Ultrafast Laser Physics

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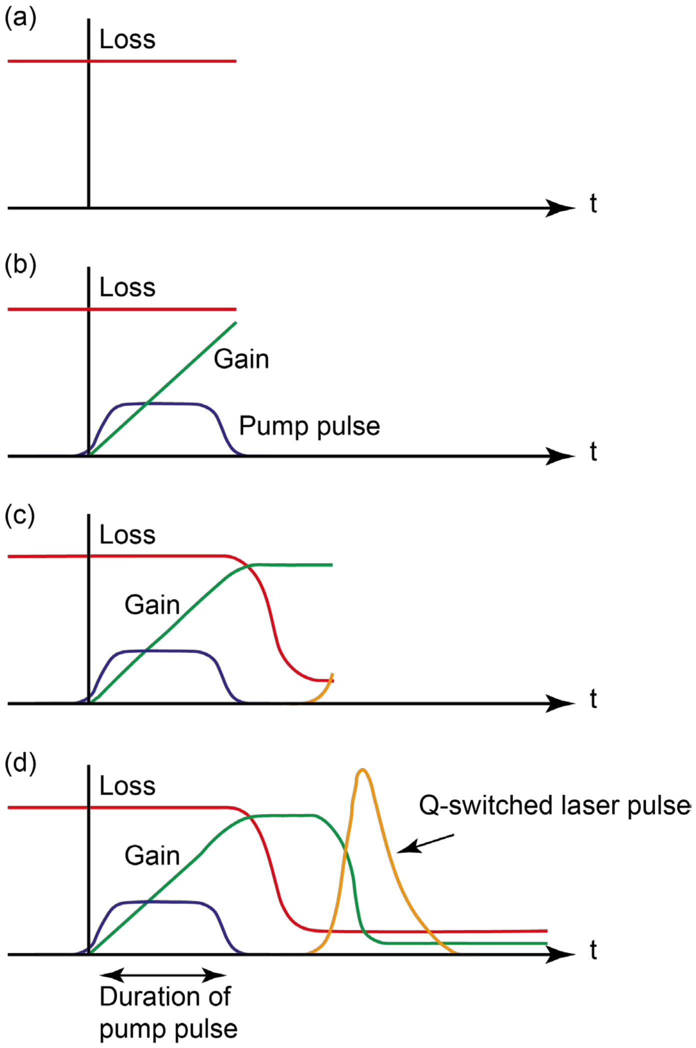
Chapter 6: Q-switching

Active Q-switching



At the beginning high loss:
beam feedback is blocked

Pump power generates a
high inversion N(t)

Loss and pump power switched off
Laser starts to oscillate with a very
high small-signal gain

Laser emission switched off
by emptying the inversion

Q-switching parameter range

Parameter	Range	Typical
Pulse duration	<ns to many ns	ns to tens of ns
Pulse energy	µJ to many J	mJ
Pulse repetition rate	Hz to MHz	kHz
Peak power	kW to GW	hundreds of kW

- Note that many of the practical laser system examples discussed in this chapter are not typical, but rather optimized for the generation of the shortest possible pulses

Watch out: Different notation!

There is however one main difference in this chapter compared to many other chapters. All loss and gain coefficients are given for the intensity and not the amplitude and are therefore a factor of 2 larger!

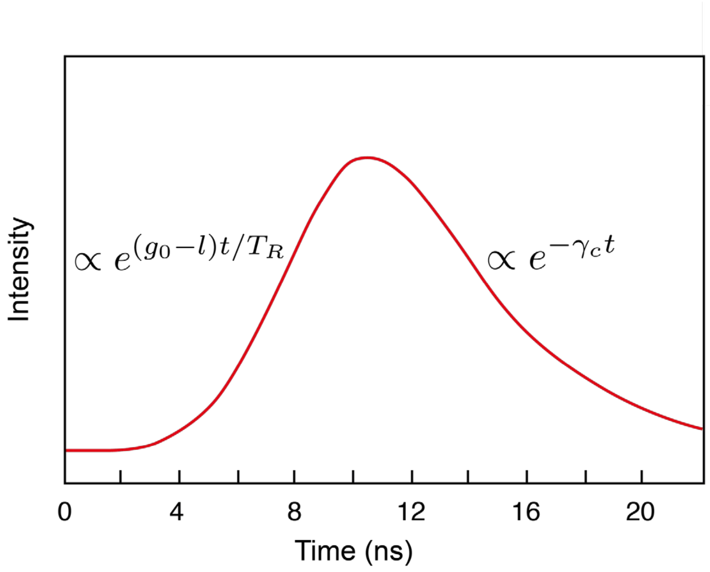
l	total nonsaturable **intensity** loss coefficient per resonator round-trip (i.e. without the saturable absorber, but includes output coupler loss and any additional parasitic loss – also the nonsaturable losses of the saturable absorber
q	saturable **intensity** loss coefficient of the saturable absorber per cavity round-trip
q_0	unbleached **intensity** loss coefficient of the saturable absorber per cavity round-trip (i.e. maximum q at low intensity)
g	saturated **intensity** gain coefficient per resonator round-trip (please note here we use intensity gain and not amplitude gain)
g_0	**intensity** small signal gain coefficient per resonator round-trip (often also simply called small signal gain). For a homogenous gain material applies in steady-state (factor 2 for a linear standing-wave resonator):

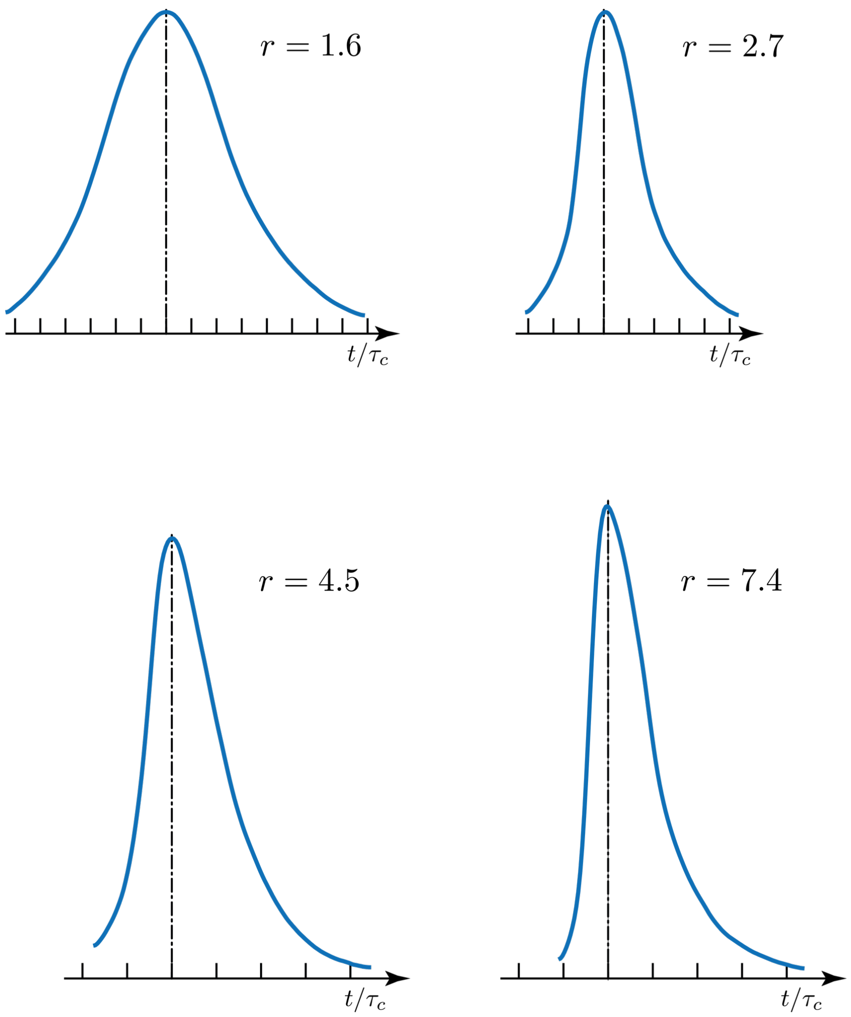
$$g = \frac{g_0}{1 + 2I/I_{sat}}$$

Pulse shape and pulse duration

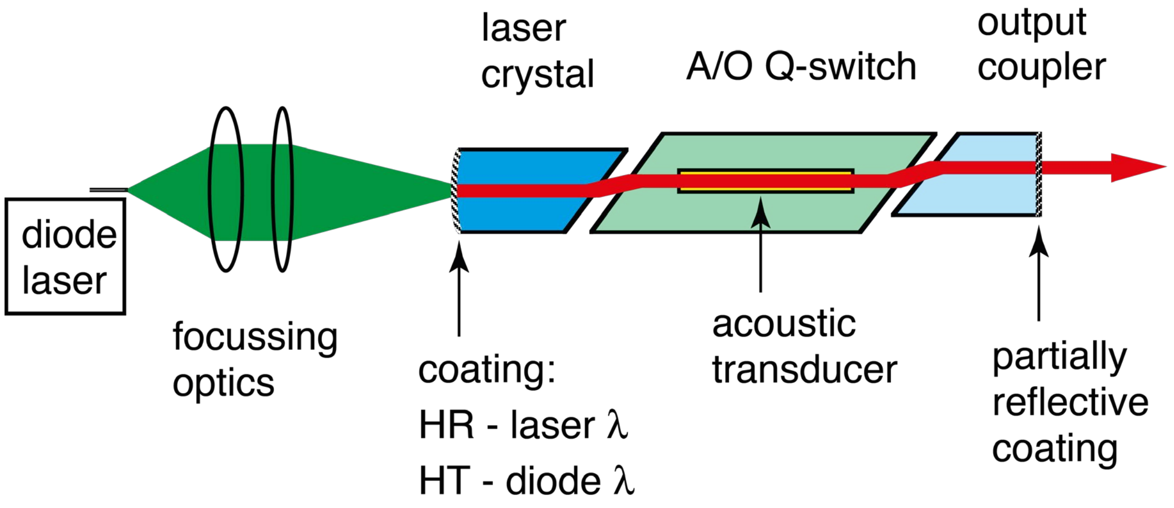
$g_0 = rl$

$\gamma_c = l/T_R$





AOM Q-switched diode-pumped ss-laser

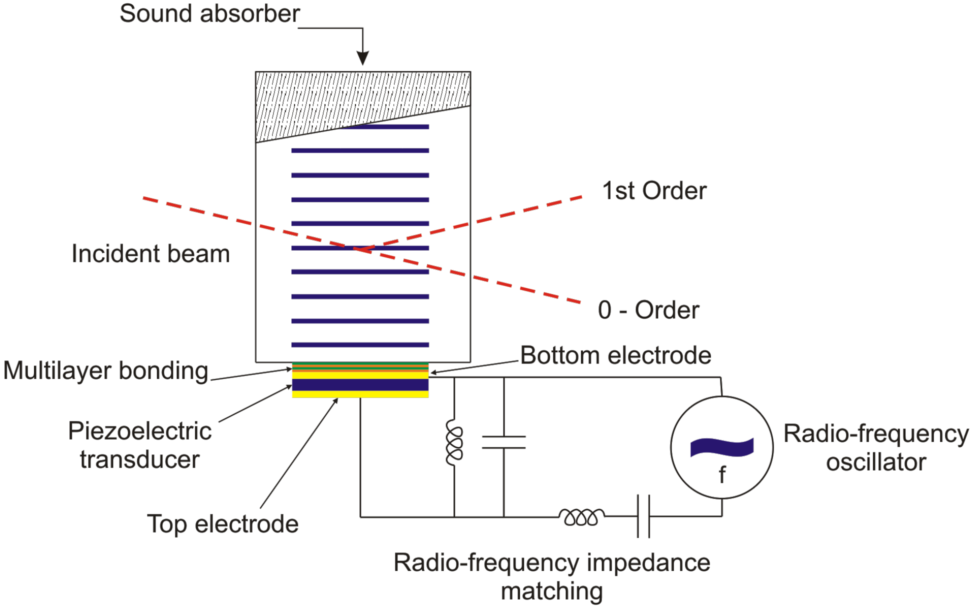


Nd:YLF: 700 ps, 1 kHz, P_{peak} = 15 kW, P_{av} = 10.5 mW, E_p = 10.5 µJ

Nd:YVO_4: 600 ps, 1 kHz, P_{peak} = 5 kW, P_{av} = 3 mW, E_p = 3 µJ

H. Plaessmann et al., *Appl. Opt.* **32**, 6616 (1993)

How an acousto-optic modulator works



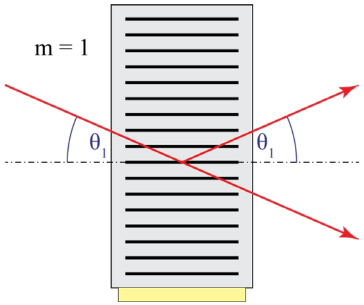
(image source: http://www.elent-a.net)

- Acoustic carrier frequency: about 10 MHz – 2 GHz
- Wavelength of acoustic wave:

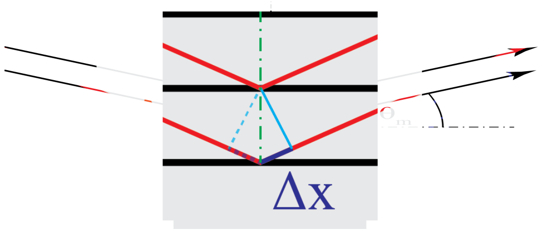
$$\Lambda = \frac{c_{\text{sound}}}{f_{\text{acoustic}}}$$

- Diffraction angle determined by Bragg condition:

$$\sin(\theta_m) = \frac{m\lambda}{2n\Lambda}$$



- When acoustic wave is present: high losses due to diffraction into 1st order
- Switch acoustic wave on and off at desired Q-switched pulse repetition rate ($f_{\text{rep}} << f_{\text{acoustic}}$)



$$k_n \cdot 2\Delta x \overset{!}{=} m \cdot 2\pi$$

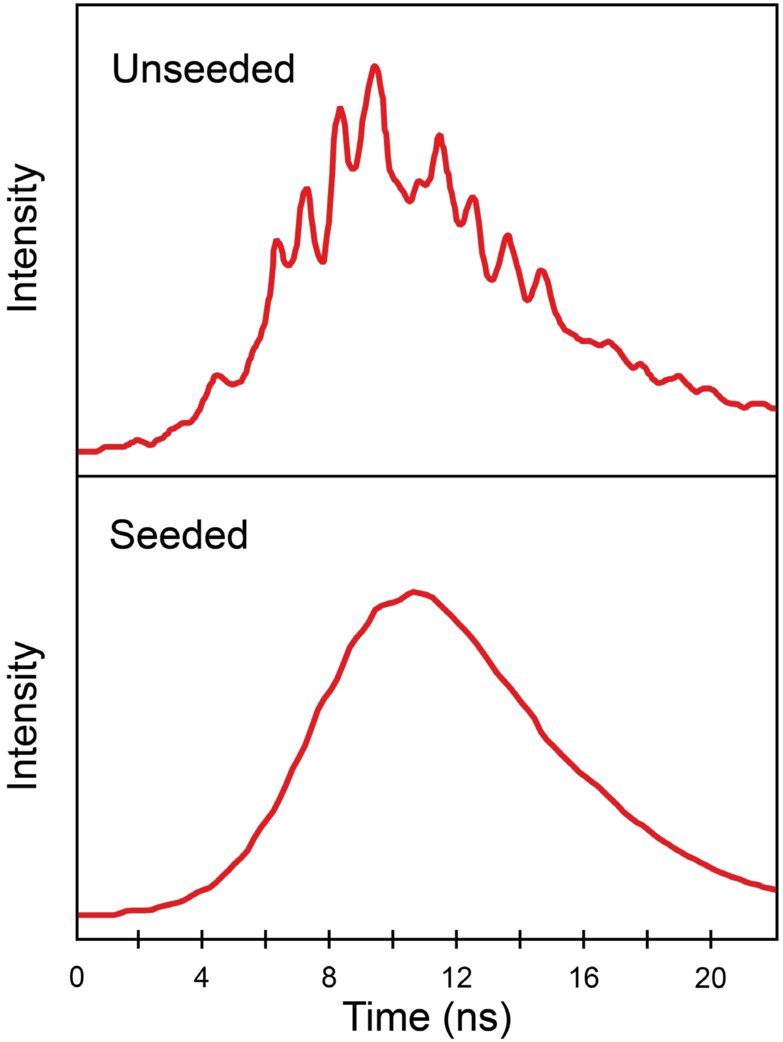
$$k_n \cdot 2\Lambda \cos(90^\circ - \theta_m) \overset{!}{=} m \cdot 2\pi$$

$$\sin(\theta_m) \overset{!}{=} \frac{m\lambda}{2n\Lambda}$$

Seeded Q-switched laser

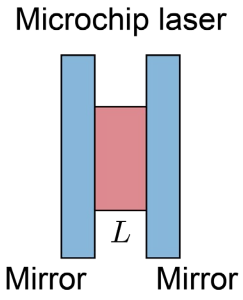
Ideally a Q-switched laser is a single axial mode laser.

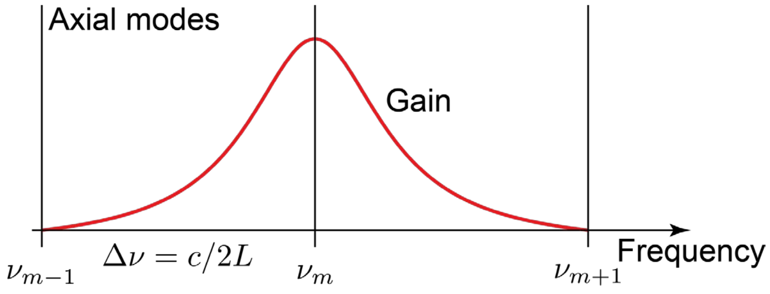
Seeding with a low-power single mode laser.



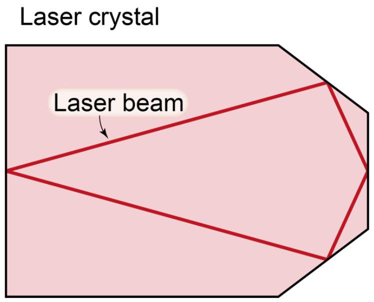
Single mode operation

- **Microchip laser**
  cavity length small: axial mode spacing larger than gain bandwidth

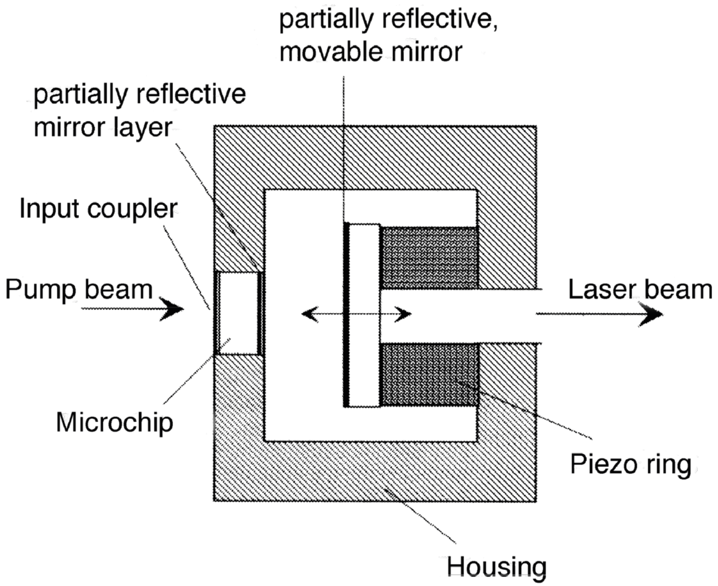


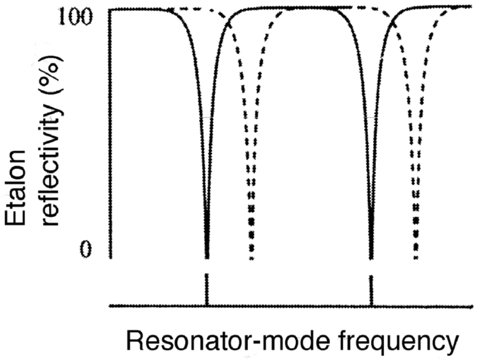


- **Unidirectional ring laser**
  no spatial hole burning: no standing wave
  example: MISER or NPRO (nonplanar ring oscillator). Applied magnetic field forces unidirectional operation (Faraday effect).



Actively Q-switched microchip laser





Tunable etalon (i.e. Fabry-Perot)

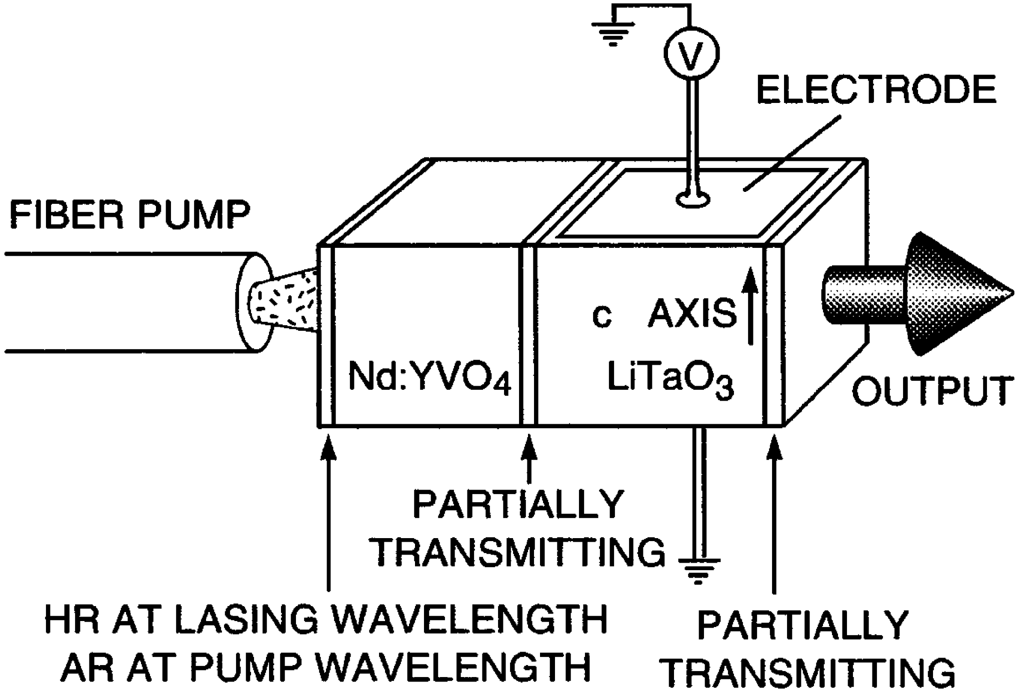
Active Q-switching by shifting the Fabry-Perot resonance frequency in and out of the microchip axial mode.

Etalon resonance shifted with a movable mirror.

J. J. Zayhowski et al., *IEEE J. Quantum Electronics* **27**, 2220 (1991)

Actively Q-switched microchip laser

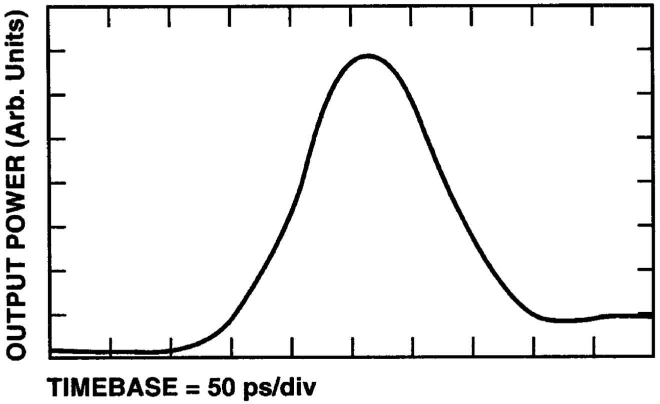
J. J. Zayhowski et al., *Opt. Lett.* **20**, 716 (1995)



Tunable etalon (i.e. Fabry-Perot)

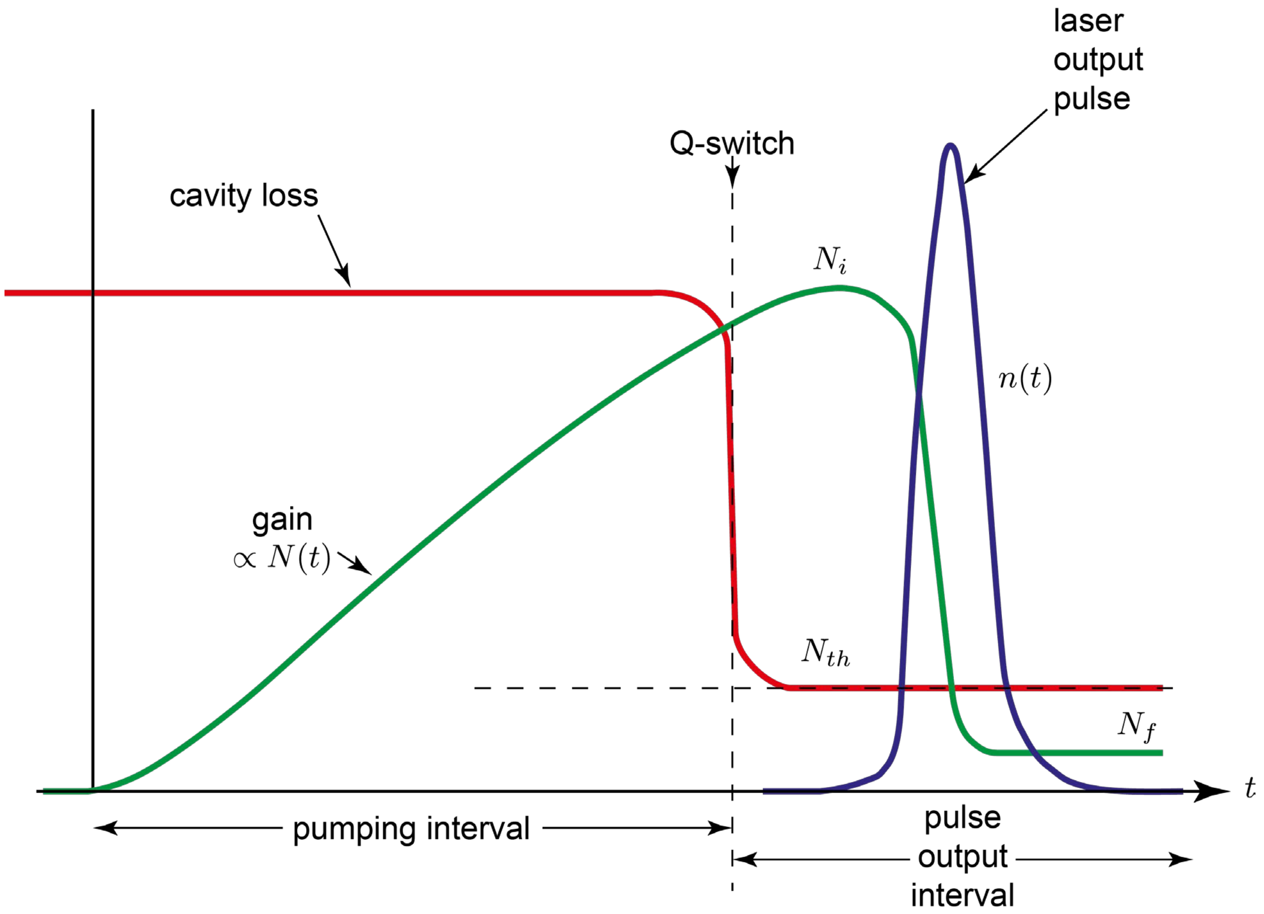
Active Q-switching by shifting the Fabry-Perot resonance frequency in and out of the microchip axial mode.

Etalon resonance shifted with an electro-optical effect.



115 ps, 1 kHz
shortest pulses with active Q-switching

Theory for active Q-switching

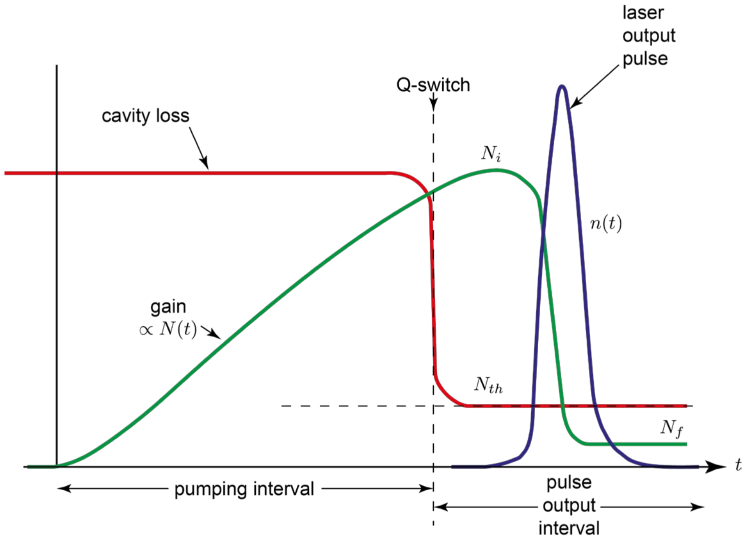


$$\frac{dn}{dt} = KNn - \gamma_c n$$

$$\frac{dN}{dt} = R_p - \gamma_L N - KNn$$

$$R_p = \frac{P_{abs}}{h\nu_{pump}}$$

Theory for active Q-switching: build-up phase



$$\frac{dn}{dt} = KNn - \gamma_c n$$

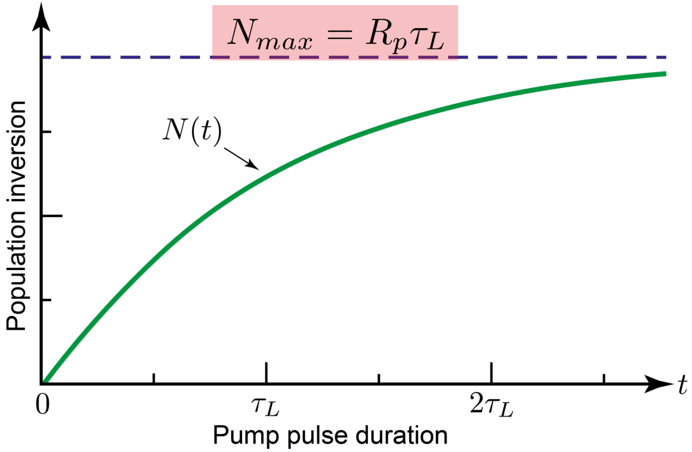
$$\frac{dN}{dt} = R_p - \gamma_L N - KNn$$

Build-up phase: loss high and lasing threshold not reached: $n(t) \approx 0, \quad R_p = \text{const.}$

It needs $\approx 3\tau_L$ to reach maximum inversion.

$$\frac{dN}{dt} \approx R_p - \gamma_L N = R_p - \frac{N}{\tau_L}$$

$$\begin{aligned} N(t) &= R_p \tau_L \left[1 - \exp\left(-t/\tau_L\right)\right] \\ &= N_{max} \left[1 - \exp\left(-t/\tau_L\right)\right] \end{aligned}$$



Theory for active Q-switching: build-up phase

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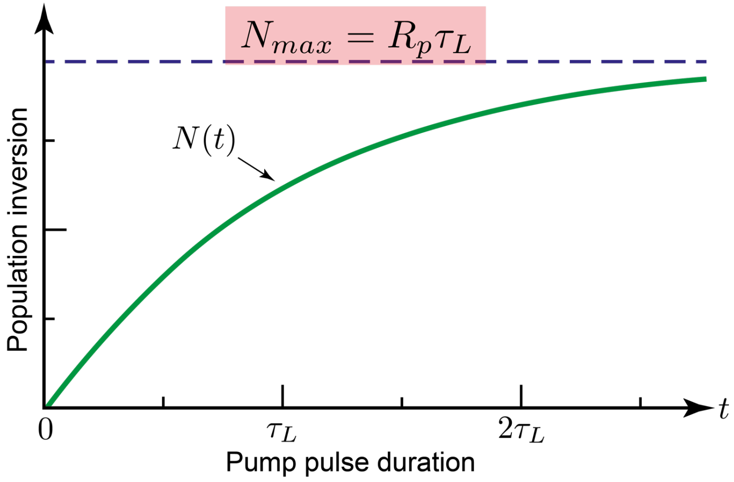
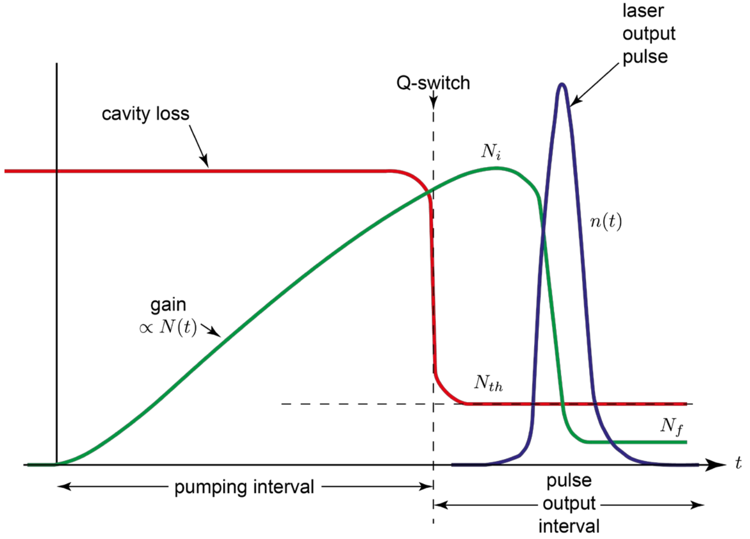


$$\boxed{E_p = \text{const.} \qquad \Longleftrightarrow \qquad T_{rep} >\approx 3\tau_L, \text{ or } \quad f_{rep} = \frac{1}{T_{rep}} <\approx \frac{1}{3\tau_L}}$$

Example: Nd:YLF, upper state lifetime 480 µs, $\frac{1}{3\tau_L} = 0.7$ kHz

Theory for active Q-switching: leading edge of pulse



$$\frac{dn}{dt} = KNn - \gamma_c n$$

$$\frac{dN}{dt} = R_p - \gamma_L N - KNn$$

$$N(t=0) = N_i$$

1. Approximation: *t* = 0 losses are instantaneously switched off $n(t=0) = n_i \approx 1$

2. Approximation: inversion not reduced during early build-up phase $N(t) \approx N_i \approx \text{const.}$

$$\frac{dn}{dt} \approx K(N_i - N_{th})n = KN_{th}(r-1)n = \frac{r-1}{\tau_c}n$$

$$r = N_i/N_{th}$$

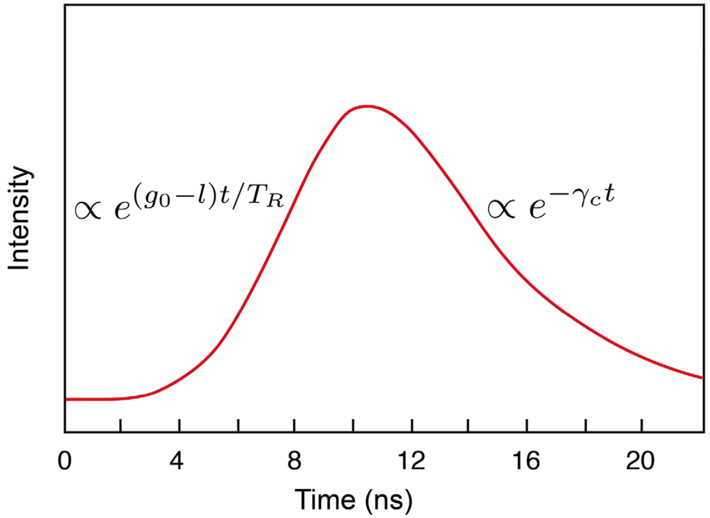
$$N_{th} = \gamma_c/K$$

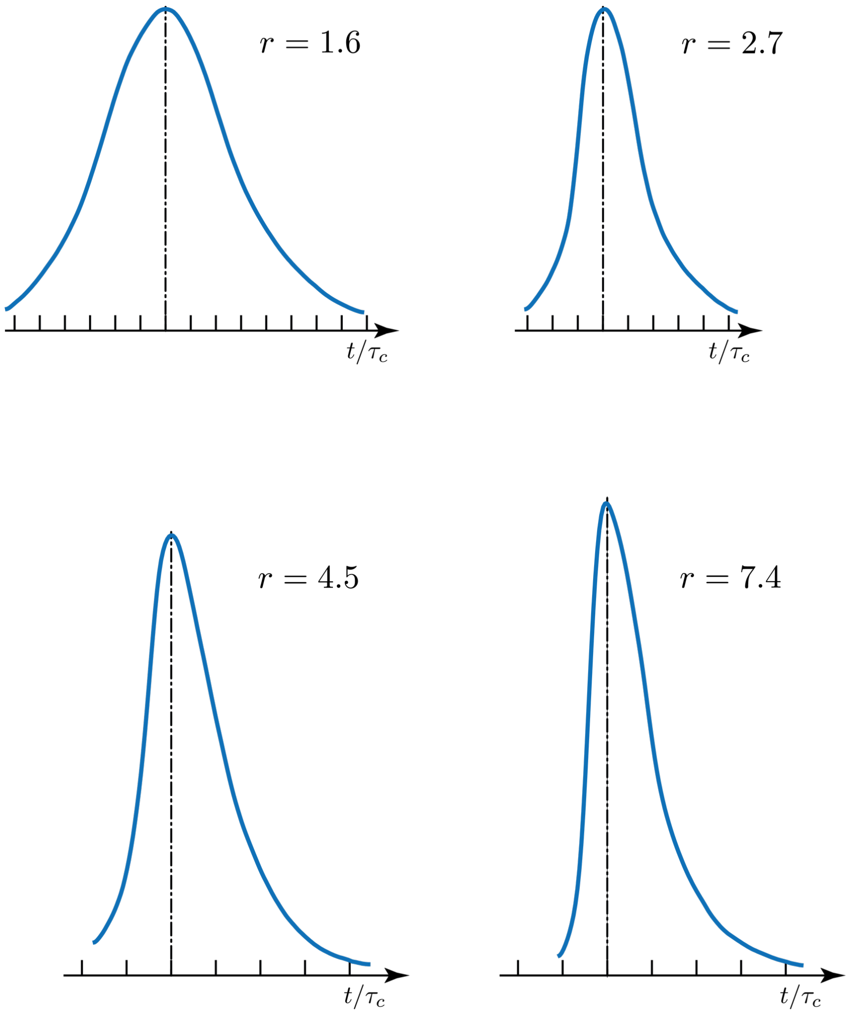
$$n(t) \approx n_i \exp\left(\frac{r-1}{\tau_c}t\right) \xrightarrow{\tau_c = T_R/l,\ g_0 = rl} = n_i \exp\left[(g_0 - l)\frac{t}{T_R}\right]$$

Ultrafast Lasers book, Subsection 8.2.3

Pulse shape and pulse duration

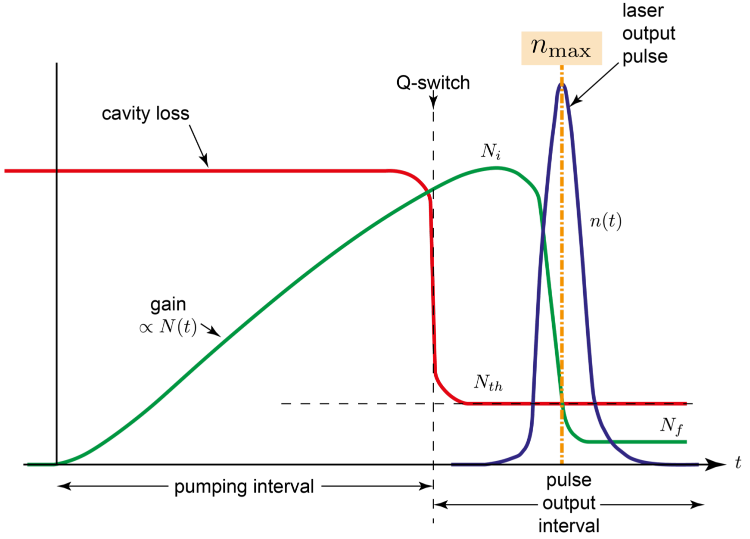
$$g_0 = rl \qquad \gamma_c = l/T_R$$





Ultrafast Lasers book, Subsection 8.1.1

Theory for active Q-switching: during pulse duration



$$\frac{dn}{dt} = KNn - \gamma_c n$$

$$N_{th} = \gamma_c / K$$

$$\frac{dN}{dt} = R_p - \gamma_L N - KNn$$

$$\frac{dn}{dt} = K(N - N_{th})n$$

$$\frac{dN}{dt} \approx -KnN$$

Approximation: spontaneous decay rate can be neglected

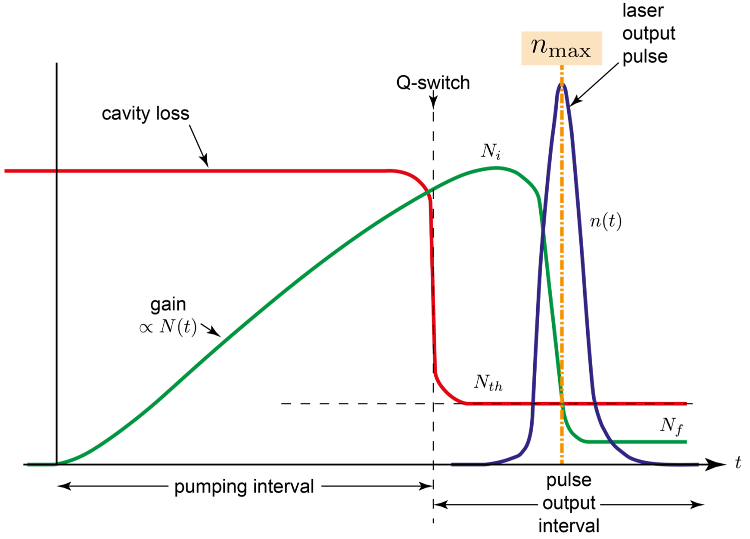
$$\frac{dn}{dN} \approx \frac{K(N - N_{th})n}{-KnN} = \frac{N_{th} - N}{N}$$

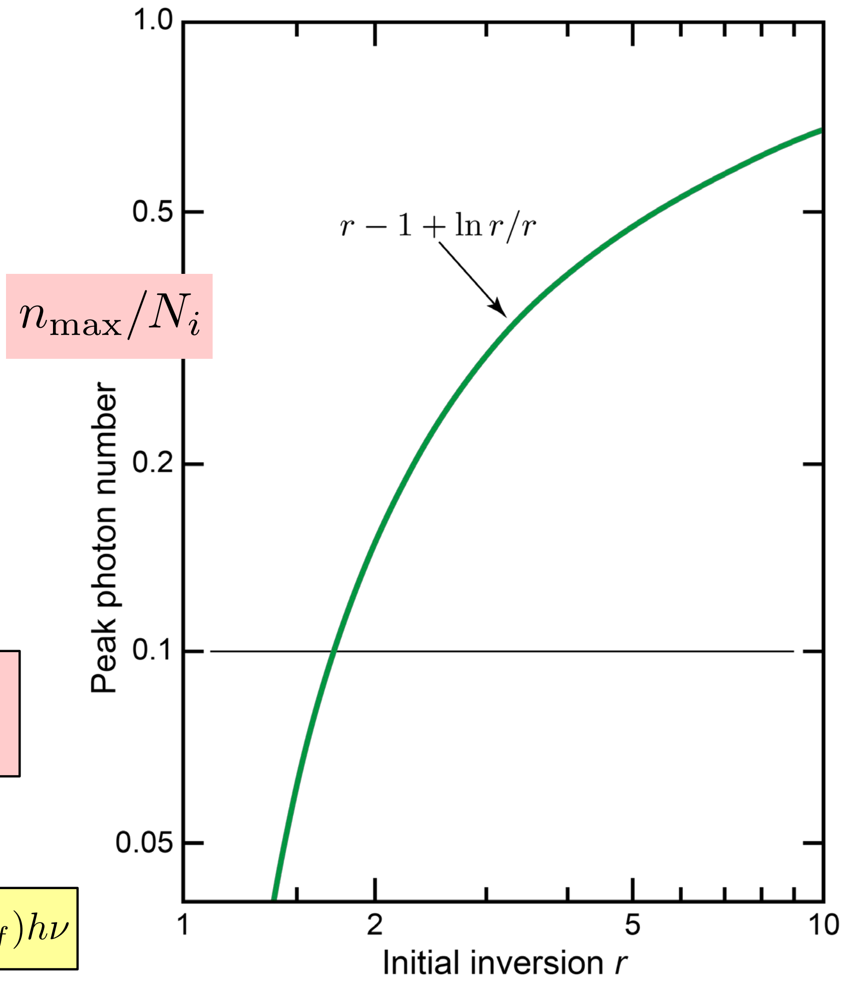
$$dn \approx \frac{N_{th} - N}{N} dN \xrightarrow{N(t=0)=N_i=rN_{th},\ n(t=0)=n_i\approx 1} \int_{n_i}^{n(t)} dn \approx \int_{N_i=rN_{th}}^{N(t)} \frac{N_{th} - N}{N} dN$$

$$n(t) \approx N_i - N(t) - \frac{N_i}{r} \ln\left(\frac{N_i}{N(t)}\right), \quad \text{with } N_i = rN_{th}$$

$$n(t) = n_{\max} \text{ for } g = l \ \Leftrightarrow \ N(t) = N_{th}$$

Theory for active Q-switching: during pulse duration





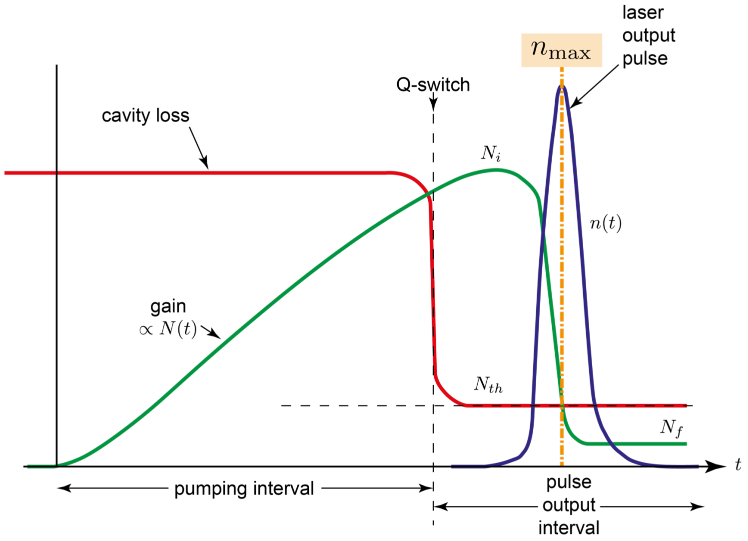
$$n(t) = n_{\max} \text{ for } g = l \;\Leftrightarrow\; N(t) = N_{th}$$

$$n_{\max} \approx \frac{r-1-\ln r}{r} N_i, \quad \text{with } N_i = rN_{th}$$

$$P_{\mathrm{p,out}} = \frac{n_{\max} h\nu}{\tau_c}$$

$$E_{\mathrm{p,out}} \approx E_p \approx (N_i - N_f)h\nu$$

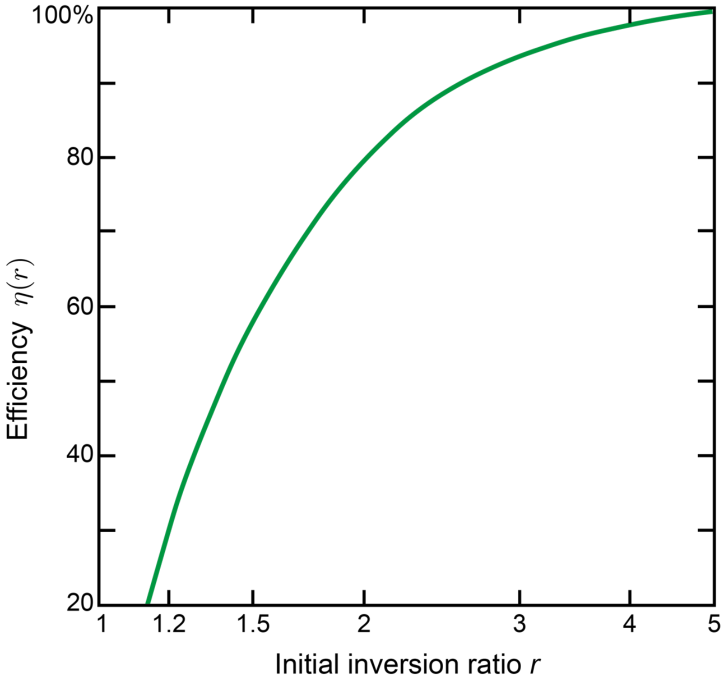
Theory for active Q-switching: during pulse duration



$$n(t) = n_{\max} \text{ for } g = l \;\Leftrightarrow\; N(t) = N_{th}$$

$$n_{\max} \approx \frac{r - 1 - \ln r}{r} N_i, \quad \text{with } N_i = r N_{th}$$

$$\eta \equiv \frac{\text{Q-switched pulse energy}}{\text{stored energy}} = \frac{(N_i - N_f)h\nu}{N_i h\nu} = \frac{N_i - N_f}{N_i}$$

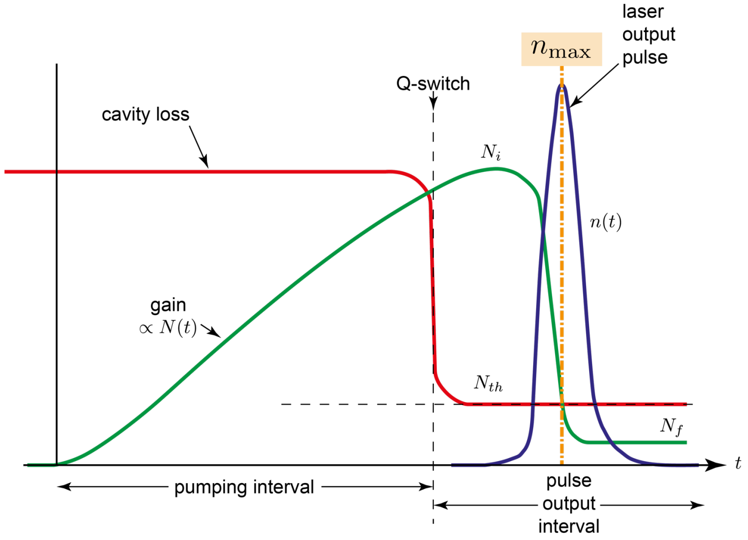


$$P_{\text{p,out}} = \frac{n_{\max} h\nu}{\tau_c}$$

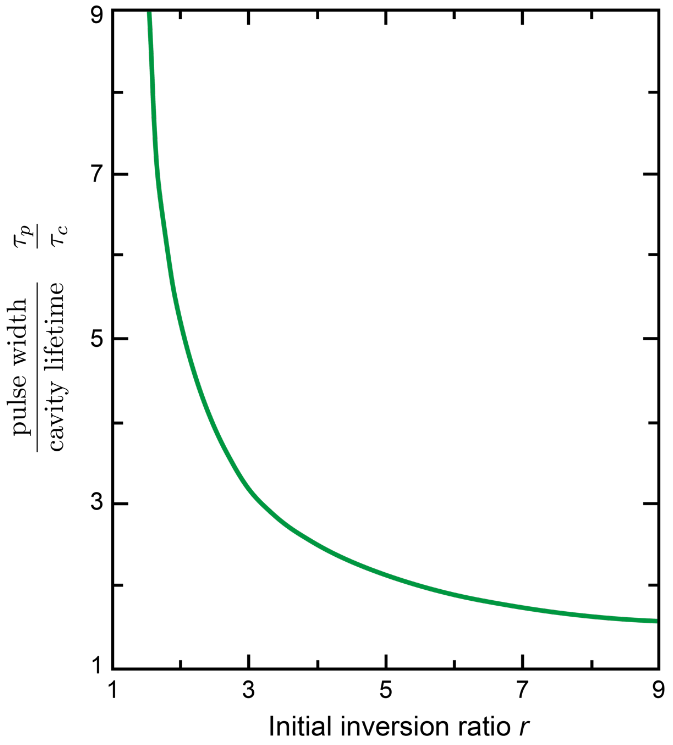
$$E_{\text{p,out}} \approx E_p \approx (N_i - N_f)h\nu$$

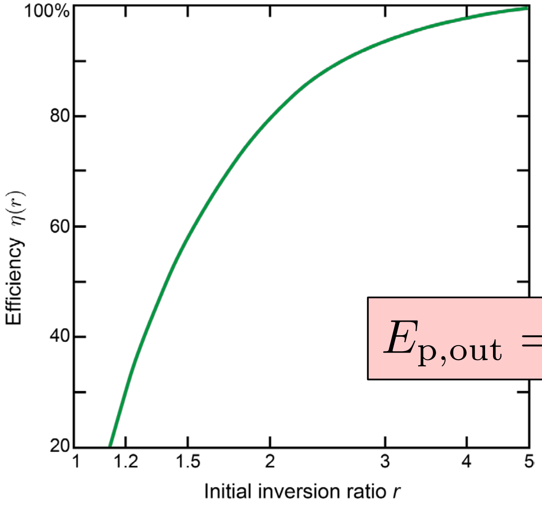
$$E_{\text{p,out}} = E_p \approx \eta(r) N_i h\nu$$

Theory for active Q-switching: during pulse duration



$$\tau_p \approx \frac{E_{\mathrm{p,out}}}{P_{\mathrm{p,out}}} \approx \frac{\eta(r)N_i}{n_{\max}}\tau_c \approx \frac{r\eta(r)}{r-1-\ln r}\tau_c$$

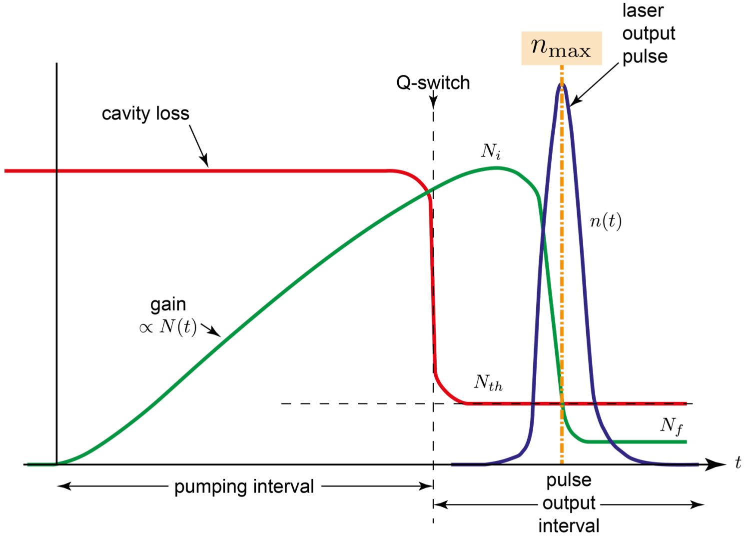


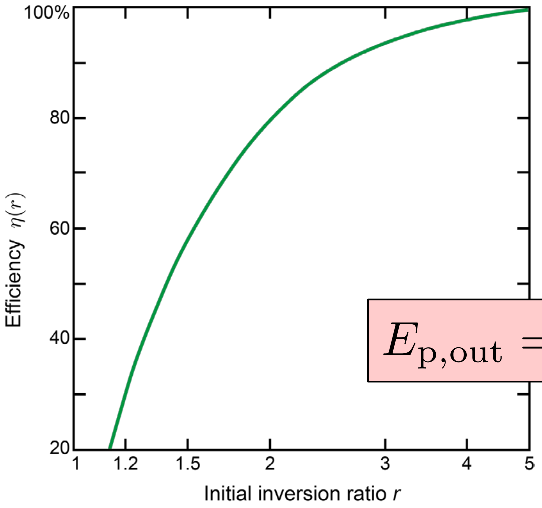


$$P_{\mathrm{p,out}} = \frac{n_{\max}h\nu}{\tau_c}$$

$$E_{\mathrm{p,out}} = E_p \approx \eta(r)N_i h\nu$$

Theory for active Q-switching: trailing edge of pulse

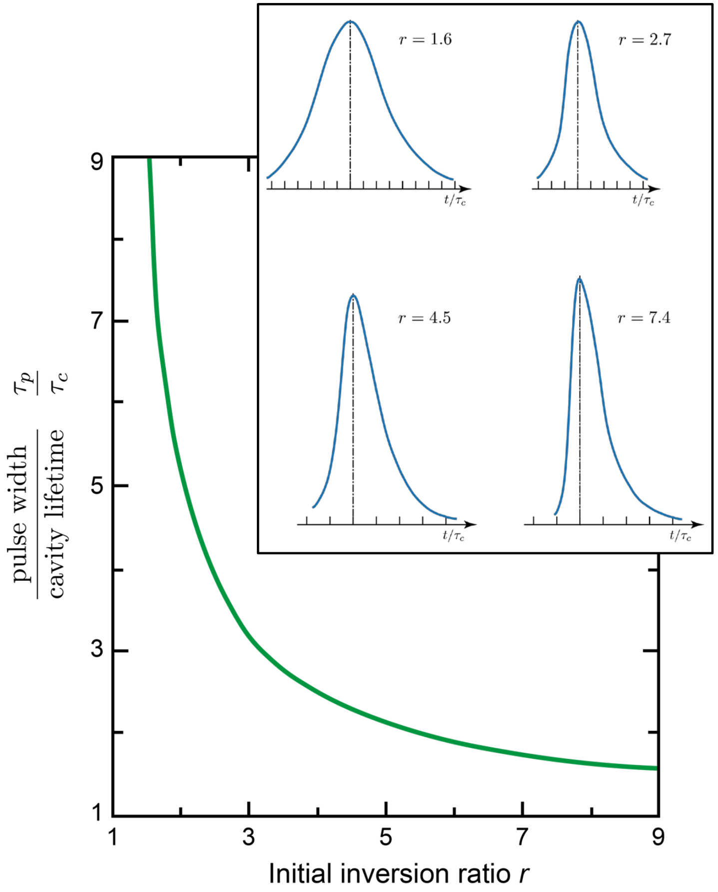




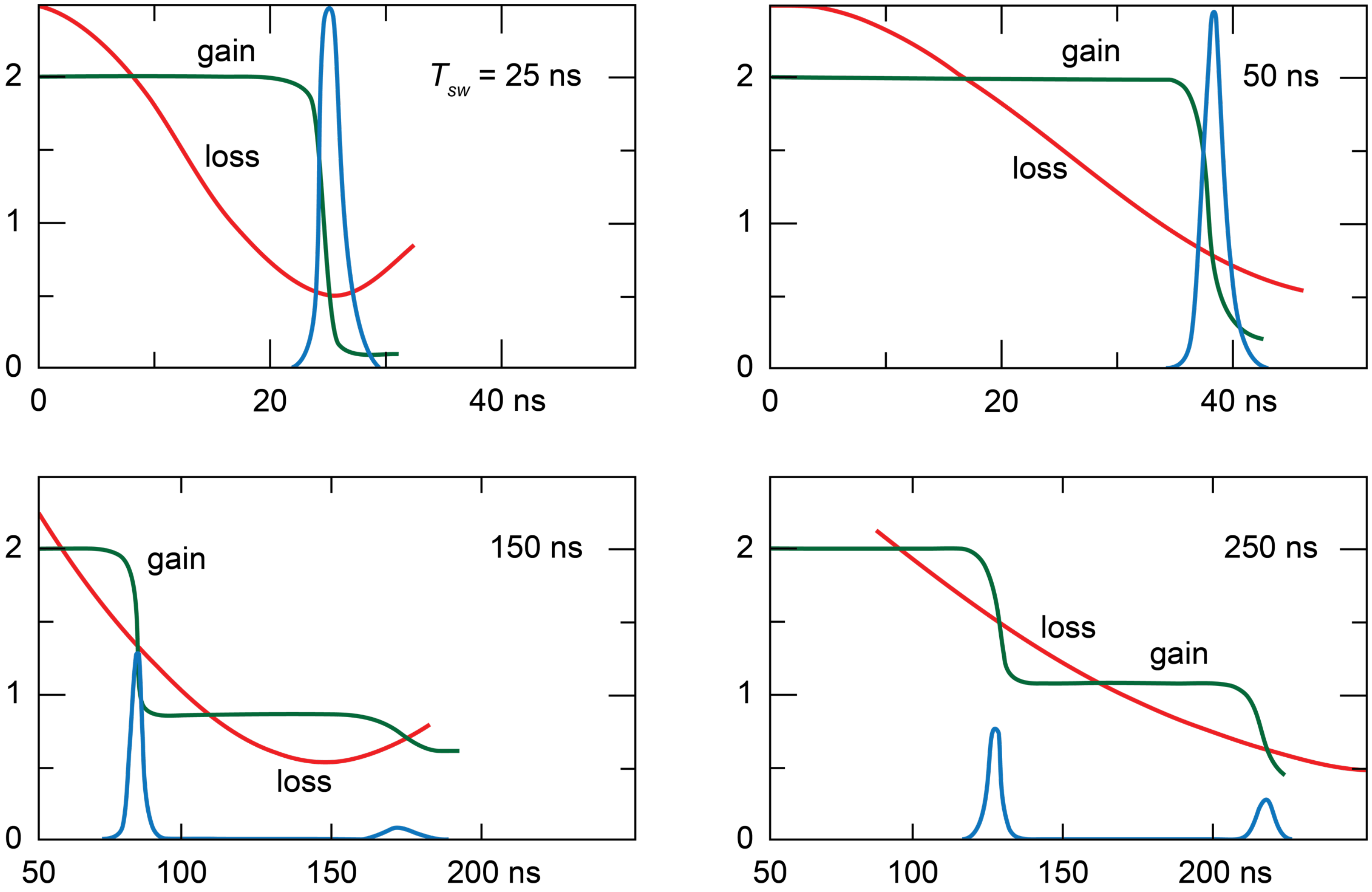
$$P_{\mathrm{p,out}} = \frac{n_{\max} h\nu}{\tau_c}$$

$$E_{\mathrm{p,out}} = E_p \approx \eta(r) N_i h\nu$$

$$n(t) = n_{\max} \exp(-t/\tau_c)$$

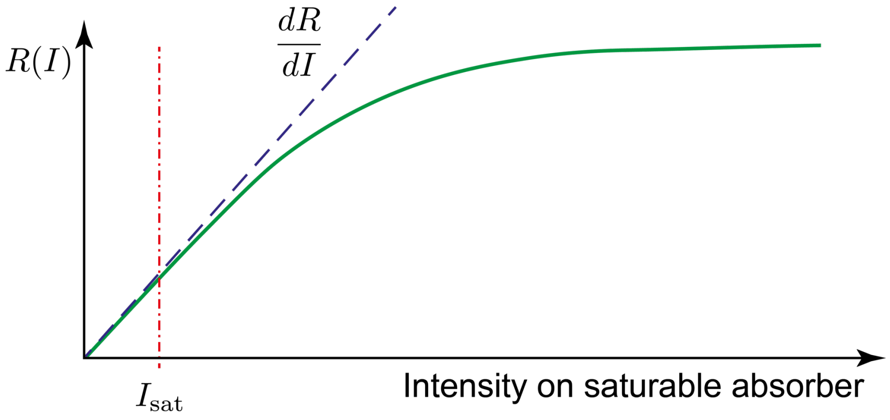


Effects of a slow Q-switch



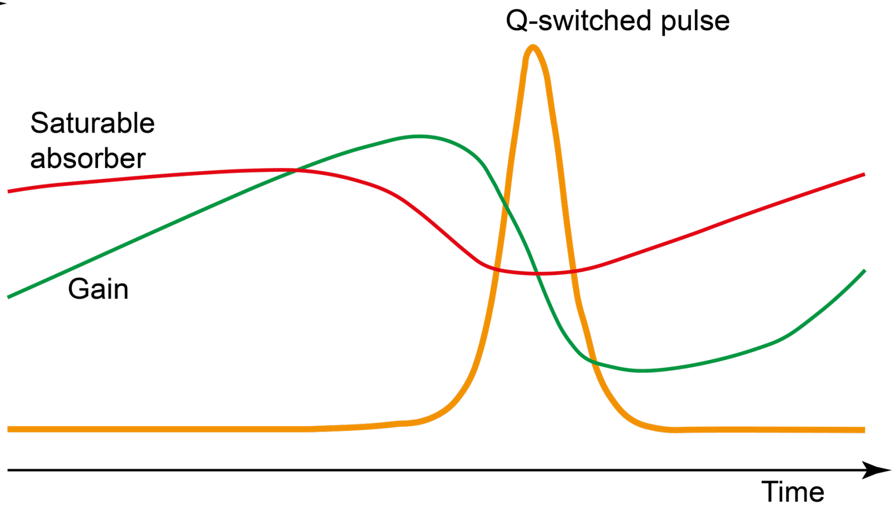
Passive Q-switching

Saturable absorber integrated into a mirror (saturable reflector)



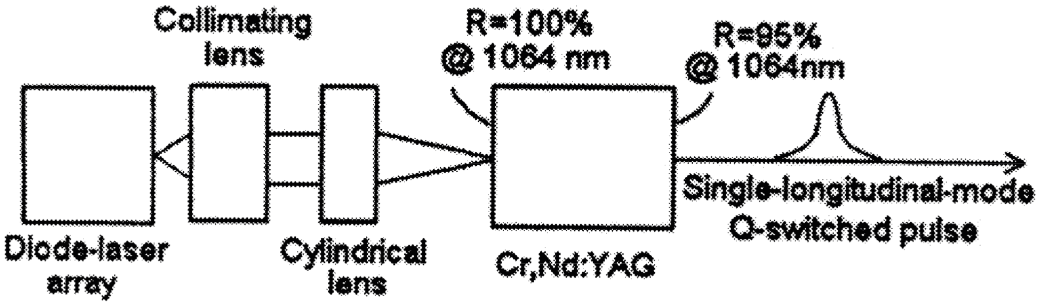
Condition for Q-switching

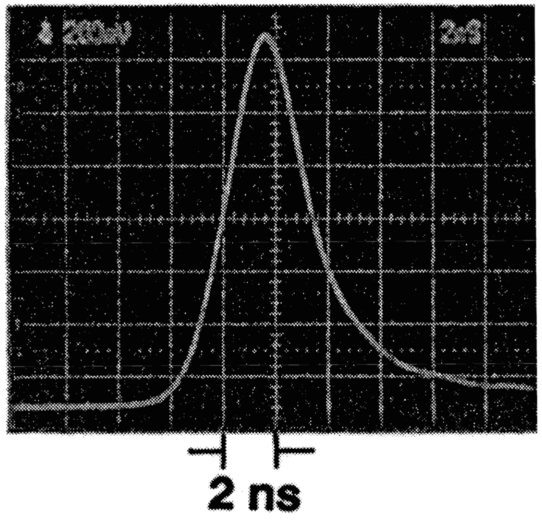
$$\boxed{\left|\frac{dR}{dI}\right| I > \frac{T_R}{\tau_{\mathrm{stim}}} \approx r\frac{T_R}{\tau_L}}$$



F. X. Kärtner, L. R. Brovelli, D. Kopf, M. Kamp, I. Calasso, and U. Keller, *Opt. Eng.* **34**, 2024 (1995)

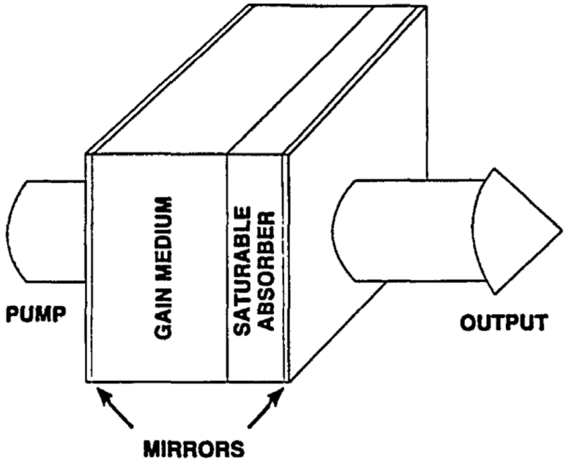
Passively Q-switched microchip laser





290 ps, 8 µJ

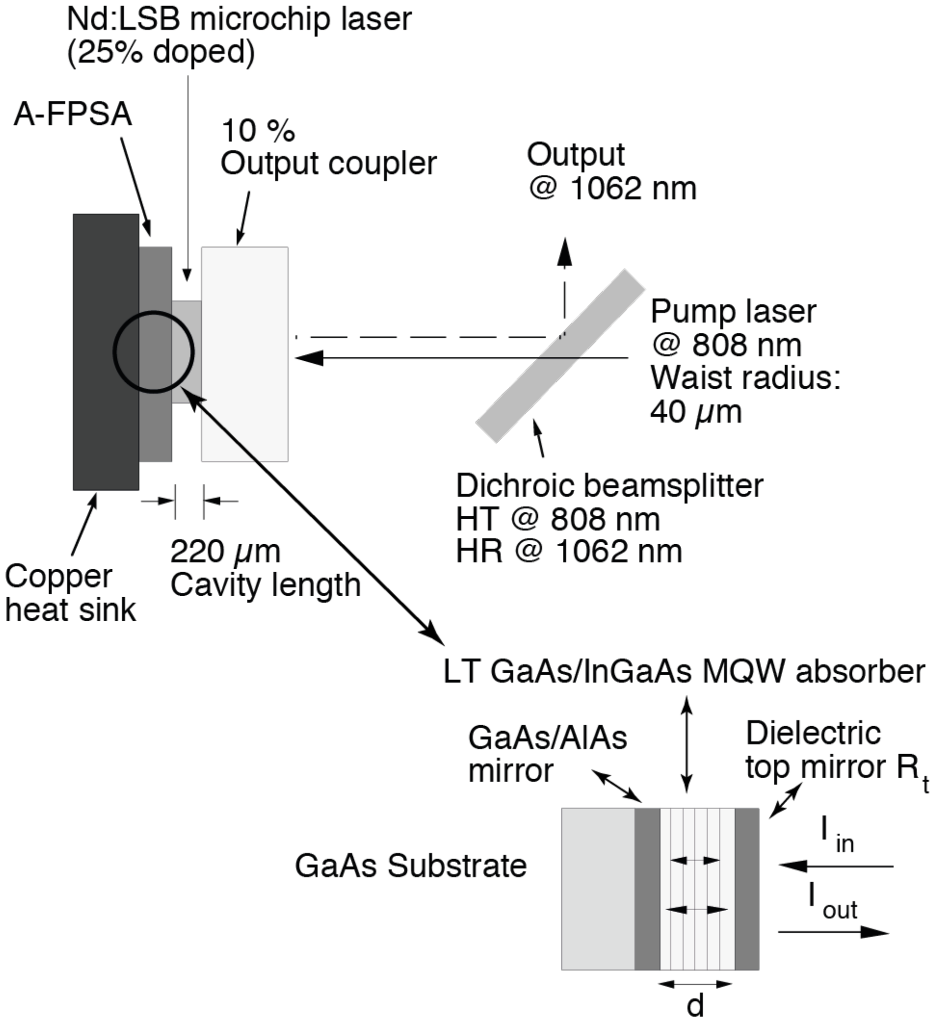
P. Wang et al, *Opt. Commun.* **114**, 439 (1995)

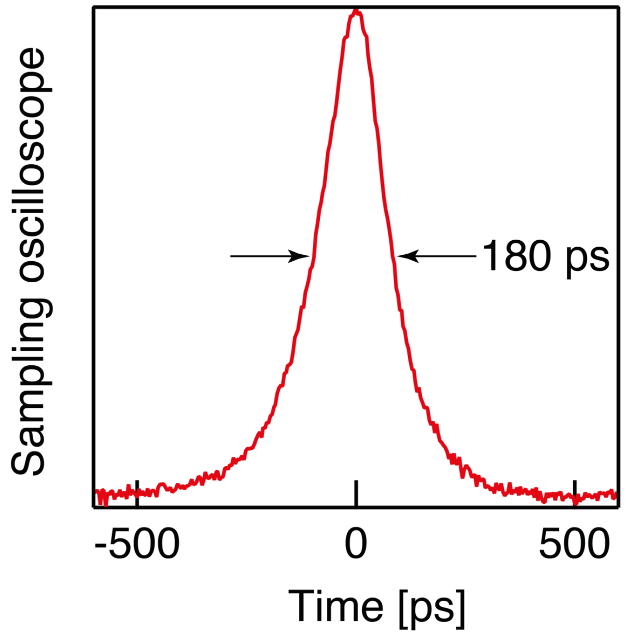


337 ps, 11 µJ, 6 kHz

J. J. Zayhowski et al., *Opt. Lett.* **19**, 1427 (1994)

Passively Q-switched microchip laser



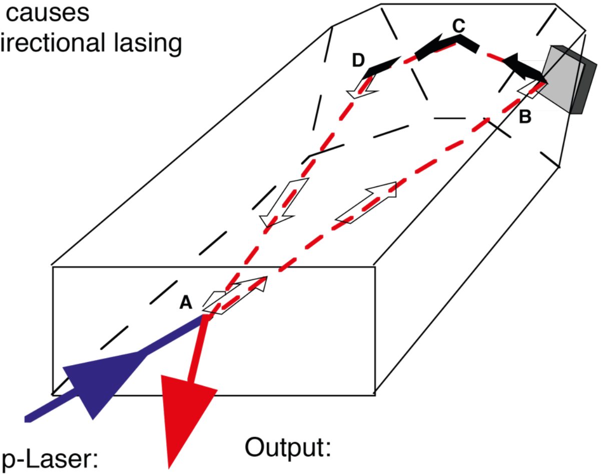


B. Braun et al., *Opt. Lett.* **21**, 405 (1996)

Passively Q-switched ring laser

MISER:
Monolithic Nd:YAG Laser
Applying a magnetic field causes unidirectional lasing

Evanescent wave coupled nonlinear semiconductor mirror

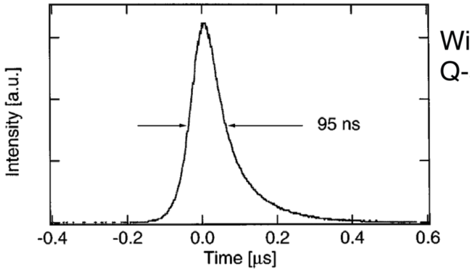


Pump-Laser:
cw Ti:Sapphire laser
@ 809 nm

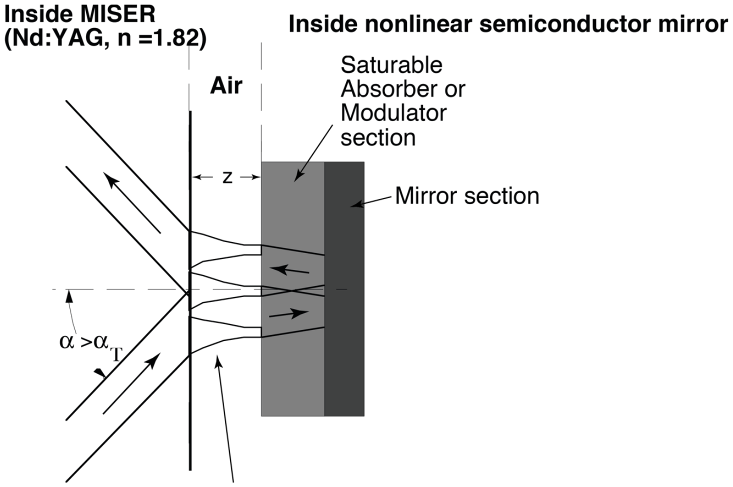
Output:

Without nonlinear mirror -> cw output, single mode due to unidirectional ring laser

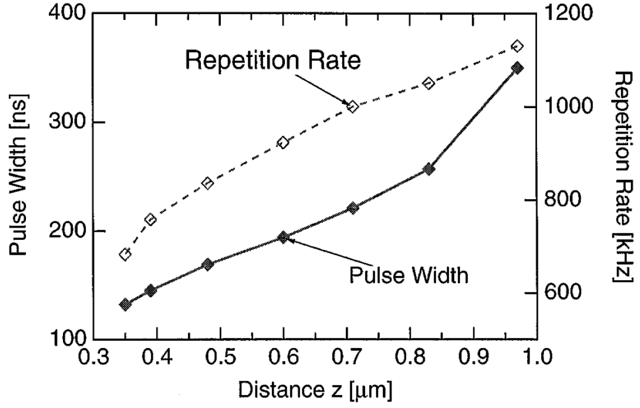
With nonlinear mirror-> single mode Q-switched



B. Braun et al., *Opt. Lett.* **20**, 1020 (1995)



Airgap:
Coupling through evanescent waves:
Frustrated total internal reflection (FTIR)

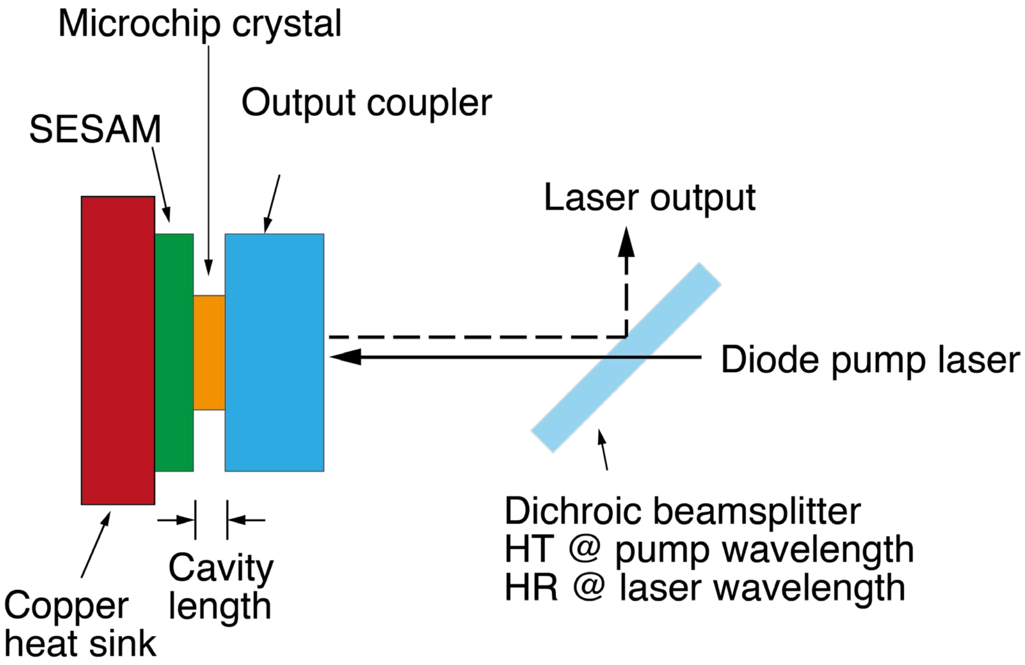


Passively Q-switched Microchip Laser

μJ-pulses with ≈ 10 kHz repetition rates ⇒ ≈ 10 mW average powers

G. J. Spühler, R. Paschotta, R. Fluck, B. Braun, M. Moser, G. Zhang, E. Gini, and U. Keller,
"Experimentally confirmed design guidelines for passively Q-switched microchip lasers using semiconductor saturable absorbers,"
J. Opt. Soc. Am. B **16**, 376-388 (1999)

Passively Q-switched Microchip Laser



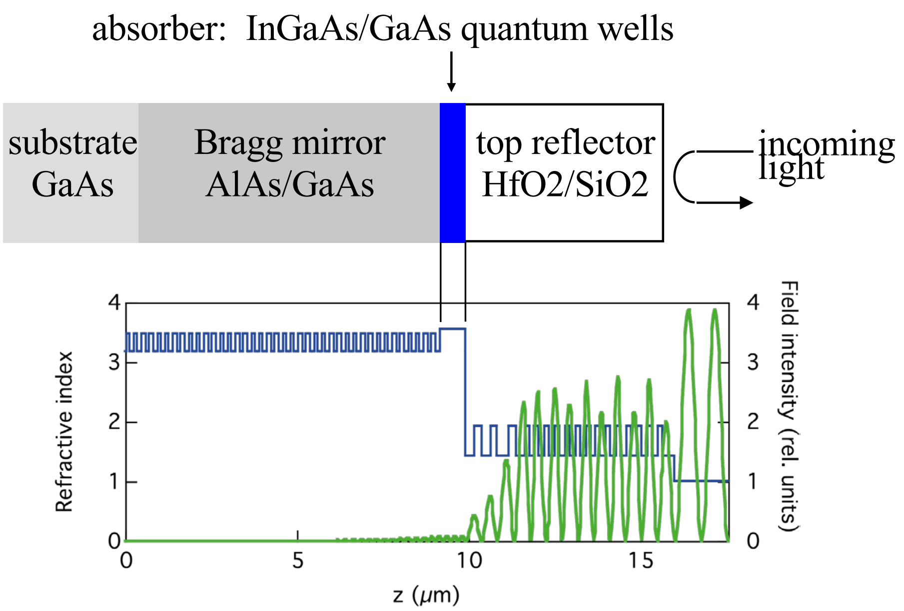
Flat/flat resonator

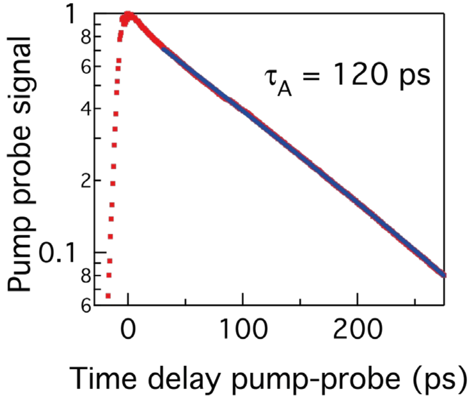
Cavity stabilization by

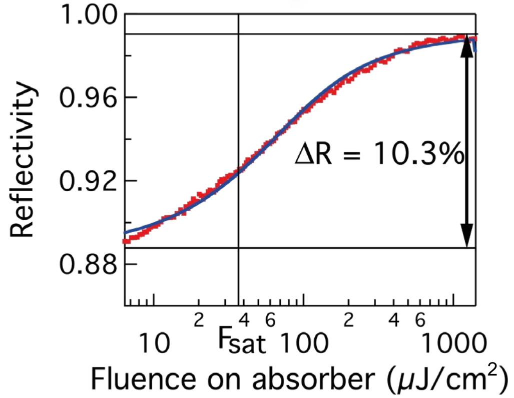
- Thermal lensing
- Thermal expansion
- Gain guiding

- Compact and simple all-solid-state laser
- Short cavity ⇒ Single longitudinal mode
  Short Q-switched pulses
- High pulse energies possible
- Good beam quality

SEmiconductor Saturable Absorber Mirror (SESAM)

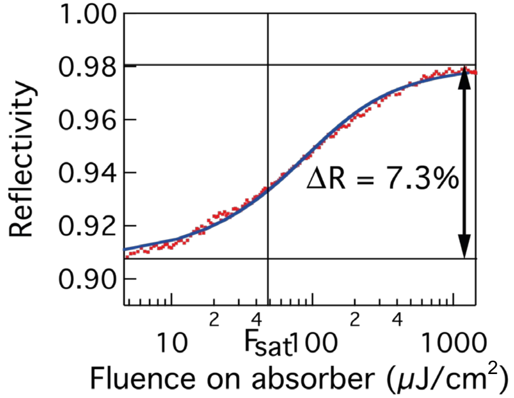






SESAM #1: $\Delta R = 10.3\%$

$F_{\text{sat}} = 36\ \mu\text{J/cm}^2$

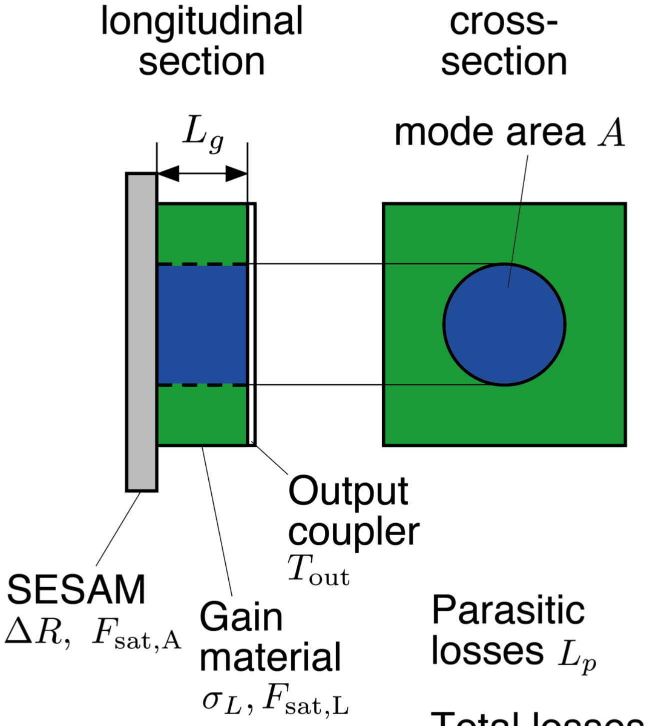


SESAM #2: $\Delta R = 7.3\%$

$F_{\text{sat}} = 47\ \mu\text{J/cm}^2$

Model

Cavity setup



longitudinal section

cross-section

L_g

mode area A

Output coupler T_{out}

SESAM $\Delta R,\ F_{\text{sat,A}}$

Gain material $\sigma_L, F_{\text{sat,L}}$

Parasitic losses L_p

Total losses

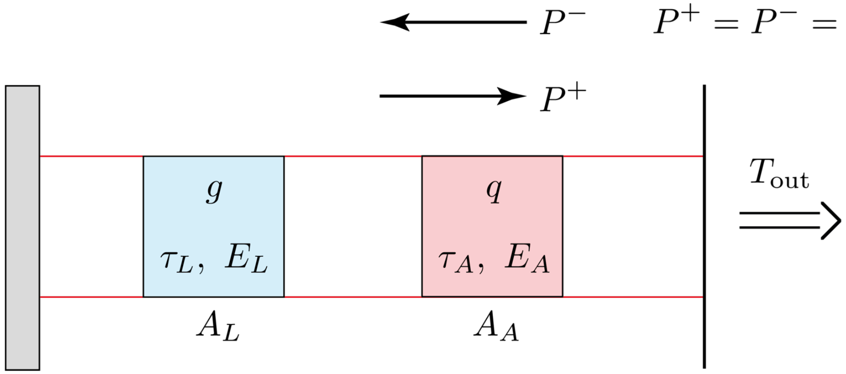
$L_{\text{tot}} = T_{\text{out}} + L_p$

$\eta_{\text{out}} = L_{\text{out}}/(L_{\text{out}} + L_p)$

Assumptions

- No spatial hole burning
- No beam divergence in cavity
- Small changes per round-trip of gain, loss, and power
- $F_{\text{sat,A}} \ll F_{\text{sat,L}} = \dfrac{h\nu_L}{2\sigma_L}$
- SESAM always $F_{\text{sat,A}} << F_{\text{sat,L}}$
- Cr:YAG/Nd:YAG Systems: $F_{\text{sat,A}} \approx F_{\text{sat,L}}$
- $\tau_A > \tau_p$

Theory for passive Q-switching



$$P^+ = P^- = P$$

$$n = \frac{P}{h\nu} T_R \xrightarrow{T_R = 2L/c} = \frac{2L}{ch\nu} P$$

$$g = L_g \frac{N_L}{V} \sigma_L \xrightarrow{V = A_L L_g} = \frac{N_L}{A_L} \sigma_L \qquad q = \frac{N_A}{A_A} \sigma_A$$

$$W^{\text{stim}} = K_L n = \frac{I}{h\nu} \sigma_L = \frac{P}{A_L h\nu} \sigma_L \qquad K_L = \frac{\sigma_L}{A_L T_R}$$

$$\frac{dn}{dt} = \left(K_L N_L - K_A N_A - \frac{1}{\tau_c} \right) n$$

$$\frac{dN_L}{dt} = -\frac{N_L}{\tau_L} - K_L n N_L + R_p$$

$$\frac{dN_A}{dt} = -\frac{N_A - N_{A0}}{\tau_A} - K_A n N_A$$

Neglect spontaneous emission into laser mode

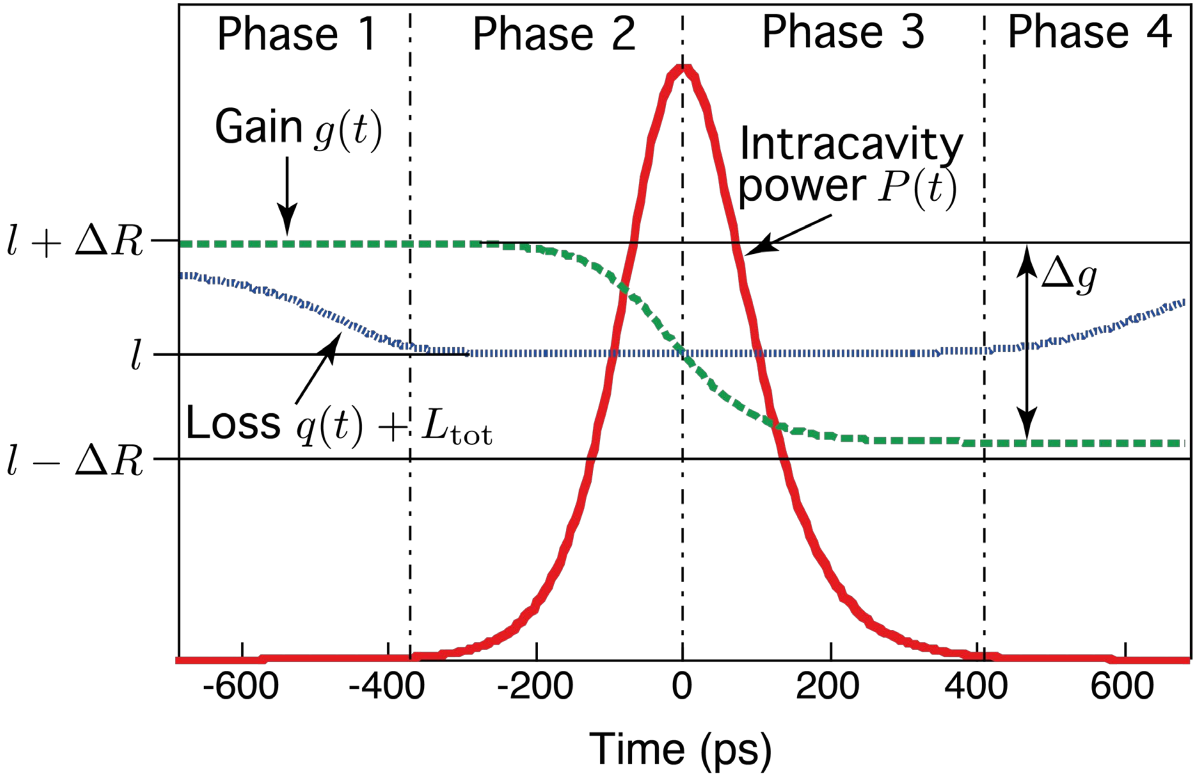
$$T_R \frac{dP(t)}{dT} = \left[g(t) - l(t) - q(t) \right] P(t)$$

$$\frac{dg(t)}{dt} = -\frac{g(t) - g_0}{\tau_L} - \frac{g(t) P(t)}{E_L}$$

$$\frac{dq(t)}{dt} = -\frac{q(t) - q_0}{\tau_A} - \frac{q(t) P(t)}{E_A}$$

Q-switched pulse

from numerical simulations



stored energy:

$$E_{\text{stored}} = E_L g$$

released energy:

E_L saturation energy of the laser

$$E_{\text{released}} = E_L \Delta g$$

l : total nonsaturable loss

l_p : parasitic loss

q_0 : saturable loss

$$q_0 \approx \Delta R$$

from rate equations:

optimum pulse energy if (if $l_p \neq 0$):

$$T_{\text{out}} + L_p \approx \Delta R$$

gain reduction: (for $L_{\text{tot}} \geq \Delta R$):

$$\Delta g \approx 2\Delta R$$

Q-switched pulse

Phase 1:

- absorber unbleached
- power grows when gain reaches loss
  $E_A << E_L$ ⇒ absorber is saturated before power grows significantly

Phase 2:

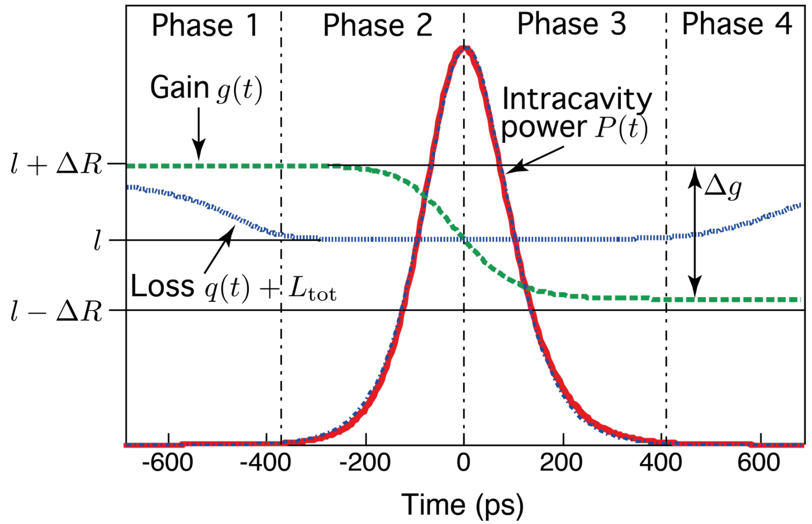
- absorber fully bleached
- power grows quickly until gain is depleted to the loss level

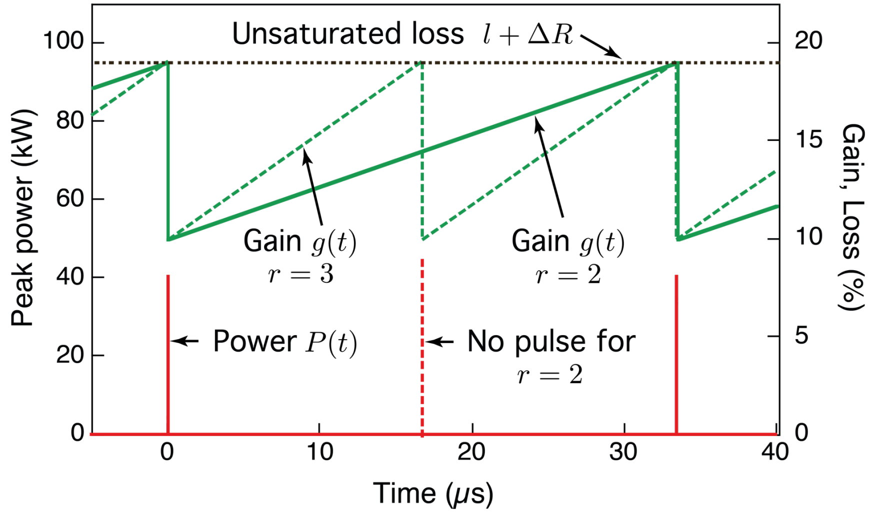
Phase 3:

- power decays
- energy is still extracted, and gain decays further

Phase 4:

- absorber recovers more quickly than gain
- next Phase 1 starts when gain reaches the unsaturated losses





Model

Pulse energy[#]: $$E_p \approx \frac{h\nu_L}{\sigma_L} A \Delta R \eta_{\text{out}}$$

$\Rightarrow$ E_p/A independent of pump power

Pulse duration[*#]: $$\tau_p \approx \frac{3.52 T_R}{\Delta R}$$

$\Rightarrow$ independent of pump power

Repetition rate[#]: $$f_{\text{rep}} \approx \frac{g_0 - (L_{\text{tot}} + \Delta R)}{2 \Delta R \tau_L}$$

pumping harder ⇒ more pulses of same width, shape and fluence

three-level lasers: replace σ_L by $\sigma_L + \sigma_L^{\text{abs}}$

[#] Spühler et al., *JOSA B* **16**, 376-388 (1999)

[*] Zayhowski et al. *IEEE J. Quantum Electron*. 27, 2220-2225 (1991)

Design guidelines: Short pulses

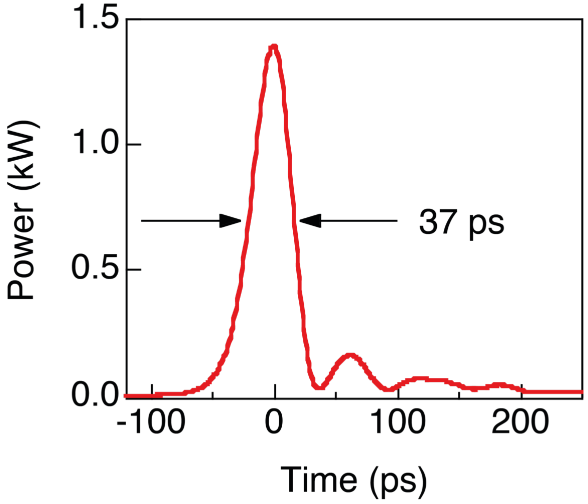
- short cavity (T_R)
- large modulation depth ΔR
- large gain cross-section σ_L

$$\tau_p \approx \frac{3.52 T_R}{\Delta R}$$

⇒ Nd:YVO_4: small absorption length, high gain

Spühler et al., *JOSA B* **16**, 376-388 (1999)

45 GHz sampling oscilloscope trace



shortest Q-switched pulses
from a solid state laser

185 µm Nd:YVO_4

P_pump = 460 mW

f_rep = 160 kHz

E_p = 53 nJ

$\Delta R \approx$ 13%

so far τ_p limited by available ΔR and available crystal thickness, not by gain