Q-switching:

prevent laser from oscillating until large inversion builds up, then let energy go all at once.

Example: a four-level system:

CW operation: $\gamma_0 = \frac{\lambda^2}{8\pi t_{sp}} g(\nu) R \tau_2$

$= \frac{\lambda^2}{8\pi} g(\nu) R \quad (\tau_2 \approx t_{sp})$

$I_s = \frac{8\pi}{\lambda^2} \frac{h\nu}{g(\nu)}$

$I_{out} = I_s T \left(\frac{\gamma_0 l}{T+L} - 1 \right)$ if L is small and $\frac{\gamma_0 l}{T} \gg 1$

$I_{out} = I_s \gamma_0 l = h\nu R l$

l = length of medium
length of cavity

Q-switched:

Have $n_p(max) = \frac{\Delta N_i}{2}$

ΔN_i = inversion w/o lasing
$= \Delta N_0$
$= R\tau_2$.

To get I_{out}:

$n_p = \frac{\text{photon}}{\text{volume}}$

energy in cavity: $h\nu n_p \cdot \bar{V}$ $\bar{V}$: mode volume

$$P_{out} = h\nu \bar{V} \frac{\partial n_p}{\partial t}\Big|_{transmission} = h\nu \bar{V} \frac{n_p}{\tau_p}$$

$$I_{out} = h\nu \frac{\bar{V}}{A} \frac{n_p}{\tau_p} = h\nu \ell \frac{n_p}{\tau_p} = \frac{1}{2} h\nu \ell R \frac{\tau_2}{\tau_p}$$

So $$\frac{I_{out}\ (peak)}{I_{out}\ (cw)} = \frac{1}{2} \frac{\tau_2}{\tau_p}$$

If $\tau_p = 1ns$, $\tau_2 = 3ms$ (Ruby)

$$\frac{I_{peak}}{I_{cw}} = 1.5 \times 10^6$$

* can actually do better: can pump harder with pulsed pump, get larger R.

But: takes $\sim \tau_2$ to build up inversion

So average intensity out:

$$\bar{I} = I_{peak} \times \frac{\tau_p}{\tau_2} = \frac{1}{2} h\nu \ell R$$
$$= \frac{1}{2} I_{cw}$$

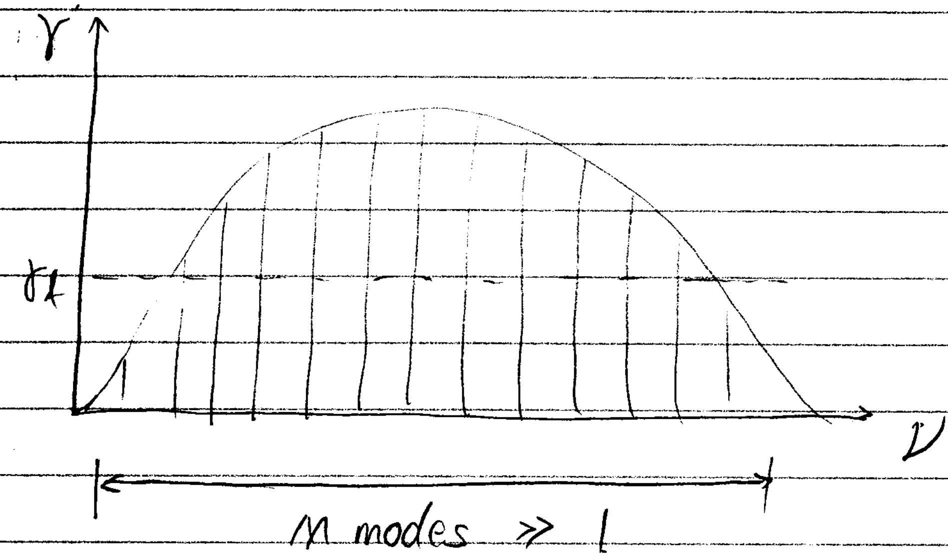
So Q-switching doesn't really change average power output, just concentrates energy into short pulse.

Other technique is fancier: Mode-locking.

Suppose medium with inhomogeneous broadening with $\Delta\nu_H \ll \nu_F \ll \Delta\nu_{IH}$.

$\nu_F = \frac{c}{2\ell}$

Then laser has multimode output



What is output field.

$$E_{out} = \sum_{m=0}^{M-1} E_m e^{i(\omega_m t + \phi_m)}$$

E_m: amplitude of mode m
ϕ_m: phase of mode m
ω_m: $\omega_0 + 2\pi m \nu_F$

Expect ϕ_m's to be randomly distributed.

So $\langle E_{out} \rangle = 0$

$$\langle |E|^2 \rangle = \sum_m |E_m|^2 = M |E_1|^2$$

$I_{out} = M I_1$ intensities add

But suppose ϕ's weren't random

say $\phi_m = 0$ for all m

For simplicity say all $A_m = A$

Then $E(t) = A e^{i\omega_0 t} \sum_{m=0}^{M-1} e^{i 2\pi m \nu_F t}$

Geometric series: $\sum_{m=0}^{M-1} x^m = \frac{1 - x^M}{1 - x}$

$$x = e^{i 2\pi \nu_F t}$$

so $E(t) = A e^{i\omega_0 t} \frac{1 - e^{i 2\pi M \nu_F t}}{1 - e^{i 2\pi \nu_F t}}$

$$= A e^{i\omega_0 t} \frac{e^{i\pi M \nu_F t}}{e^{i\pi \nu_F t}} \cdot \frac{e^{i\pi M \nu_F t} - e^{-i\pi M \nu_F t}}{e^{i\pi \nu_F t} - e^{-i\pi \nu_F t}}$$

$$= A e^{i\omega_0 t} e^{i\pi (M-1) \nu_F t} \frac{\sin M\pi \nu_F t}{\sin \pi \nu_F t}$$

And the intensity $I \propto |E|^2$.

$$I(t) = I_0 \frac{\sin^2 M\pi \nu_F t}{\sin \pi \nu_F t}$$

Familiar from optics: intensity patten produced by M-slit diffration grating.

Peak $I(t) = M^2 I_0$ when $t = \frac{n}{\nu_F}$ integer n.

($\sin^2$ in denominator $= 0$)

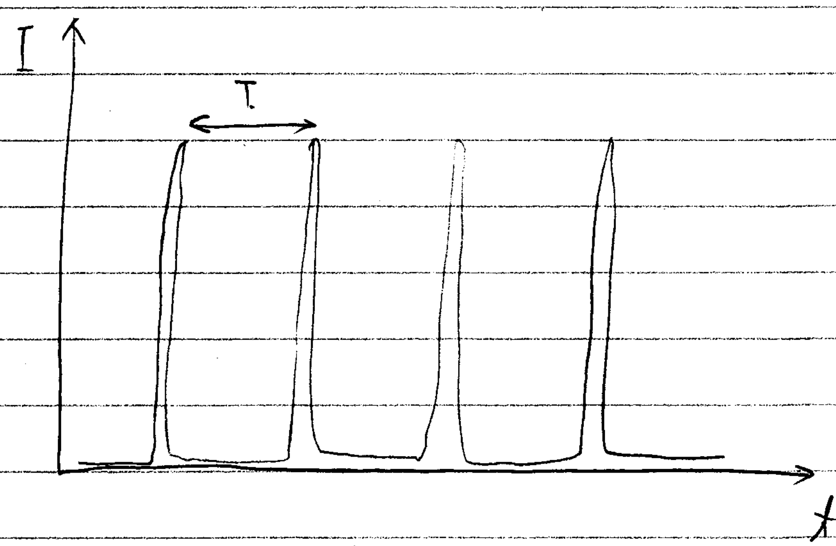
Pulse train, period $T = \frac{1}{\nu_F} = \frac{2\ell}{c}$

width of pulse:

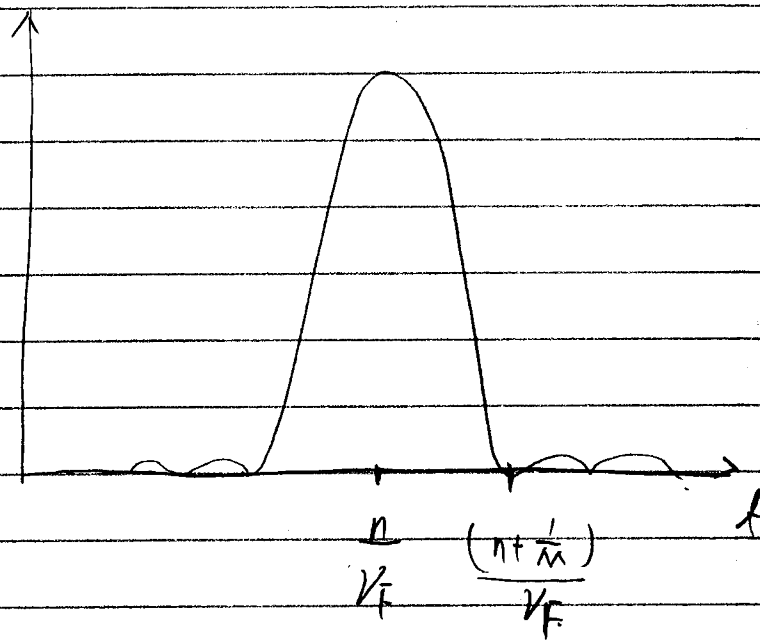
$$\Delta t = \frac{1}{M\nu_F} \quad \text{(when nominator} = 0)$$

$$= \frac{T}{M}$$

Picture:



One pulse:



So $\Delta t = \frac{1}{M\nu_F} = \frac{1}{\Delta\nu_{IH}}$ limitied by gain bandwidth

Pulses can be very short

Ti: Sapphire: gain from 700nm to 1000nm

$\Delta\nu_{IH} \gtrsim 10^{14}\ Hz$

So $\Delta t = \frac{1}{\Delta\nu_{IH}} = 10^{-14}s = 10fs$

Estimate peak power:

cw operation. $P_{cw} = M P_1$ P_1 = Power in one mode.

Peak of pulse: $P_{peak} = M^2 P_1 = M P_{cw}$

averge power $P_{ave} = P_{peak} \cdot \frac{\Delta t}{T}$

$= M P_{cw} \cdot \frac{1}{M}$

$= P_{cw}$

Again, energy is just concentrated into pulse

For Ti: Sapphire, $M = \frac{\Delta \nu}{\nu_F}$ say $\nu_F = 100\,MHz$

$= 10^8\,Hz$

$M = 10^6$