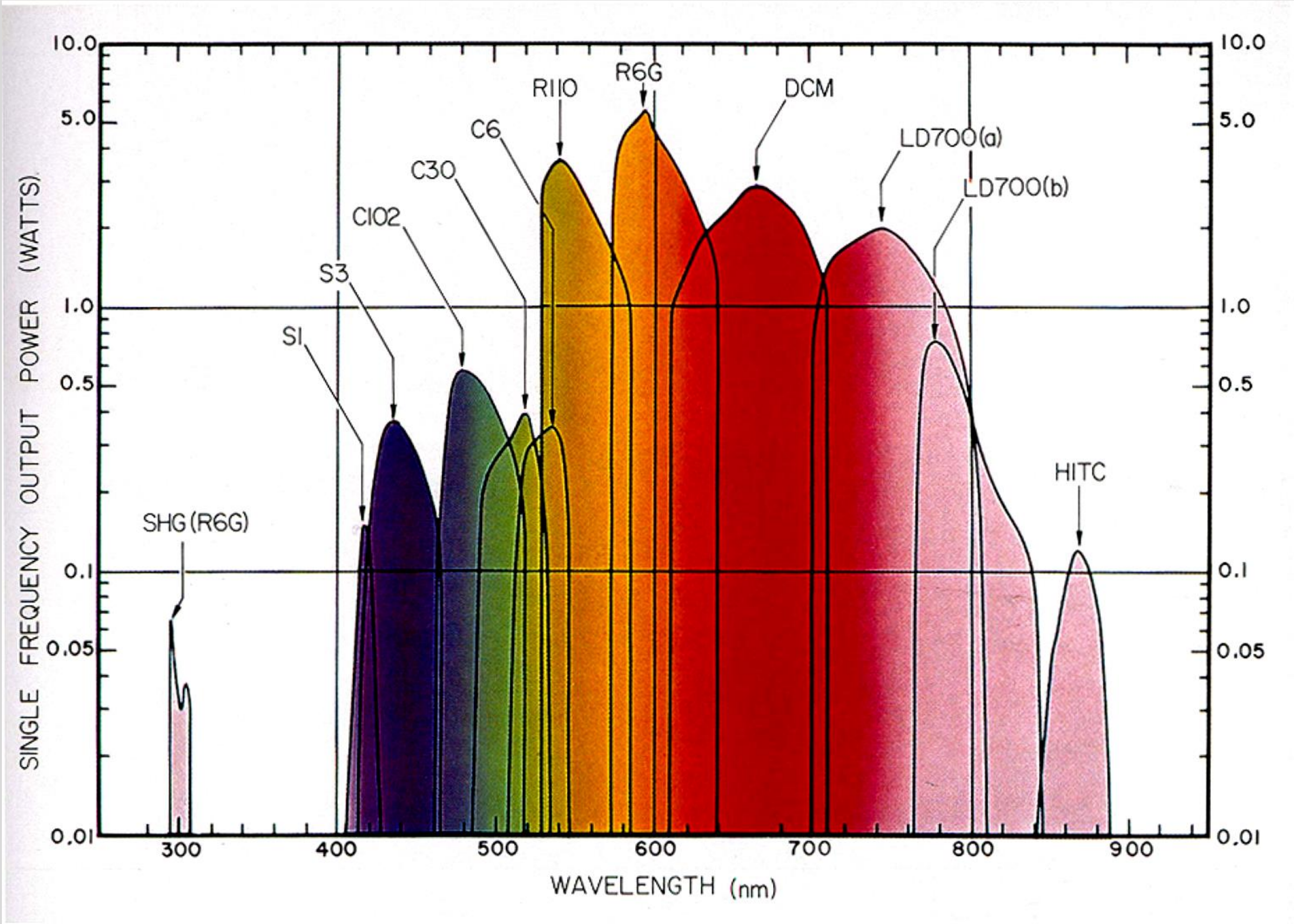


Long vs. short pulses of light

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

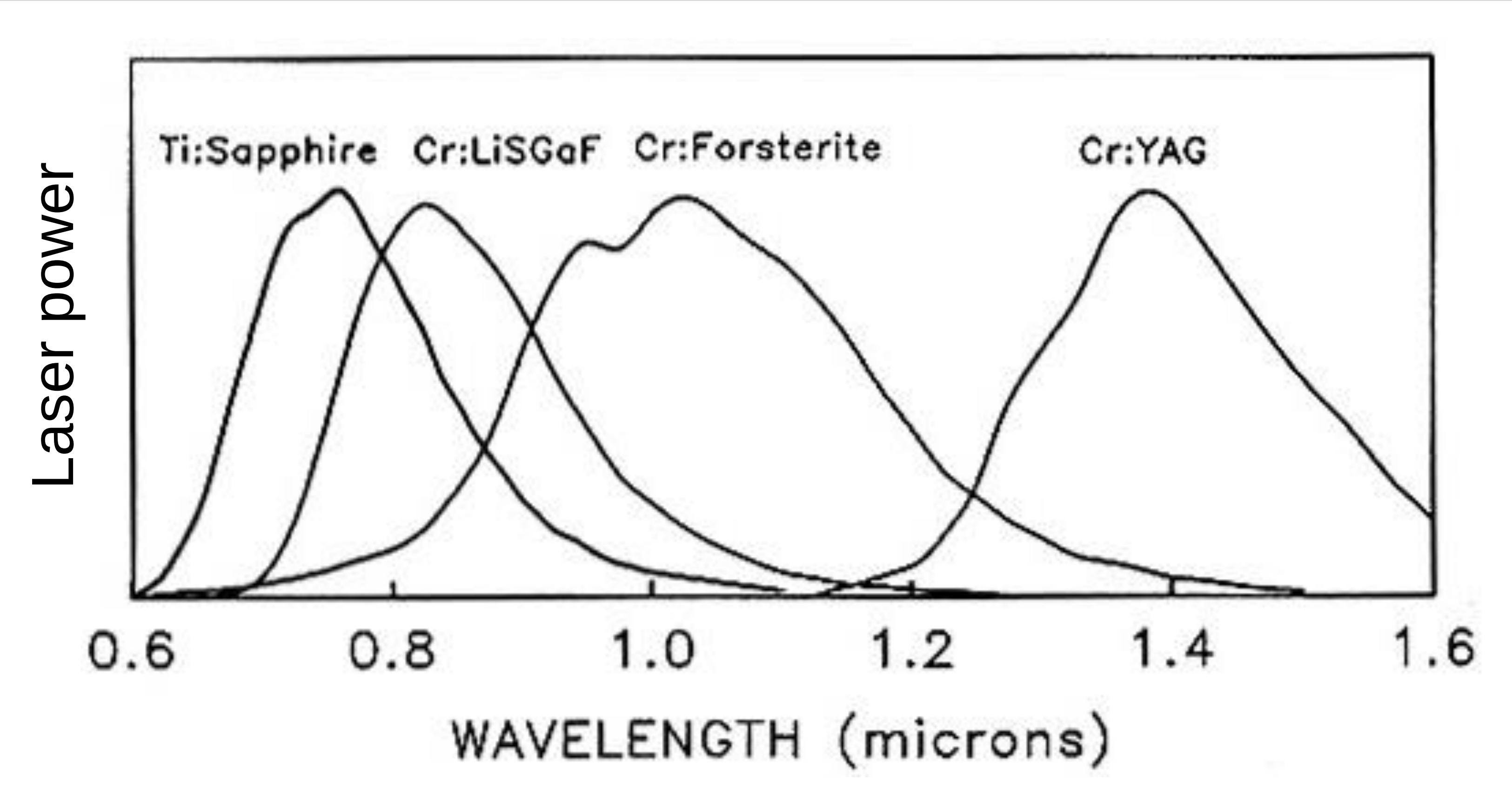


For many years, dyes have been the broadband media that have generated ultrashort laser pulses.



Ultrafast solid-state laser media have recently replaced dyes in most labs.

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

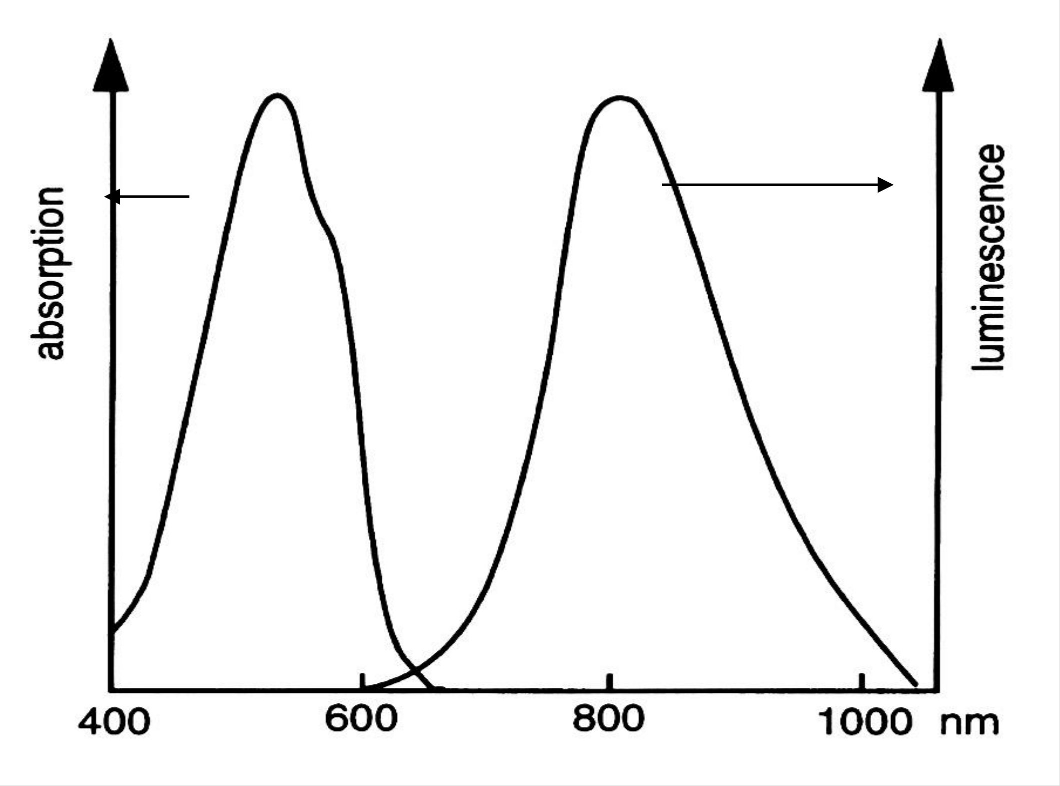


Titanium Sapphire

➢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.

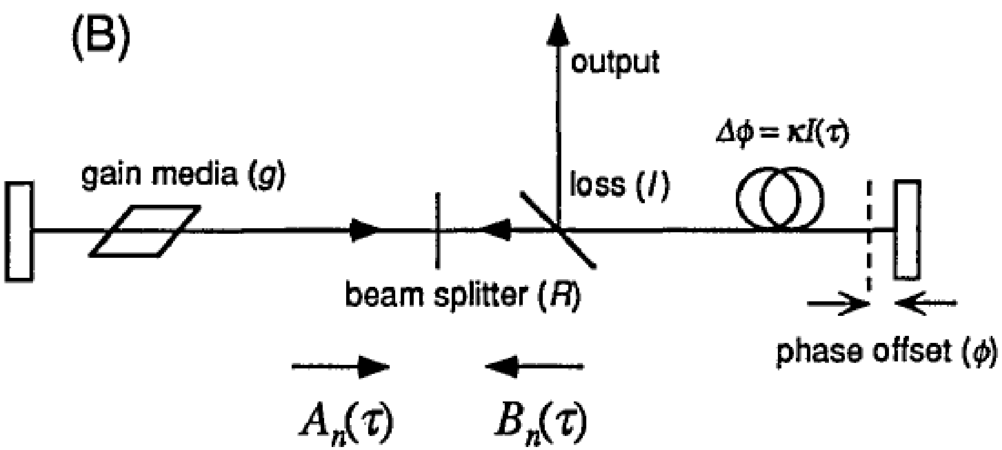
It can be pumped with a (continuous) Argon laser (~450-515 nm) or a doubled-Nd:YAG laser (532 nm).

It lases well between 700 and 1000 nm.



Ti:sapphire laser

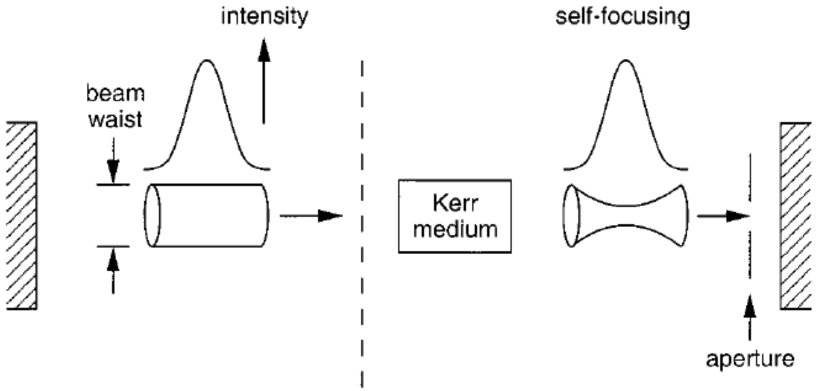
- Series of **broad-bandwidth**, **solid-state laser** materials were developed
  - The most notable : **Ti:sapphire (Ti:Al_2O_3)**
    - Lased over a **continuous band** stretching 680 ~ 1100 nm.
- Pulse width as shorter as **200 fs** in late 1989 using **additive pulse mode-locking (APM)**
  - APM is accomplished by **feeding back** into the laser part of its output after it has been **nonlinearly modulated** in an **external cavity**



An intracavity interferometer with a nonlinear phase modulator, to which an additive-pulse mode-locking laser is equivalent. OPTICS LETTERS / Vol. 16, No. 14 / July 15, 1991

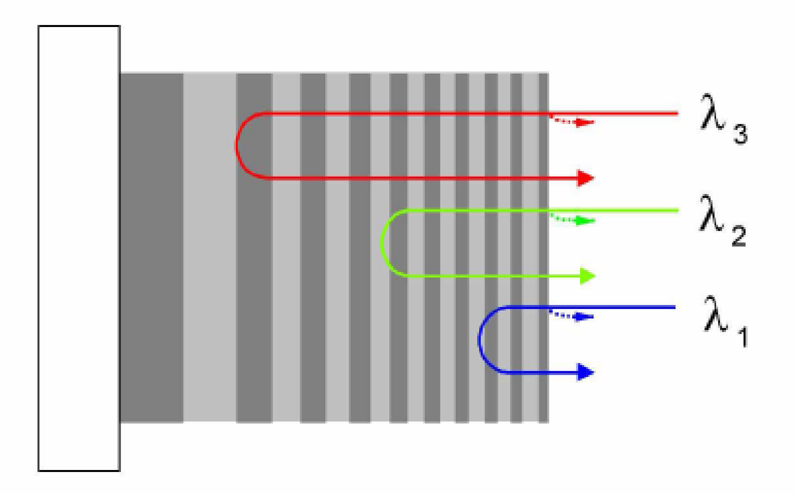
Ti:sapphire laser

- In 1991, observed **self-mode-locking** or **Kerr lens ML**
  - Because of **nonlinearity** present in laser crystal
- Nonlinear refraction index n_2 introduces an intensity dependent index given by $n = n_0 + n_2 I$
  - n_0 : linear index of the crystal
  - I : instantaneous laser pulse intensity
- **Self-focusing** when light focuses into crystal
  - Nonlinear phase delay of the beam will be highest at center of the beam
  - Additional lens in cavity with intense pulse (not for low-intensity)
- Cavity alignment can be adjusted
  - Pulse spatial mode suffers less loss than CW spatial mode

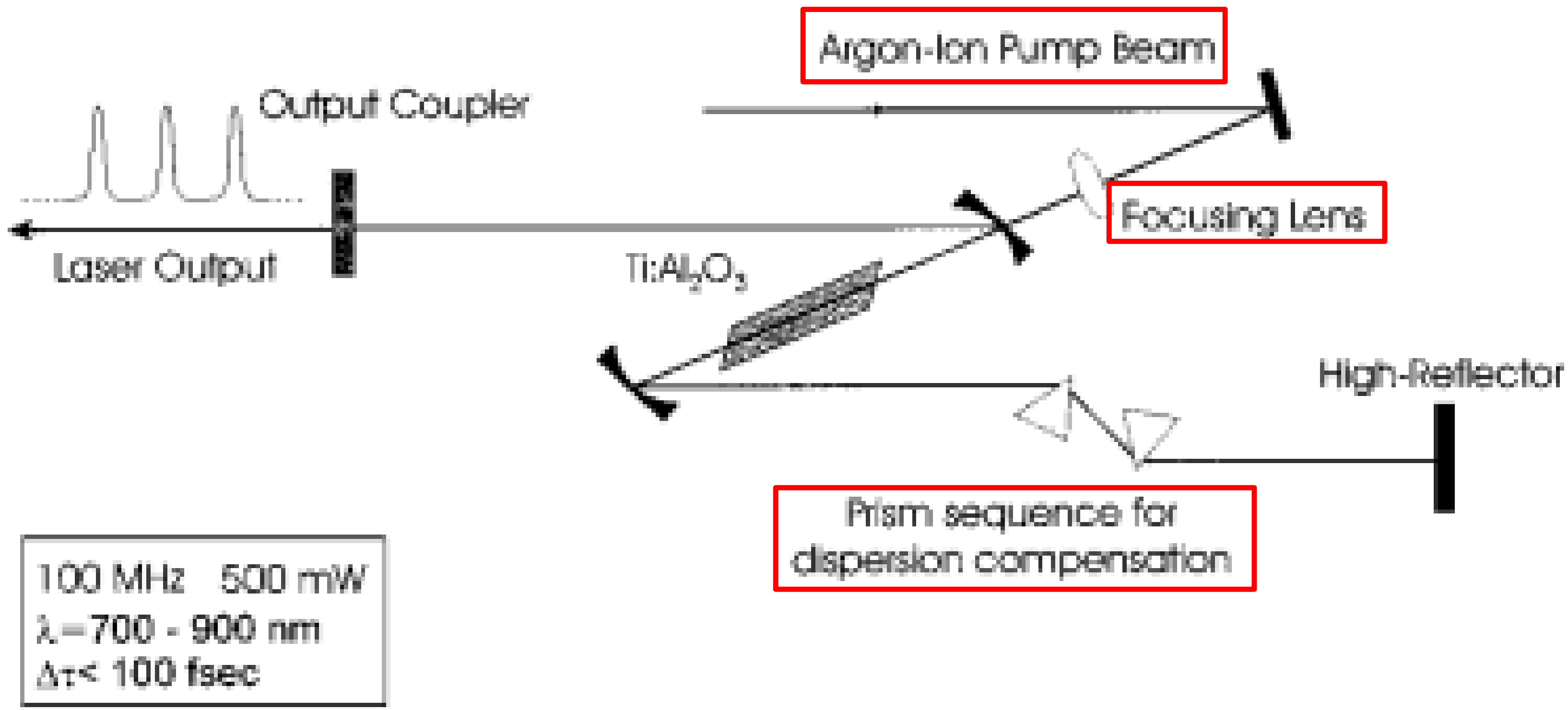


Ti:sapphire laser

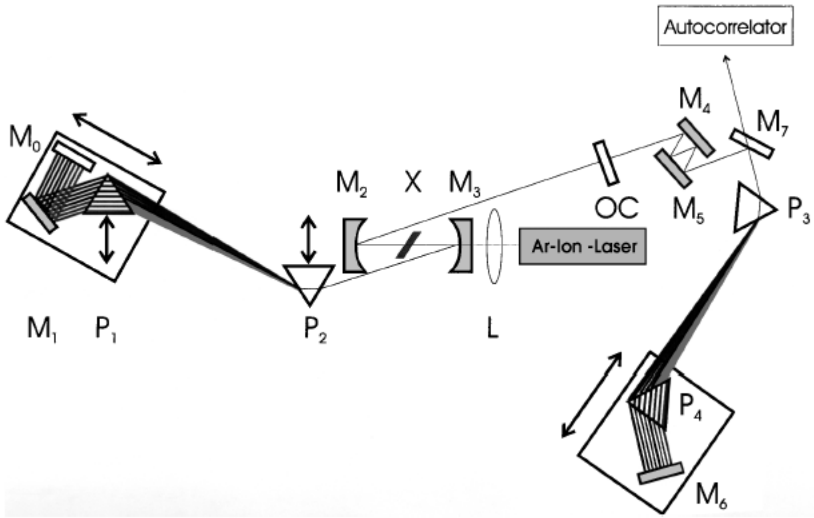
- When **self-focusing** is induced the ML profile will match the **pump mode**, and will favor pulse operation
  - Because this ML is induced by the pulse itself, is said to self-ML, and the effect is the same as if a fast SA were present in cavity
- Today Ti:sapphire lasers can generate 25 fs pulses with not to much difficulty
  - Allowing researchers to explore **semiconductor dynamics** at very short time scales
- 6.5 fs pulses from a Ti:sapphire laser
  - Combination of **prism pair** & **double-chirped mirror** for dispersion compensation



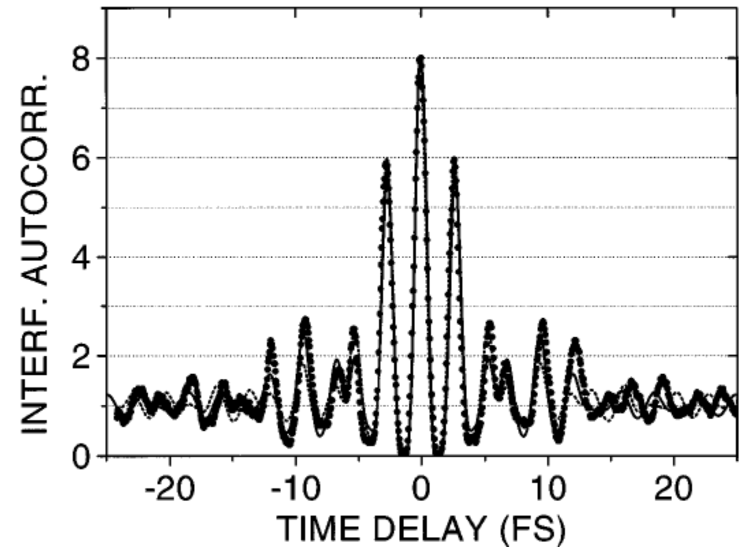
Ti:sapphire laser (Z-configuration)

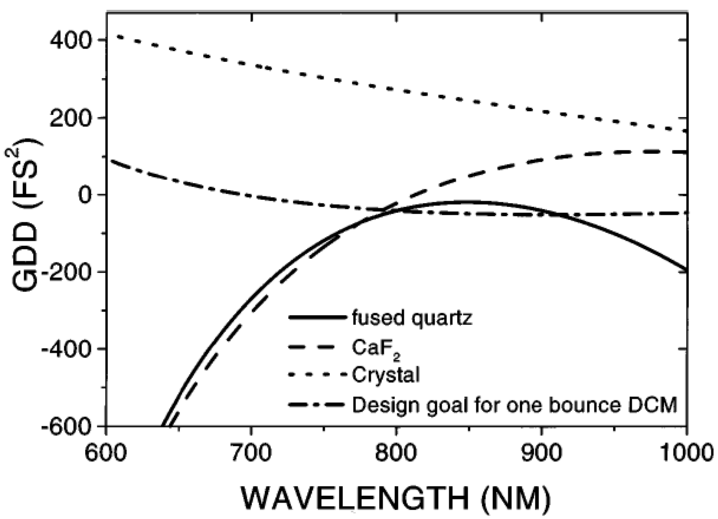


Sub-two-cycle pulses from a Kerr-lens mode-locked Ti:sapphire laser



Interferometric autocorrelation

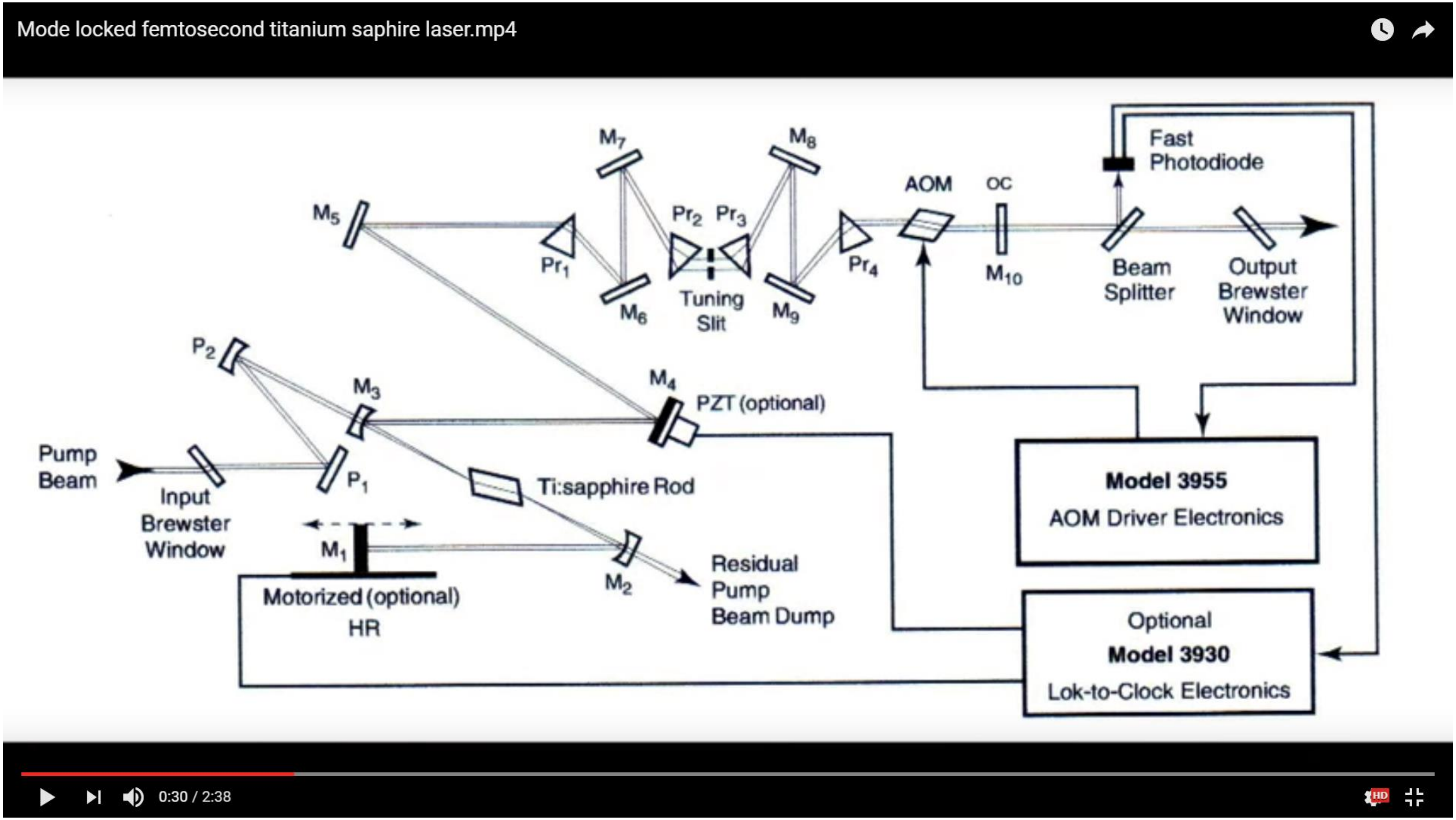




The dashed curve is a fit of a sinc function with a FWHM of 5.4 fs, and the solid curve is the calculation from the spectrum

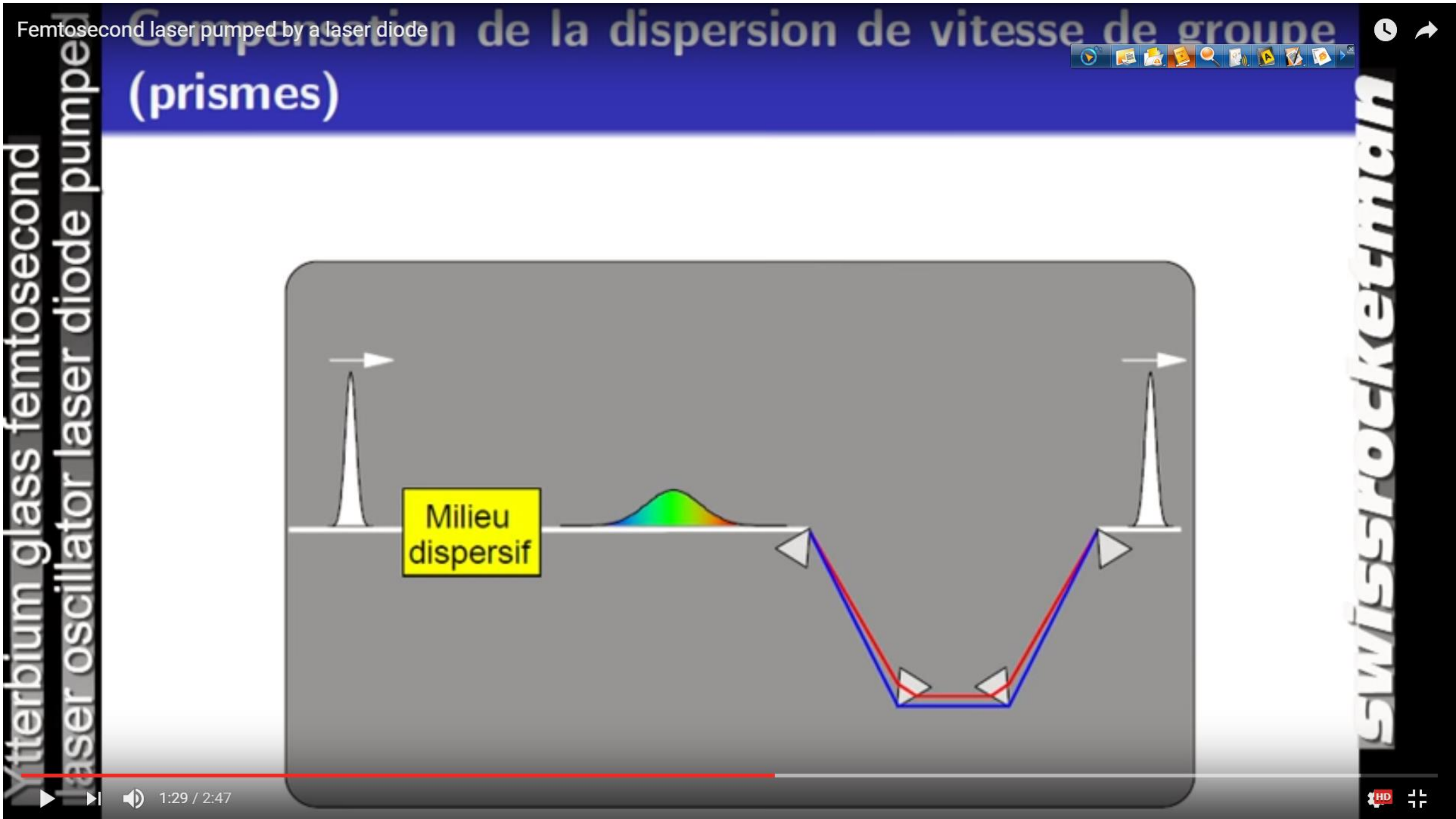
Video of Ti:sapphire laser

https://www.youtube.com/watch?v=KX6h9CVXYkA



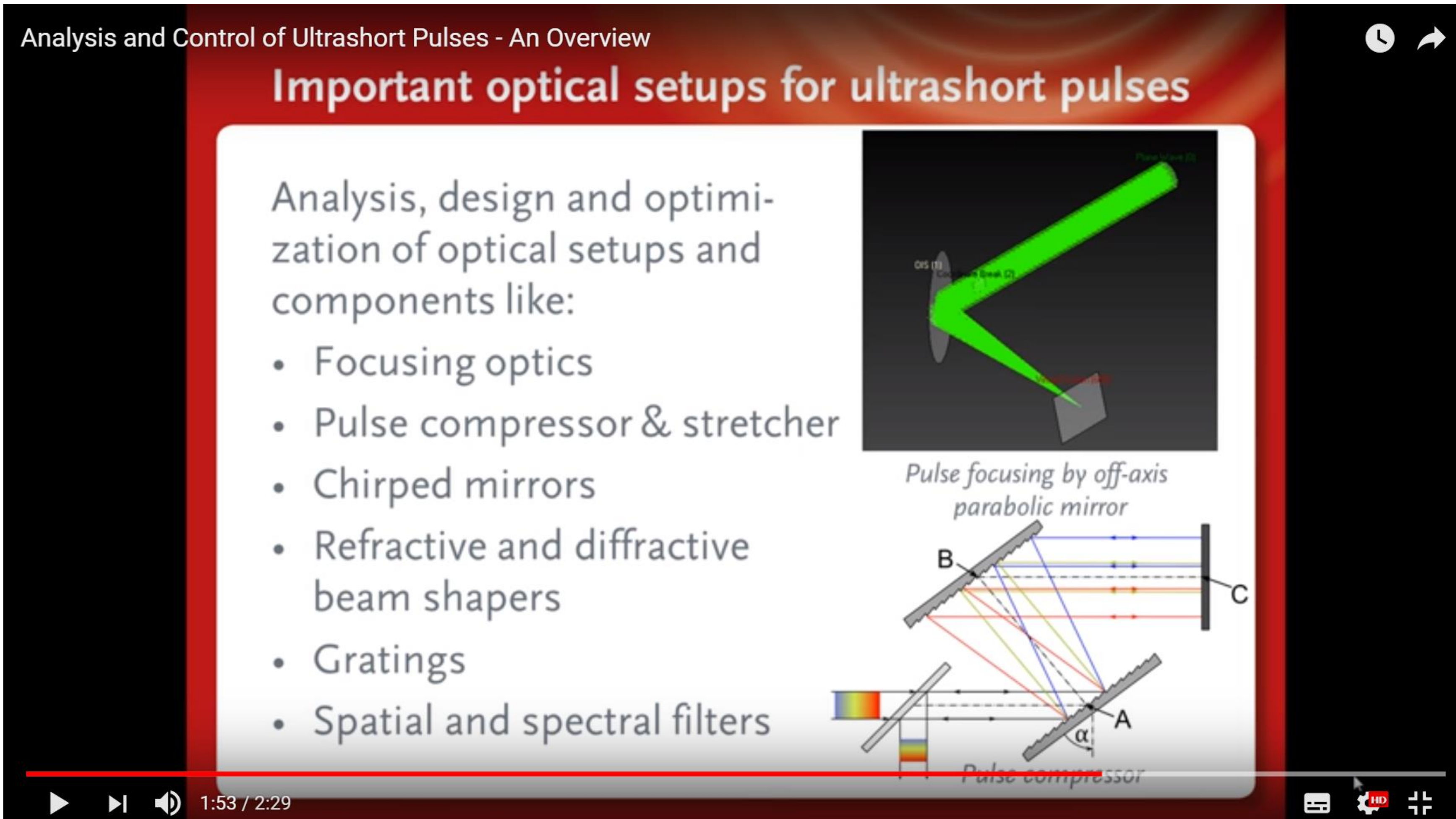
Pulse compression (SPM+GVD)

- https://www.youtube.com/watch?v=l62aDMONhf0



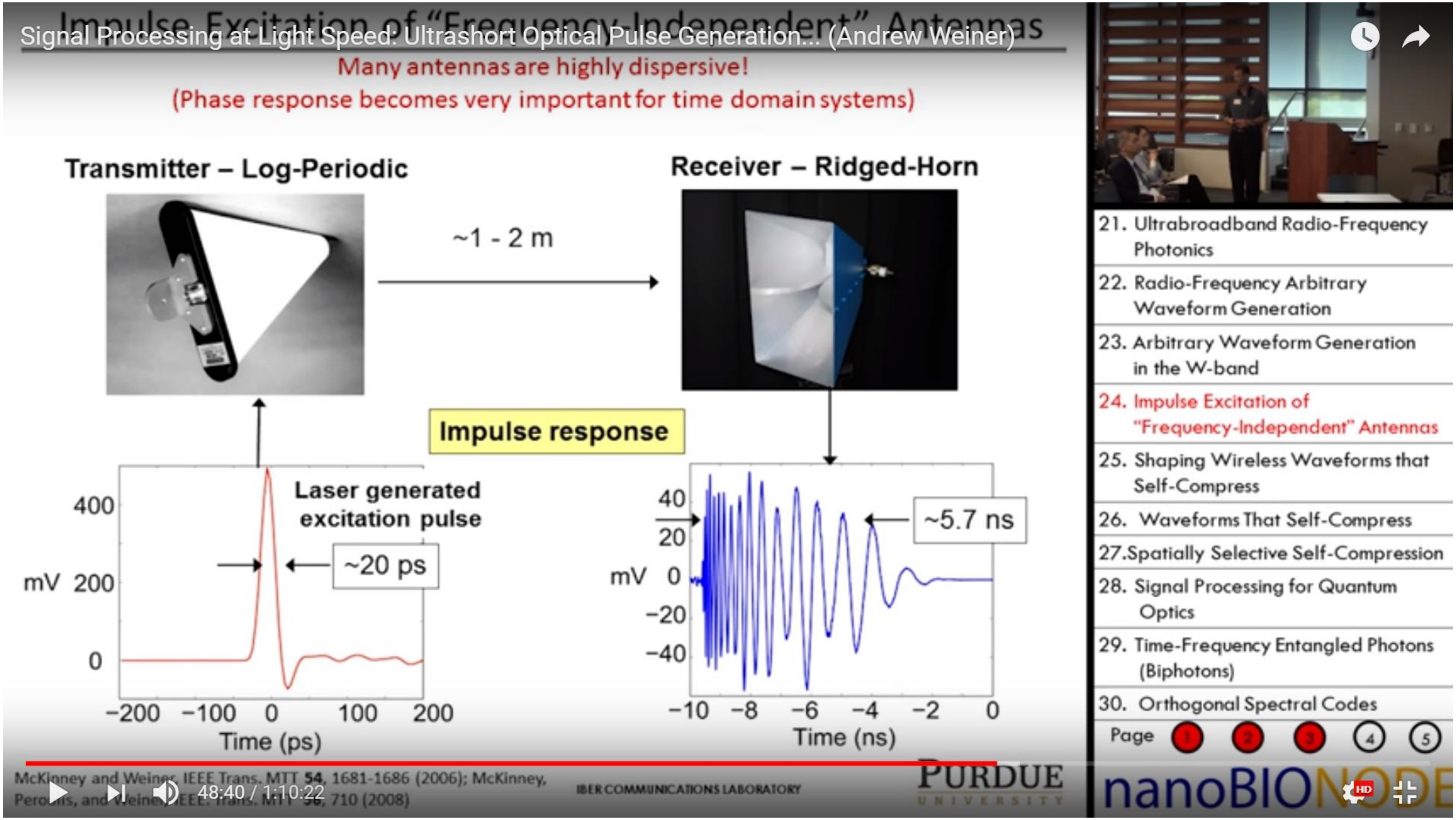
Pulse compression by GVD

- https://www.youtube.com/watch?v=BeXWyfAk5O4

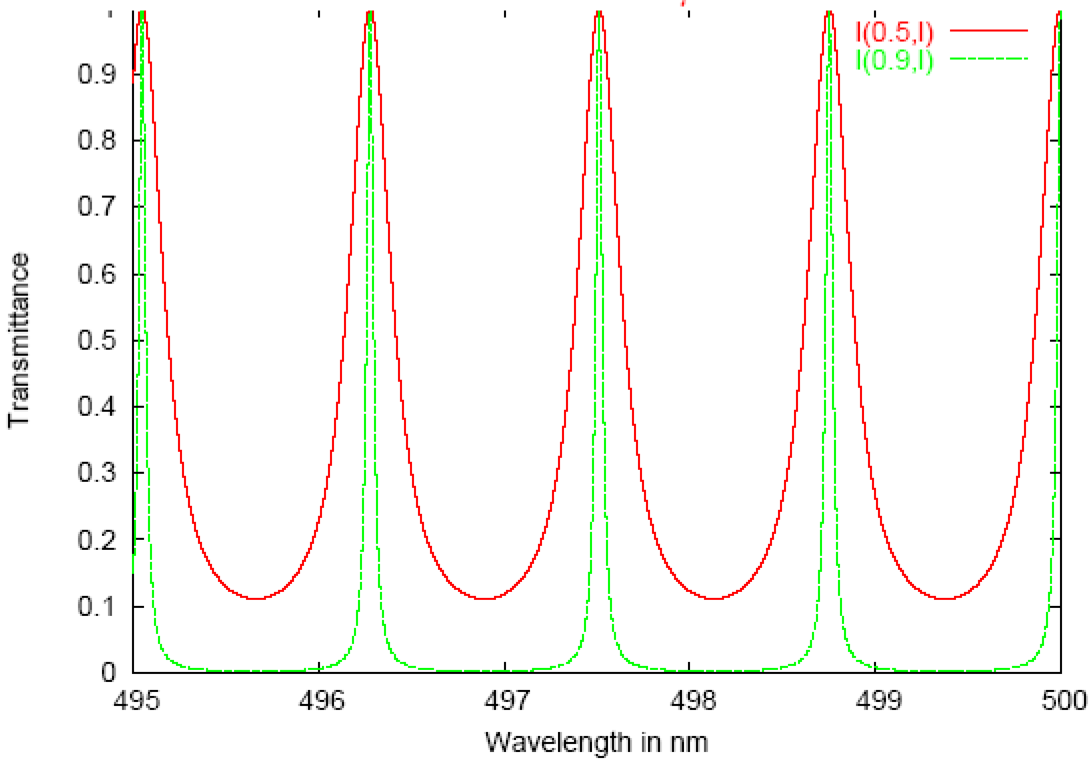


Signal Processing at Light Speed

- https://www.youtube.com/watch?v=yh3hXI4ywq0



The full output in plotted with $d = 100\,\mu\text{m}$, for two mirrors with $R = 0.5$ and $R = 0.9$.



Series of transmission peaks as the reflectance increase.

The Fabry-Perot is thus operating as a very narrow band pass-filter.

A generic ultrashort-pulse laser

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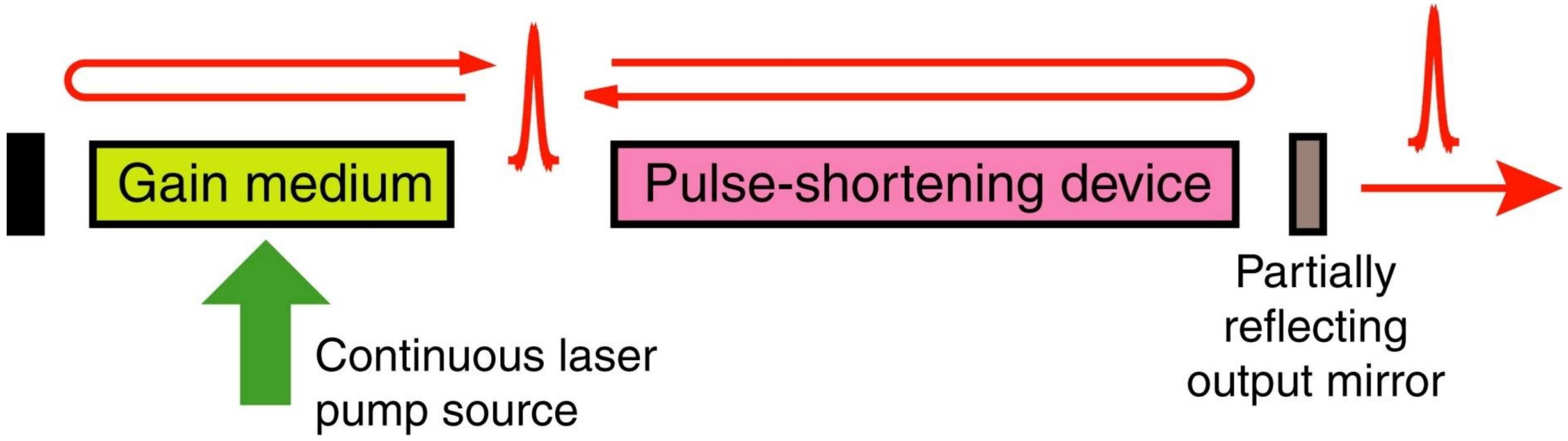

Many pulse-shortening devices have been proposed and used.

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