Lecture 9
Transient Laser Behavior*

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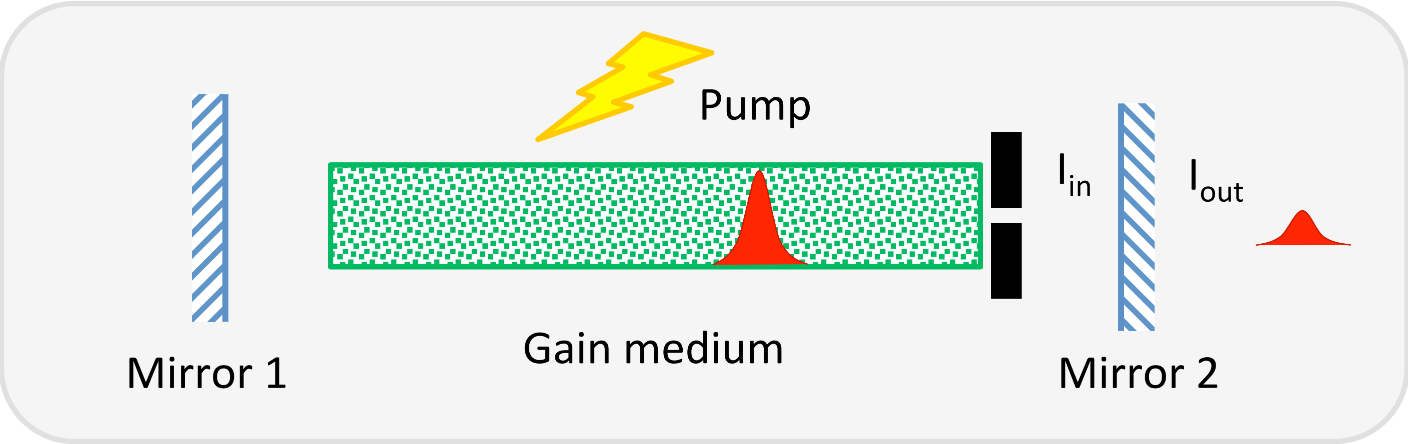
* Some figures and texts belong to: O. Svelto, *Principles of Lasers*, 5th Ed., Springer.

Reading

- *Principles of Lasers* (5th Ed.): Chapter 8.
- Skip: 8.4.4, 8.6.4.
- Squeeze: 8.2.1.

Laser



- R_p and γ are a function of time
  - An inherent property of lasers (as a nonlinear system)
  - Purposely introduced (via pump and loss modulation)

Contents

Content	Time
1. Relaxation oscillation	5’
2. Q-switching	30’
3. Gain-switching	5’
4. Mode-locking	35’
5. Cavity-dumping	5’
Total:	**80’**

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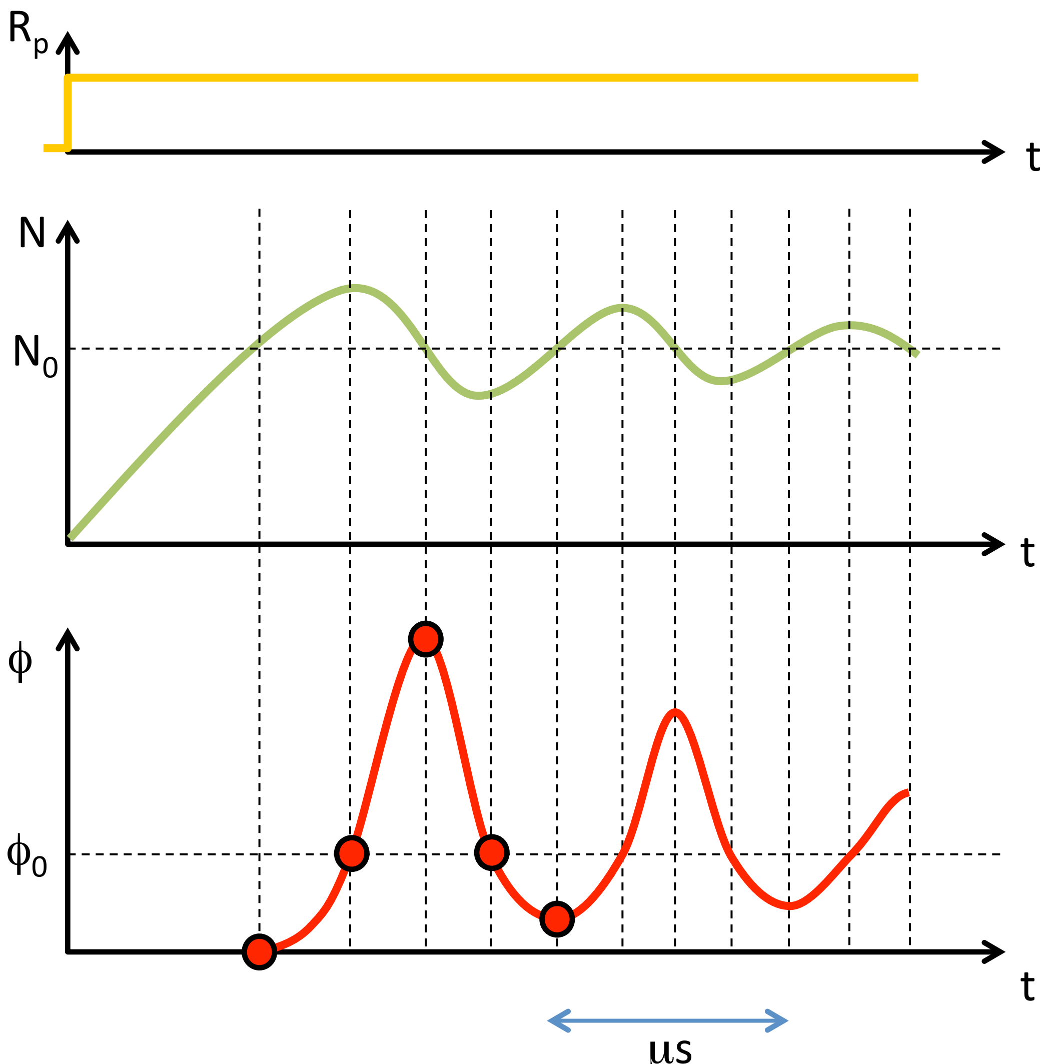
Relaxation oscillation

- 4-level case
- Single-mode



- Laser spikes
- Periodic after ~10 oscillations
- N leading by T/4
- $N \propto \exp(-t/t_0)\cos(\omega t+\beta)$
- $\phi \propto \exp(-t/t_0)\sin(\omega t+\beta)$

If $\frac{1}{t_0} < \omega$

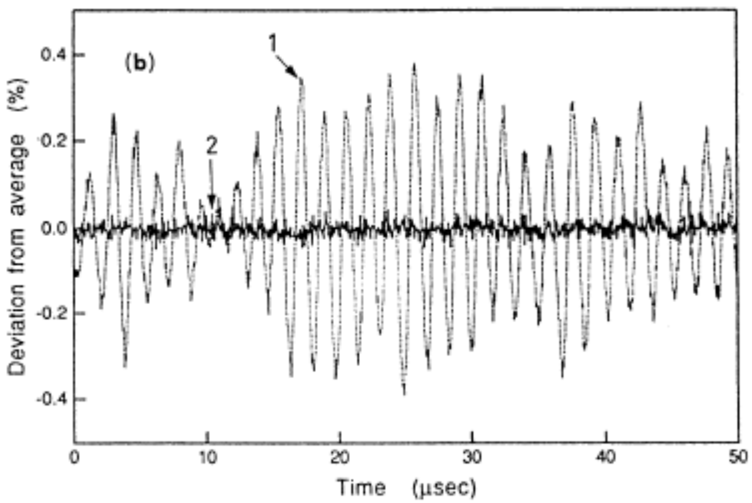
$$t_0 = \frac{2\tau}{x}$$

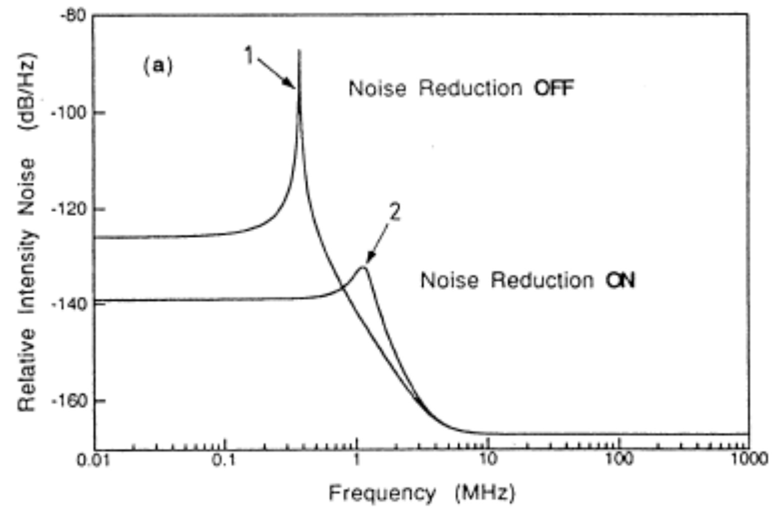
$$\omega \approx \sqrt{\frac{x-1}{\tau_c \tau}}$$

where $x = \frac{R_p}{R_{cp}}$

Pulsation

Nd:YAG





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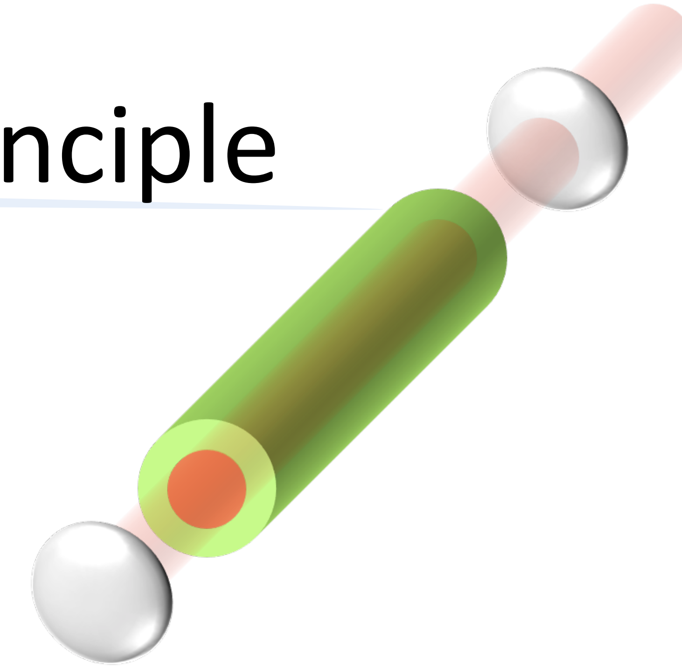
Q-switching: Principle



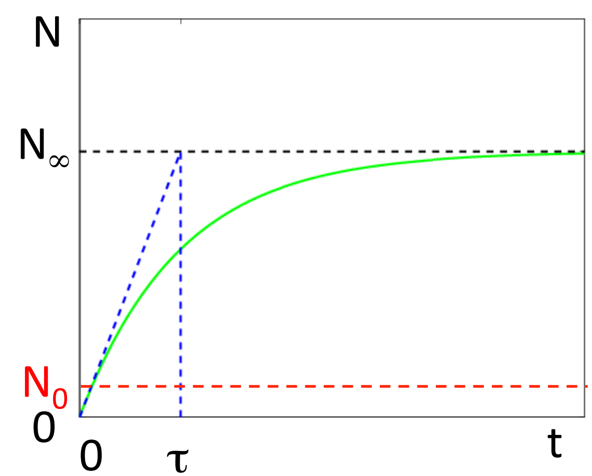
- **CW laser**: $N_0=N_c$
- **Q-switched laser** (4L)

$$\frac{dN}{dt} = R_p - B\phi N - \frac{N}{\tau}$$

Let $\phi=0$, $$\frac{dN}{dt} = R_p - \frac{N}{\tau}$$

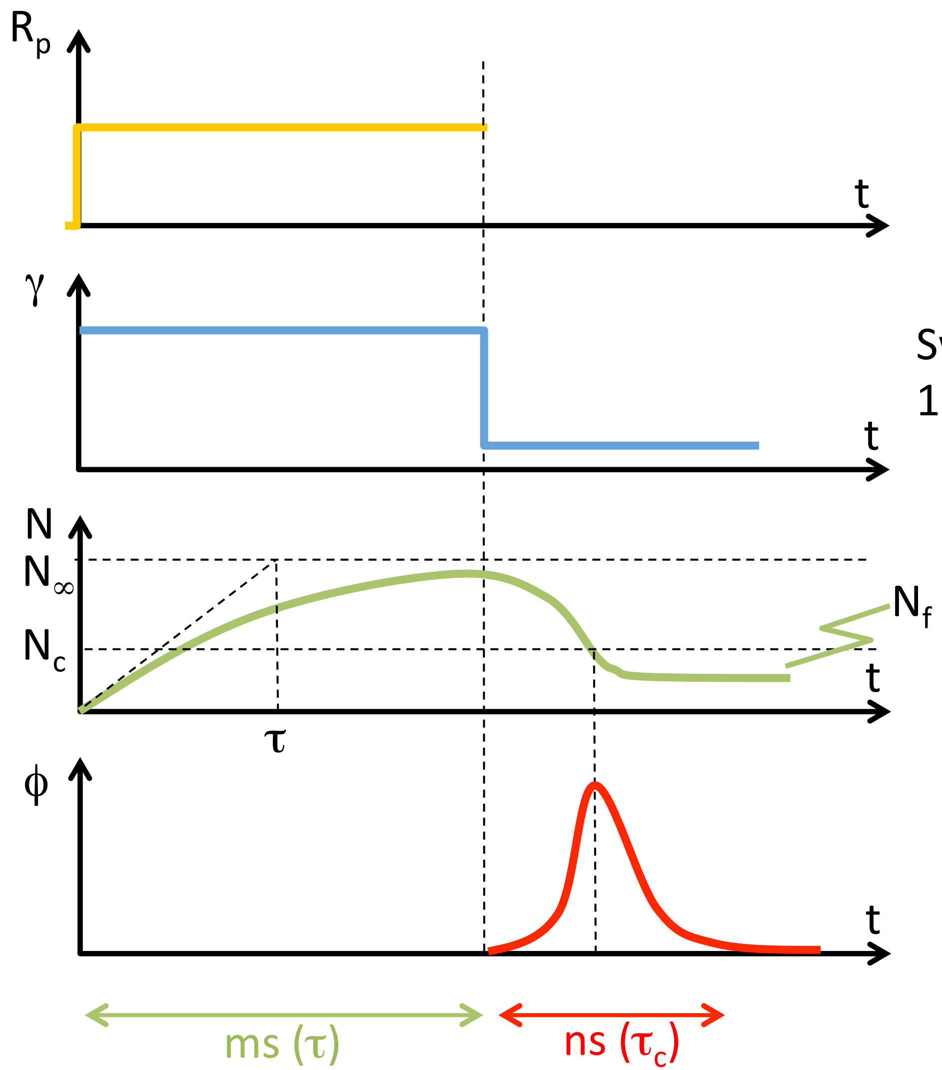
One has $$N(t) = N_\infty \left[1 - \exp\left(-\frac{t}{\tau}\right)\right]$$

with $$N_\infty = R_p \tau$$



- Longer τ (ms) preferred (larger N_∞)
- Pump duration < τ
- Lasers applicable: most solid-state lasers (Nd, Yb, Eb, Ho based) and some gas lasers (CO_2, iodine)

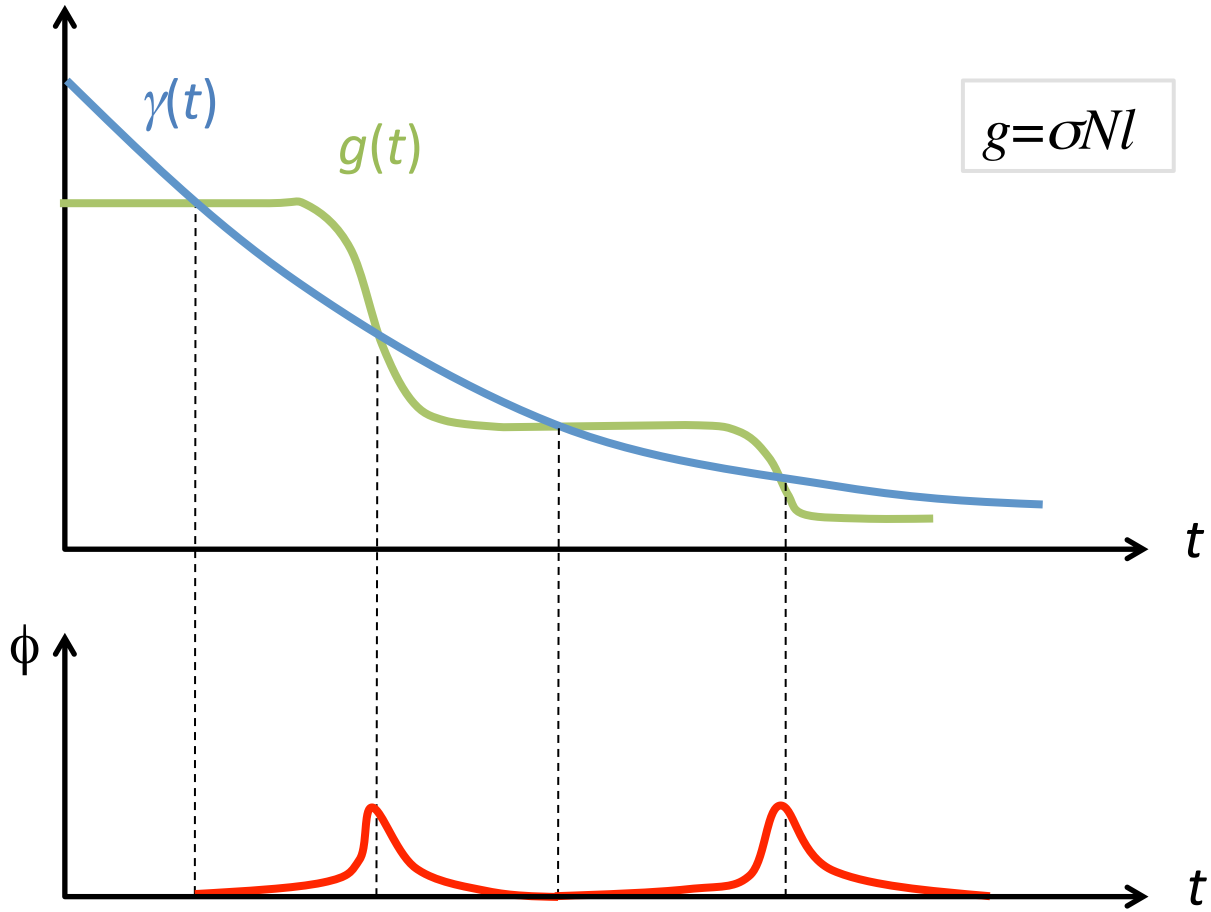
Q-switching: Fast



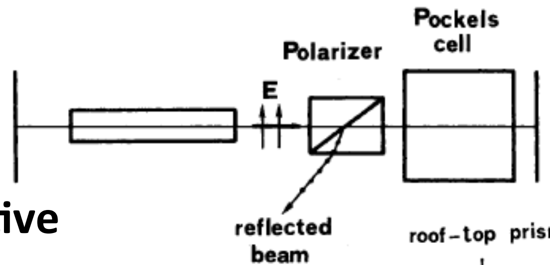
Switching time:
10 ps ~ 100 ns

Pulse spatial width:
Δz_p=2ns·c=0.6m

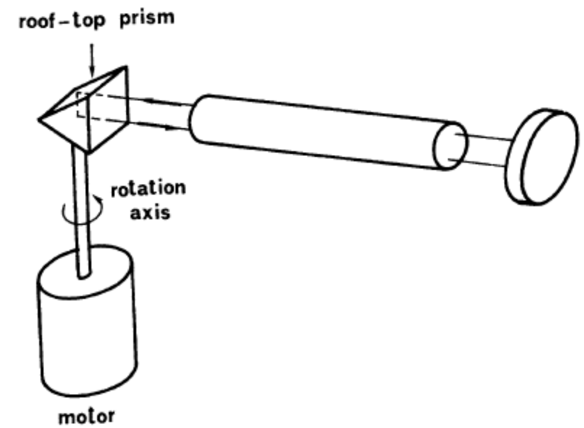
Q-switching: Slow



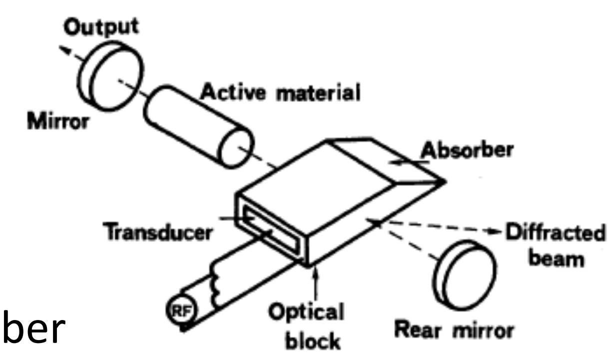
Q-switching: Methods



- **Electro-optical**
  - Most common **active**
  - Fast (t_s<20ns)
  - High voltage (up to 5kV)

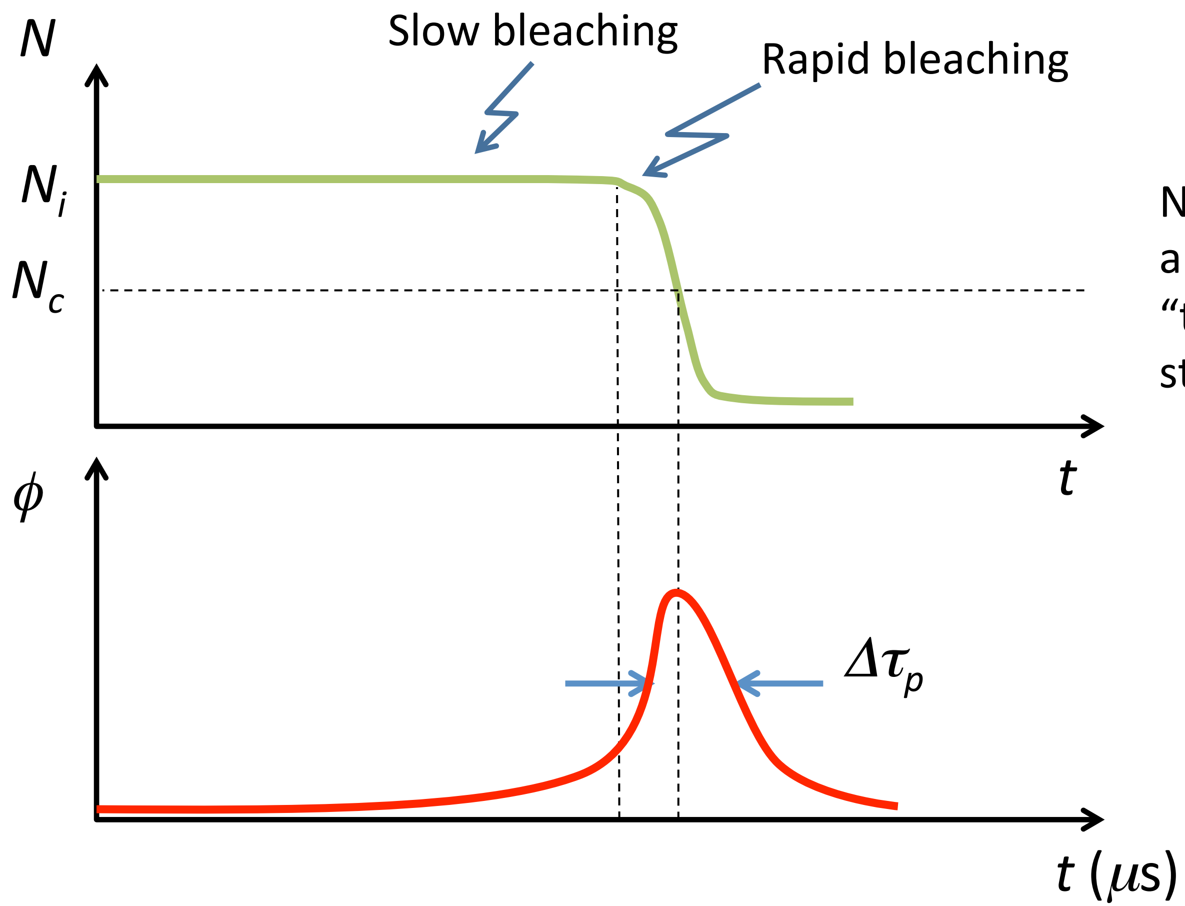


- **Rotating mirror**
  - Simple, inexpensive, any wavelength
  - Noisy, slow (t_s=400ns for 400rps)
- **Acousto-optic**
  - Low insertion loss, high repetition (kHz)
  - Slow (due to acoustic wave propagation)



- **Saturable-absorber**
  - Most common **passive**
  - Favor **single-mode**
  - Photochemical degradation of (dye) absorber
  - (Hence) low average power lasers

Saturable-absorber Q-Switching

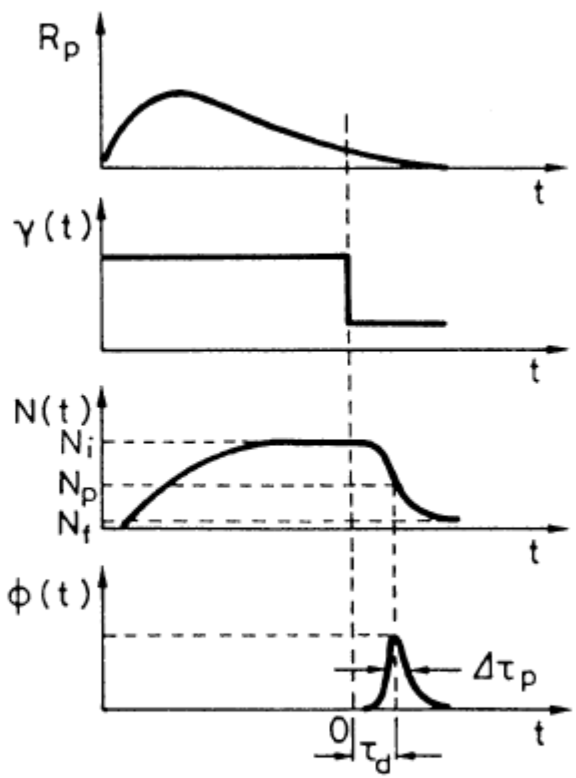


N_c is for the absorber at its "transparent" state

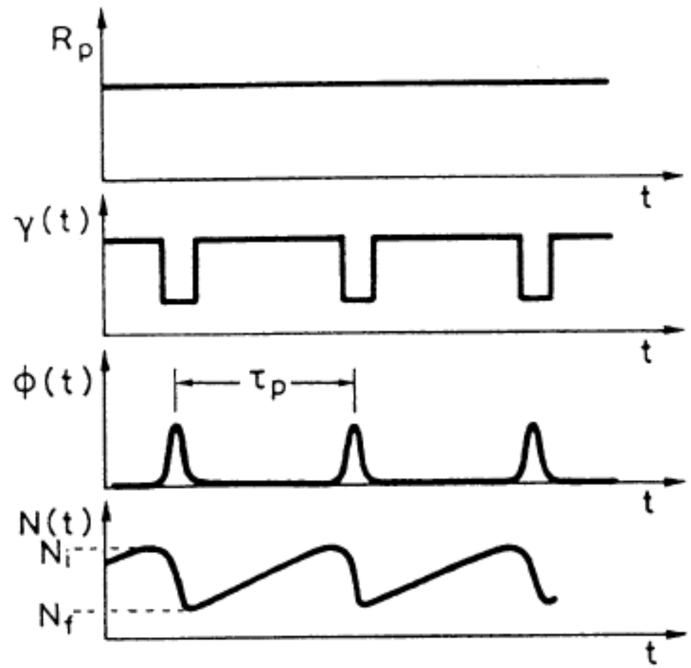
Slow bleaching (μs): promotes the mode with lowest loss/highest gain

Operation schemes

- **Pulsed** (R_p) (<100Hz)
- Electro-optical or mechanical shutters



- **Continuously pumped** Repetitively Q-switched (kHz~<100kHz, low gain)
- Acousto-optic, mechanical, saturable absorber shutters



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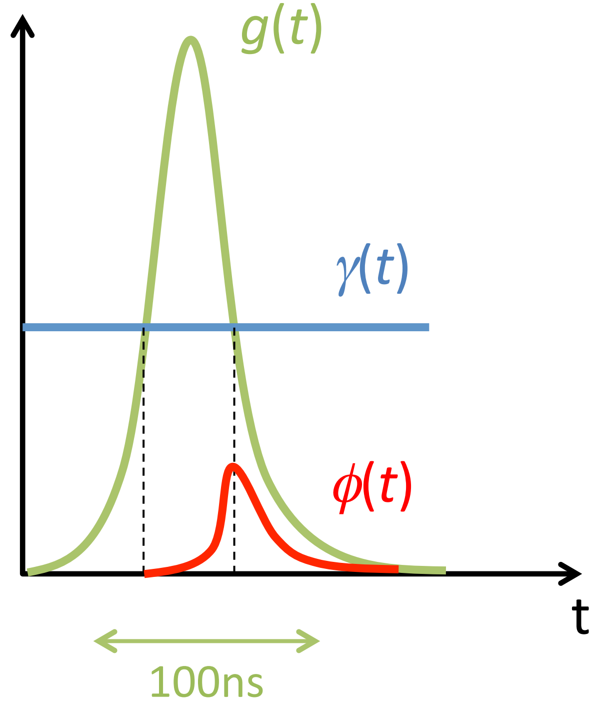
Total:	**80’**

Gain switching

- **Q switching:** Loss ↓ rapidly
- **Gain switching**: gain ↑ rapidly
  - Pump duration 5-20 τ_c (<1μs)
  - Rp peak: 4-10 times R_{cp}
  - Laser spiking



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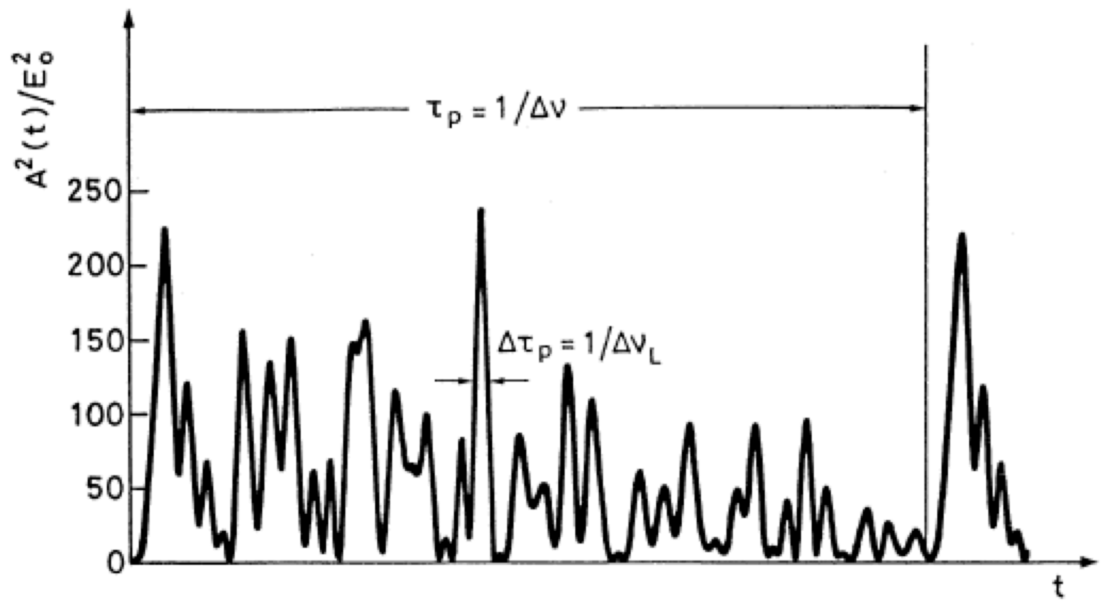
Before mode-locking

- **CW laser with multiple longitudinal modes**:

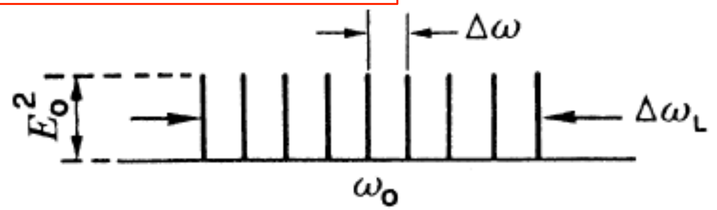
phases among modes are random → approx. constant output



$$E(t) = \sum_{l=0}^{30} E_0 \exp\{j\,[(\omega_0 + l\Delta\omega)t + \varphi_l]\}$$

Mode-locking: Principle

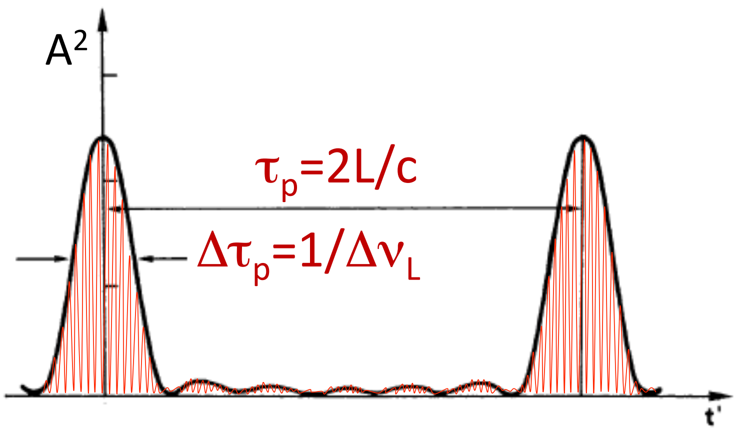
- **Mode-locked**: Phases are correlated → pulsed output



Equal-amplitude case:

Let $\varphi_l - \varphi_{l-1} = \varphi$

$$E(t) = \sum_{l=-n}^{n} E_0 \exp\{j\left[(\omega_0 + l\Delta\omega)t + l\varphi\right]\}$$
$$= \sum_{l=-n}^{n} E_0 \exp\left[jl(\Delta\omega t + \varphi)\right] \exp(j\omega_0 t)$$
$$= A(t)\exp(j\omega_0 t)$$



Let $t' = t + \varphi/\Delta\omega$

$$A(t') = \sum_{l=-n}^{n} E_0 \exp\left(jl\Delta\omega t'\right)$$
$$= E_0 \frac{\sin\left[\frac{(2n+1)\Delta\omega t'}{2}\right]}{\sin\left(\frac{\Delta\omega t'}{2}\right)}$$

- **Max** $\frac{\Delta\omega t'}{2} = m\pi \rightarrow t' = m\frac{2\pi}{\Delta\omega} = m\frac{1}{\Delta\nu} = m\frac{2L}{c}$

  $E_{\max}^2 = (2n+1)^2 E_0^2$

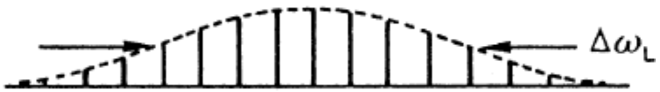
- **Min** $t' = \frac{2\pi}{(2n+1)\Delta\omega} = \frac{1}{\Delta\nu_L}$

(m=0, pulse width)

Mode-locking: Pulse width

Gaussian gain profile

$$\Delta\tau_p = \frac{0.441}{\Delta\nu_L}$$

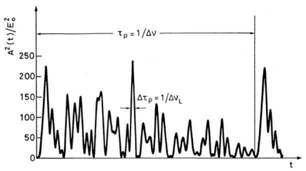


In general a **transform-limited pulse** has: $\Delta\tau_p = \frac{\beta}{\Delta\nu_L}$ with $\beta \approx 1$

- **Inhomogeneously** broadened gain medium (>> threshold): $\Delta\tau_p \approx \frac{0.441}{\Delta\nu_0}$
- **Homogeneously** broadened gain medium: $\Delta\tau_p \approx \frac{0.45}{\sqrt{\Delta\nu\Delta\nu_0}}$

Example:
If $\Delta\nu_0$=200GHz $\rightarrow$ $\Delta\tau_p \approx$2ps $\rightarrow$ $\Delta z_p = \Delta\tau_p \cdot c \approx$0.6mm
If $\Delta\nu_0$=2THz $\rightarrow$ $\Delta\tau_p \approx$200fs $\rightarrow$ $\Delta z_p = \Delta\tau_p \cdot c \approx$0.06mm

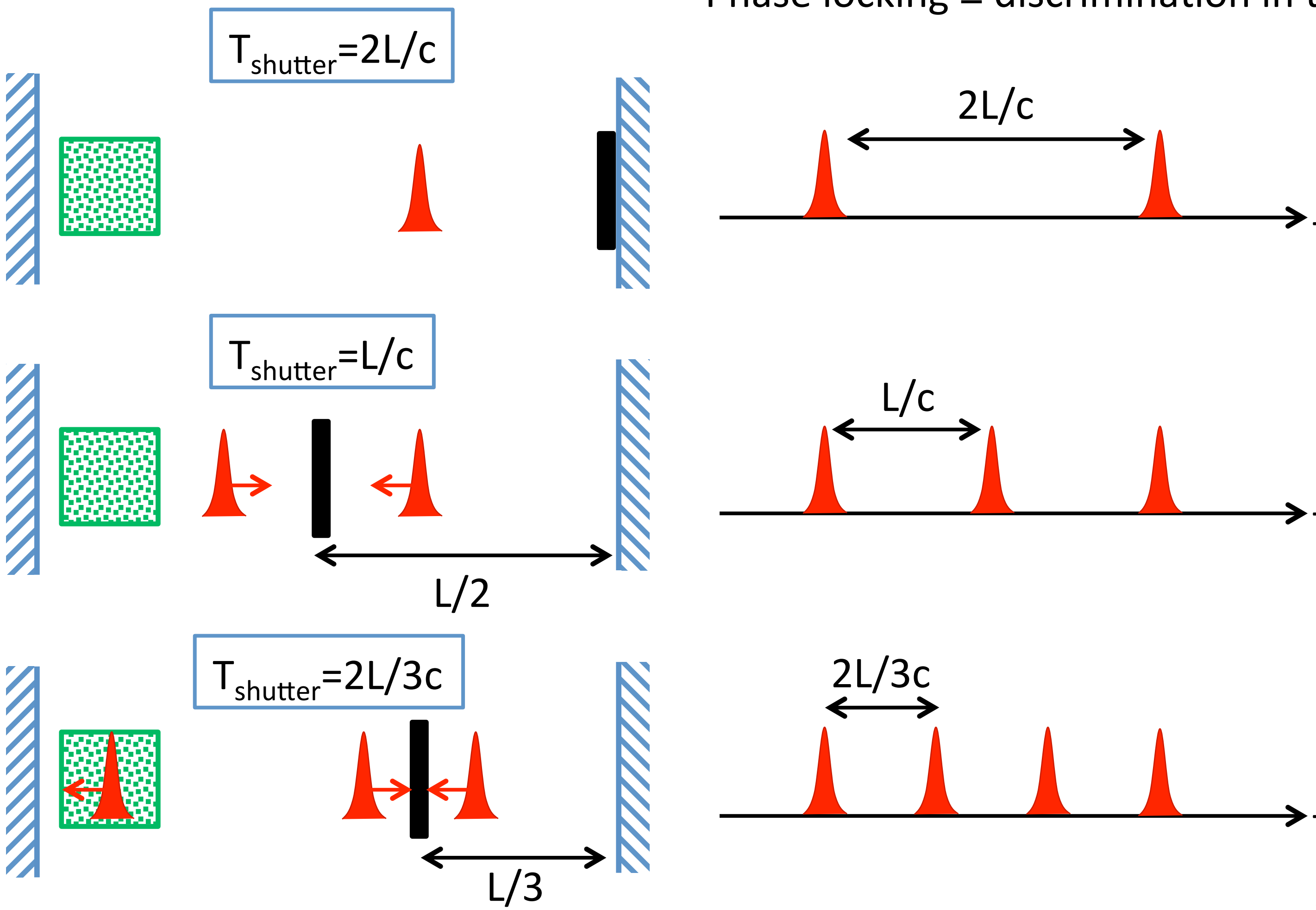
Mode-locking: Implementation



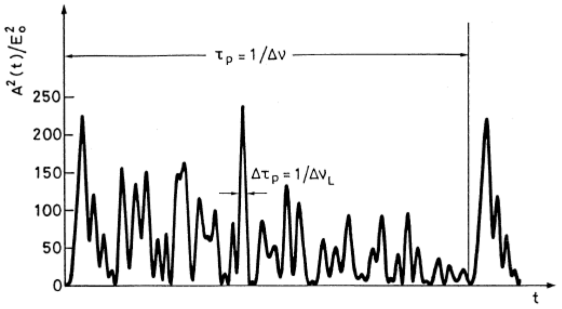
Phase locking ≡ discrimination in time

Fundamental

Harmonic



Mode-locking: Methods



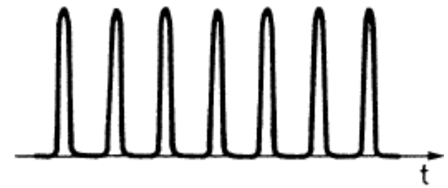
- **Active**
  - Amplitude-modulation (AM)
    - Principle: change γ ($\omega_m = 2\pi\Delta\nu$)
    - Approach: Pockels cell, or acousto-optic modulator
  - Phase-modulation (FM) [less used]
    - Principle: change L_e (oscillating mirror)
    - Approach: Pockels cell
  - Synchronous-pumping [less used]

- **Passive**
  - Fast* saturable absorber [10s of ps, strongest survives]
  - Kerr lens [$n=n_0+n_2I$, self-focusing, instantaneous response]

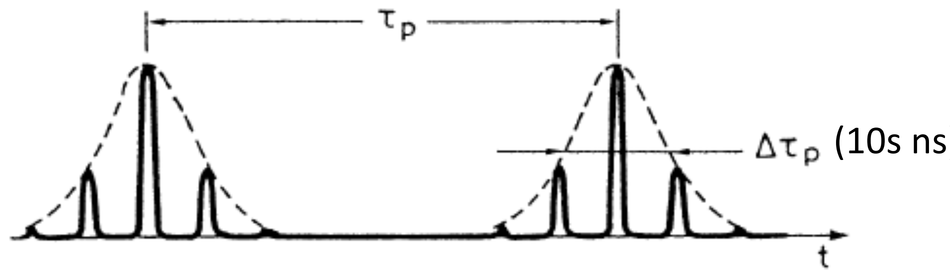
* **Absorber** is FAST if its relaxation time is comparable to a ML pulse duration.
* **Gain medium** is FAST if its lifetime is comparable to cavity round-trip time.

Mode-locking: Pumping schemes

- **Continuous pump**
  - Active/passive ML
  - Passive ML: Q-switching can emerge (slow gain medium)

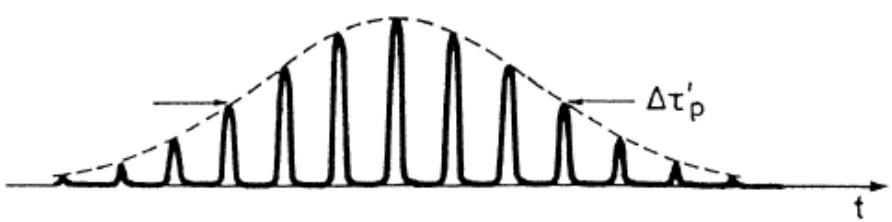


Fast shutter + fast gain medium



Fast saturable absorber + slow gain medium (100s μs)
(Repetitive Q-switching + ML)

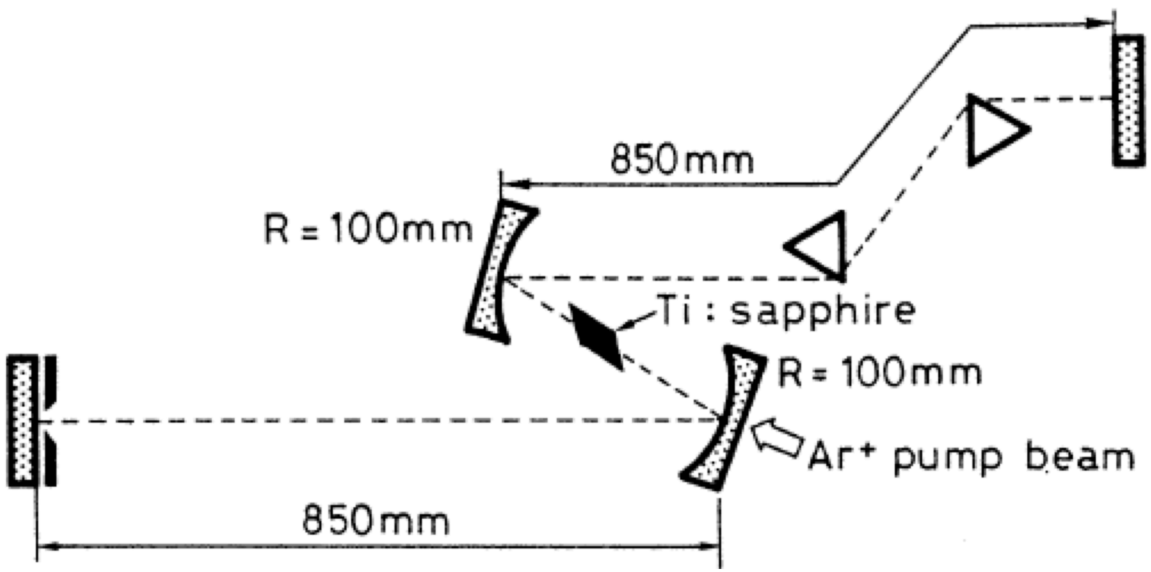
- **Pulsed pump**
  - Active/passive ML
  - Passive ML: $\Delta\tau_p$' can be pump time or due to Q-switching



* **Absorber** is FAST if its relaxation time is comparable to a ML pulse duration.
* **Gain medium** is FAST if its lifetime is comparable to cavity round-trip time.

Ti:Sapphire Laser

Laser medium	$\Delta\nu_0$	$\sigma[10^{-20}\,\mathrm{cm}^2]$	$\tau[\mu s]$	$\Delta\tau_p$	$\Delta\tau_{mp}$
Ti:sapphire	100 THz	38	3.9	6–8 fs	4.4 fs



Ti:Sapphire plate: 10mm thick

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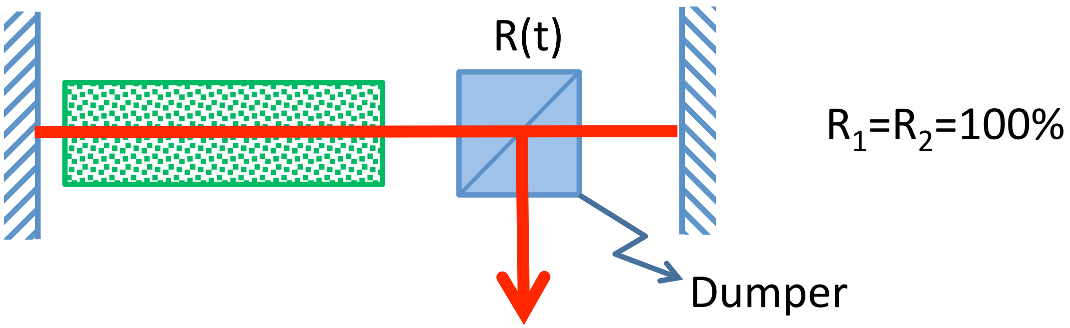
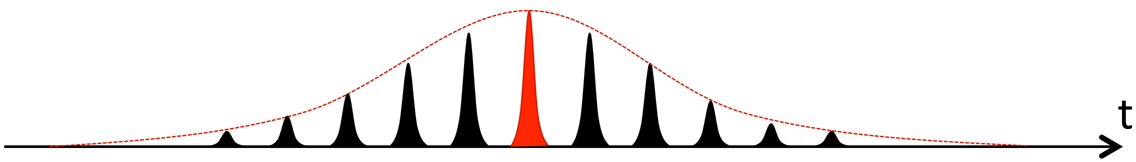
Cavity dumping

Applicable to CW, **mode-locked**, and Q-switched lasers.



- **Pulsed-pump ML**: dump pulse with highest intensity [Pockels cell]



- **CW-pump ML**: dump a train of laser pulses of lower repetition rate (100k~1MHz) & higher peak power [Acousto-optic grating]