Optical nonlinearities, mode locking, and ultrashort pulse generation in quantum cascade lasers

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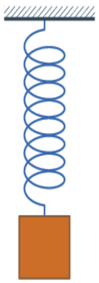
Outline

- Optical nonlinearities in QCLs
- Limits on the speed and amplitude of modulation
- Physics of mode locking
  - Passive mode locking
  - Active mode locking
- Active mode locking in QCLs
  - Prior results
  - Multi-section cavity
  - External ring cavity
- Conclusions

Potential applications for mode-locked QCLs

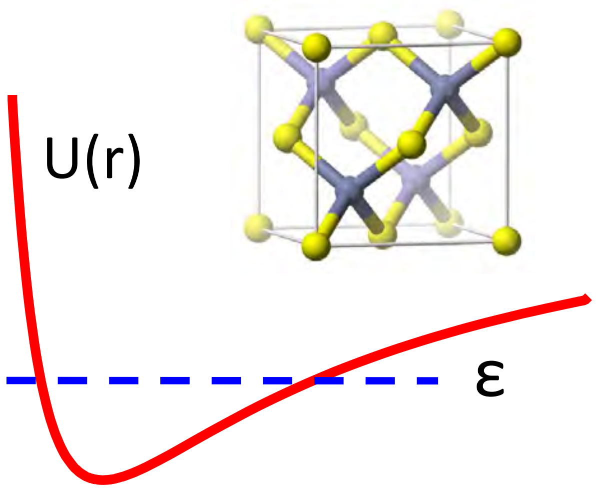
- Mid-infrared and THz frequency combs
  - Talk by Jerome Faist
- Time-resolved studies of ultrafast processes
- Excitation of collective modes: plasmons, polaritons, etc.
- High peak power for material processing, biomedical applications, remote sensing
- High peak power for nonlinear optics

Optical nonlinearities. Dielectric crystals



Anharmonic oscillations of localized electrons

$$\ddot{x}_k + \omega_k^2 x_k + \beta x_k^2 + \ldots \approx \frac{e}{m} E_0 e^{-i\omega t}$$



$$P = \frac{1}{V} \sum e x_k = \chi^{(1)} E + \chi^{(2)} E^2 + \chi^{(3)} E^3 + \ldots$$

For electron displacement *a*
and binding energy U_b ~ 5-10 eV,

$$\frac{P^{(2)} \sim \chi^{(2)} E^2}{P^{(1)} \sim \chi^{(1)} E} \sim \frac{eaE}{U_b} \sim \frac{E}{E_{at}}$$

Scales as work done by the field during one oscillation period divided by binding energy

$\chi^{(2)} \sim 10^{-6}$ esu ~ 10^{-10} m/V in narrow-gap semiconductors

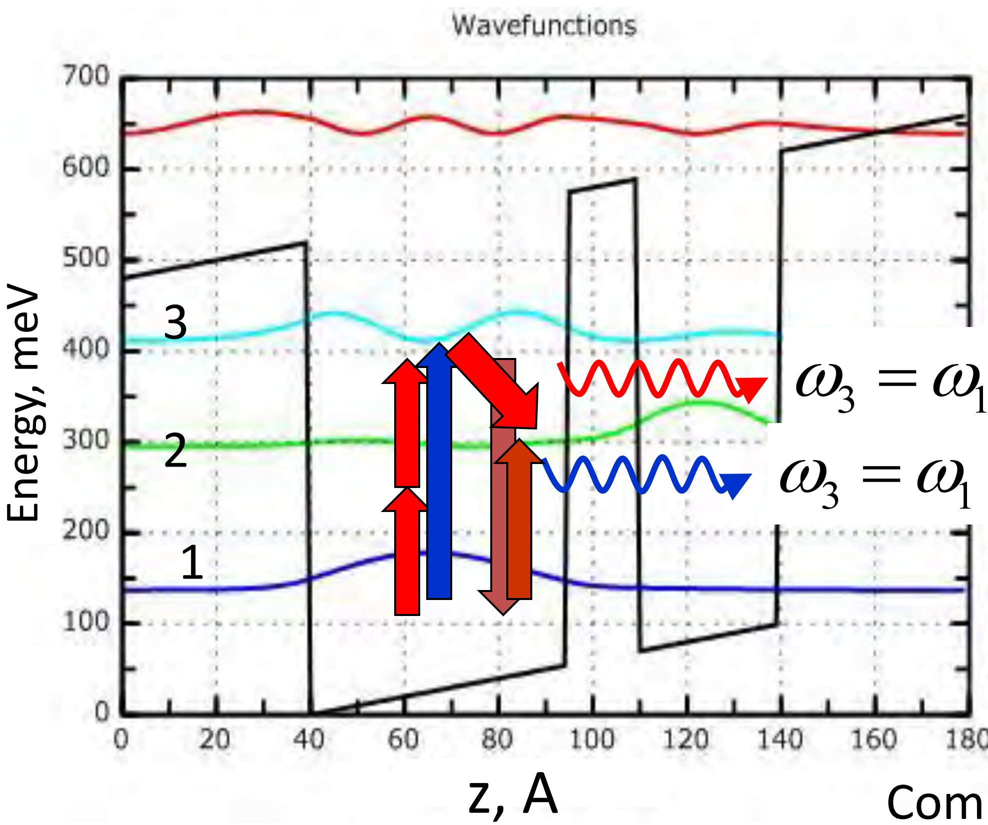
$\chi^{(2)} \sim 10^{-7}$ esu ~ 10^{-11} m/V in standard nonlinear crystals

Typical $\chi^{(3)} \sim 10^{-12} – 10^{-15}$ esu ($10^{-20} – 10^{-23}$ m^2/V^2)

Resonant nonlinearities by design

(Not the topic of this talk)

Coupled quantum well structures can be designed to have huge resonant optical nonlinearity (known for 30 years)



$$\omega_3 = \omega_1 - \omega_2$$

$$\omega_3 = \omega_1 + \omega_2$$

$$\left|\chi^{(2)}\right| \sim \frac{N_e d_{12} d_{13} d_{23}}{\hbar^2 (\gamma_{12}^2 + \Delta_{12}^2)(\gamma_{13}^2 + \Delta_{13}^2)}$$

Δ_{ij} – detunings

γ_{ij} – linewidths

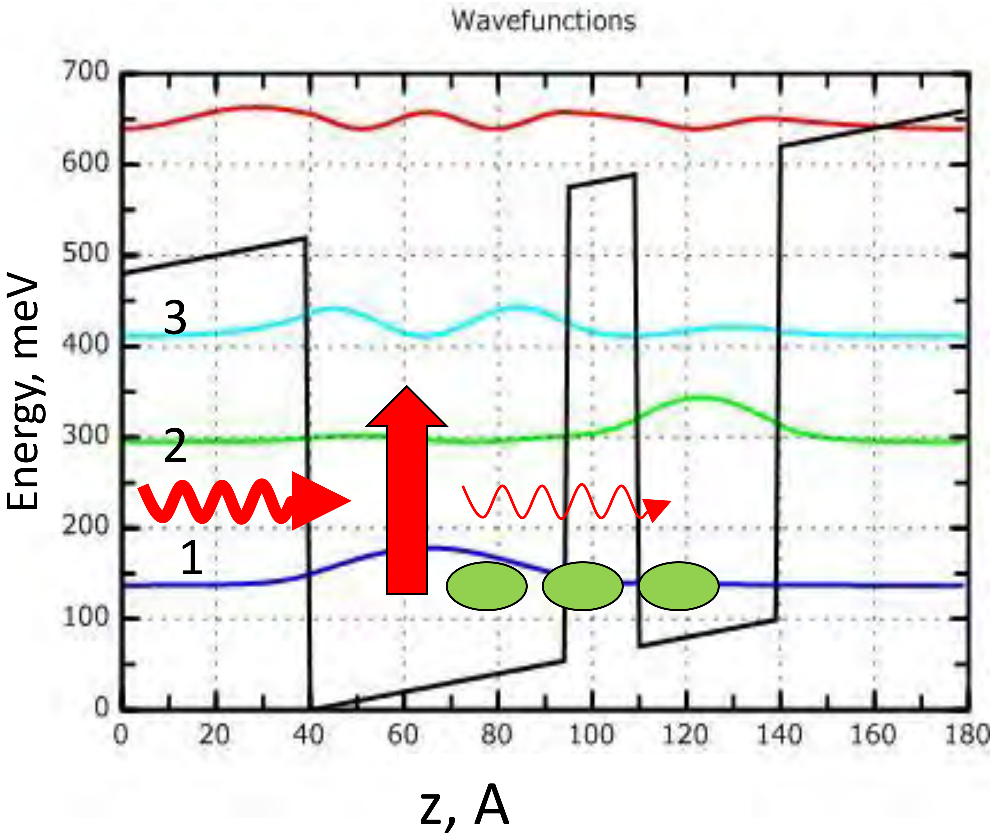
d_{ij} – dipole moments

$$\left|c^{(2)}\right| \sim 10^4 \text{ - } 10^6 \text{ pm/V}$$

Compare with 1-100 pm/V for bulk crystals

A way to get around resonant absorption

Resonant optical nonlinearity is accompanied by resonant absorption



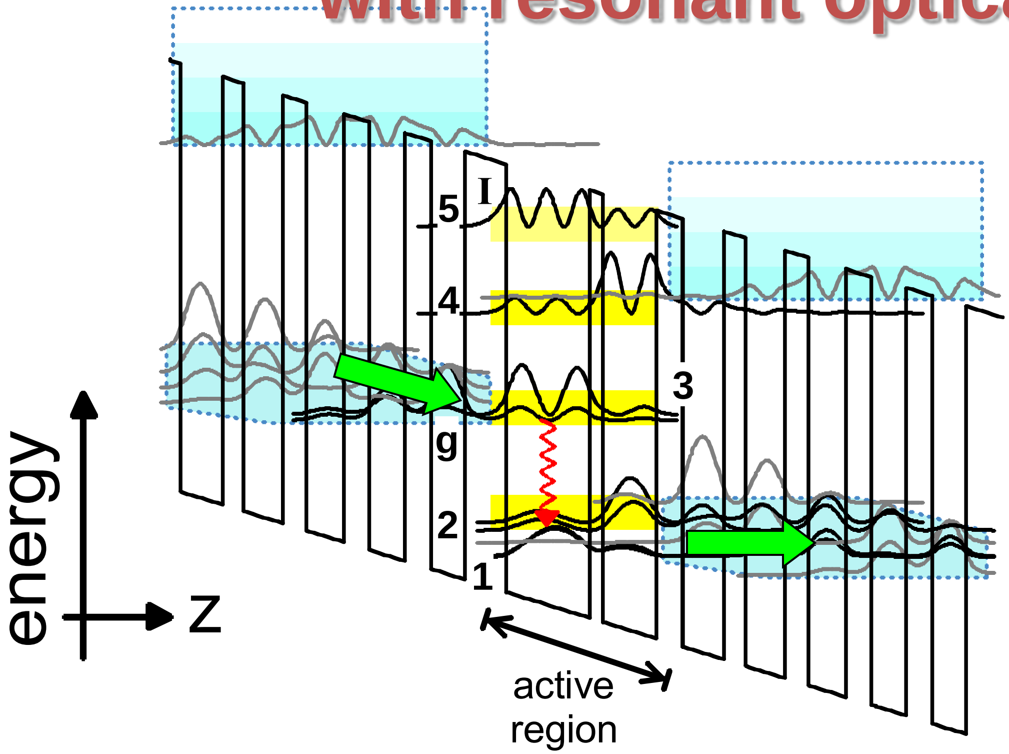
$$\left|\chi^{(2)}\right| \sim \frac{N_e d_{12} d_{13} d_{23}}{\hbar^2(\gamma_{12}^2 + \Delta_{12}^2)(\gamma_{13}^2 + \Delta_{13}^2)}$$

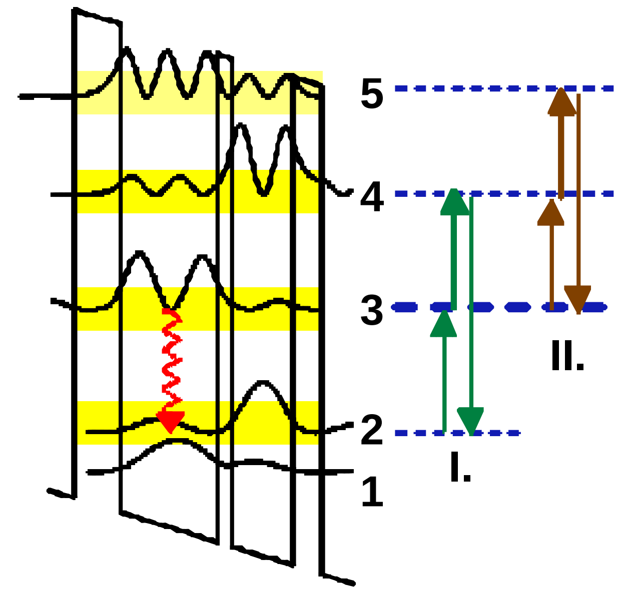
Solution: resonant nonlinear medium with gain

This leads to nonlinear semiconductor lasers

Belyanin et al. PRA 2001

Quantum-cascade lasers with resonant optical nonlinearities





Second harmonic generation

PRL 2003, APL 2004

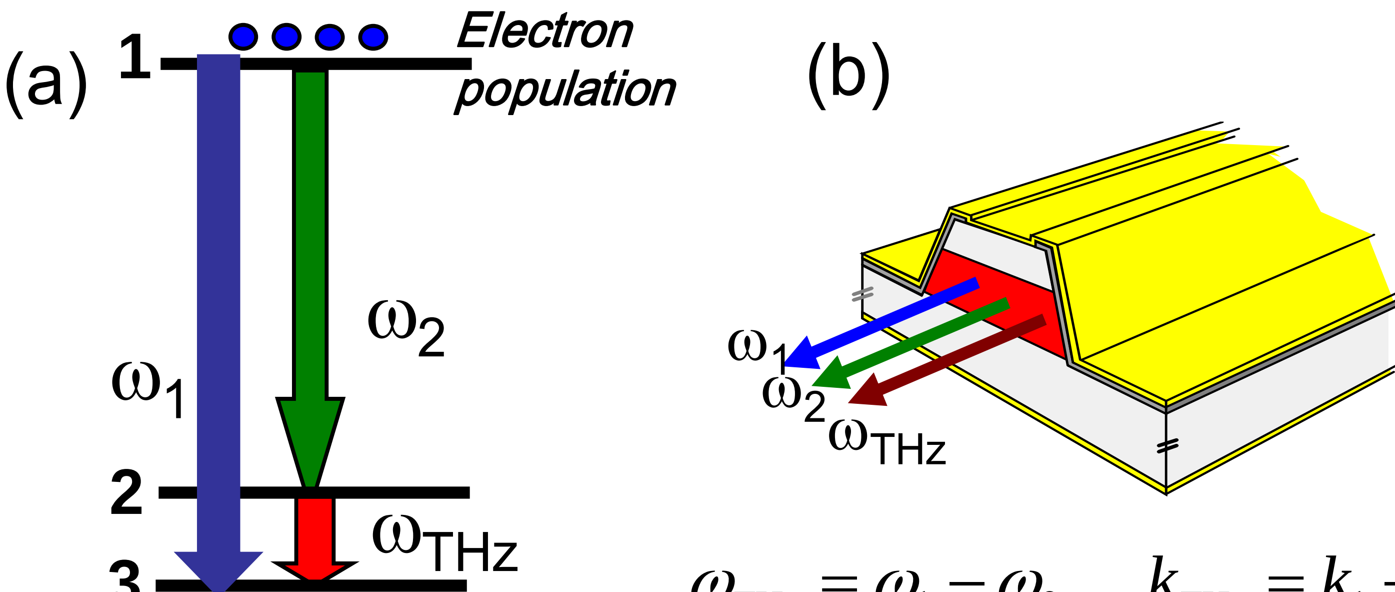
- Maximizing the product of dipoles $d_{23}d_{34}d_{24}$
- Quantum interference between cascades I and II

$\chi^{(2)}$ ~ 10^5 pm/V at ~ 7-9 μm laser wavelength

Milliwatt power in SHG:
O. Malis et al. EL 2004
Collaboration with F. Capasso and C. Gmachl

This is NOT sequential photon absorption/reemission

Room-temperature THz injection laser based on difference frequency generation in mid-IR QCLs



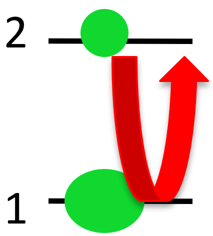
$$\omega_{THz} = \omega_1 - \omega_2, \quad k_{THz} = k_1 - k_2$$

Fig. 11. Schematics of the THz DFG process with population inversion in our devices (a) and the schematic view of the THz source based on intra-cavity DFG in dual-wavelength mid-IR QCL. The active region (shown in red) generates light output at mid-IR frequencies ω_1 and ω_2 through the laser action and light output at THz frequency ω_{THz} through the DFG process.

- Powerful mid-IR QCL emitting at two modes
- Strong nonlinearity for frequency mixing process
- Low-loss, phase-matched waveguide for all three modes

Collaboration with Capasso group:
Nature Phot. 2007, APL 2008 (with Faist)
Subsequent development by Belkin, Razeghi et al.
Similar ideas developed for interband diode lasers

Saturation nonlinearity



(b) two-level “atoms”

$$\ddot{d}_k + 2\gamma\dot{d}_k + \omega_k^2 d_k \approx -\frac{2\omega_k|\mu_k|^2}{\hbar}\Delta N_k E(r,t)$$

$$P = \frac{1}{V}\text{å}\, d_k$$

Population difference:

$$N_{k2} - N_{k1} = \Delta N_k$$

$$-1 \leq \Delta N_k \leq 1$$

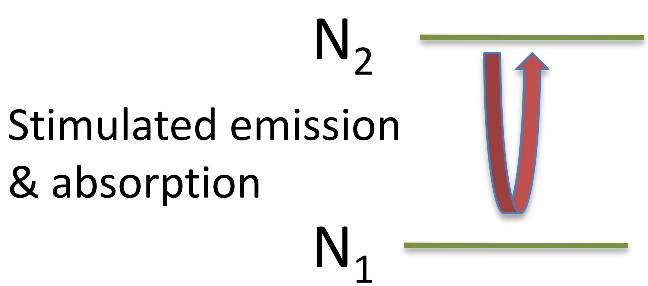
$$\frac{\partial \Delta N_k}{\partial t} = \frac{\Delta N_{eq} - \Delta N_k}{T_1} + \frac{2}{\hbar\omega_0}\frac{\partial d_k}{\partial t}E \quad \sim \vec{j}\vec{E} \sim -|E|^2$$

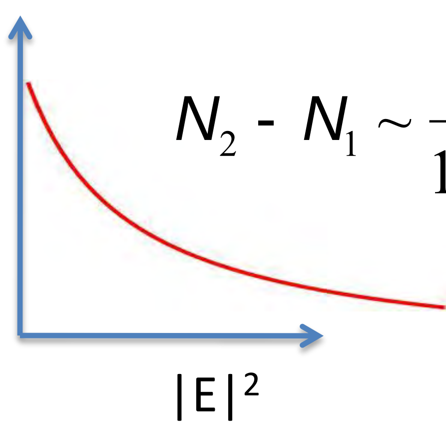
$T_{1:}$ relaxation time of ΔN_k

γ: relaxation rate of the polarization P

Saturation nonlinearity and its many faces

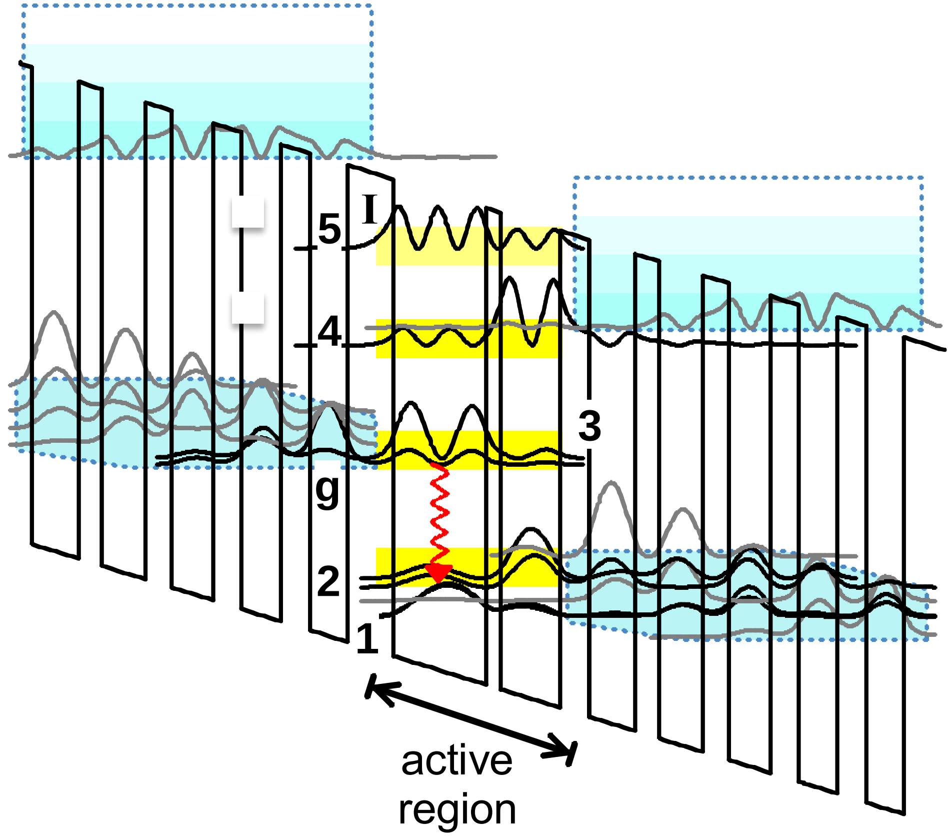
- Limits growth of the EM field and polarization
- Determines steady-state output power
- Couples different EM modes, leading to phase coupling and mode locking
- Determines laser response to fast modulation

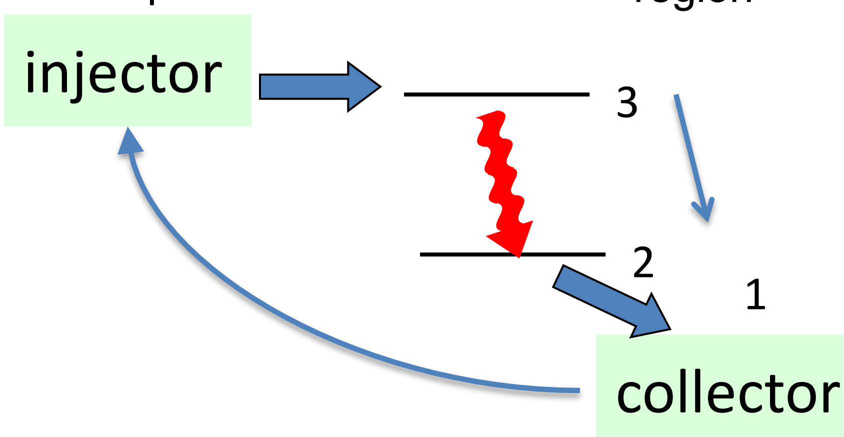




$$N_2 - N_1 \sim \frac{(N_2 - N_1)_{E=0}}{1 + (1/I_s)\sum E_m E_n}$$

Peculiarities of a QC laser

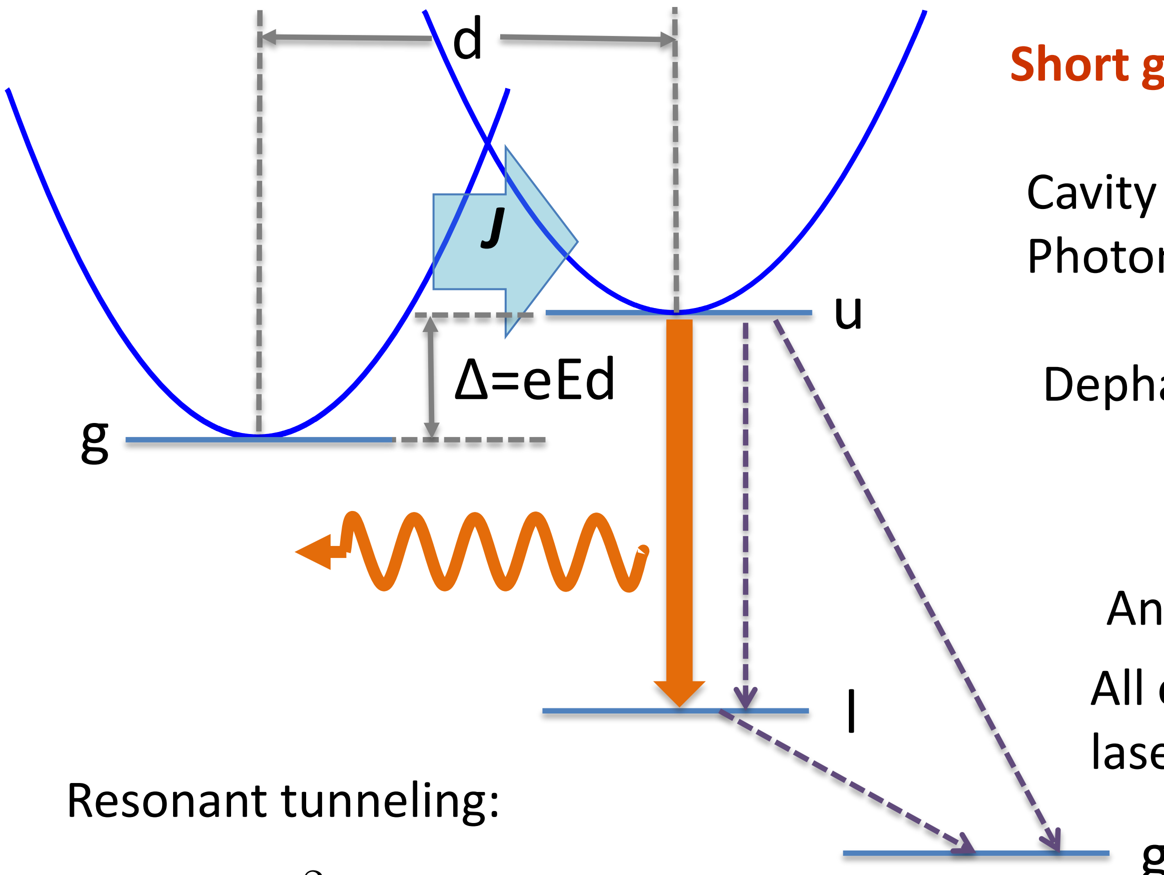




Pumping current is coupled with laser intensity (like in all injection lasers)

Unique combination of relaxation times

Simplest model of transport



Short gain relaxation time T_1~ 1 ps

Cavity roundtrip time T_{RT} ~ 50 ps
Photon lifetime T_p ~ 10 ps

Dephasing time T_2 ~ 0.1 ps

$$T_2 < T_1 << T_{r,c}$$

An overdamped Class-A laser!

All other solid-state and diode lasers are Class B: $T_2 << T_{RT,p} << T_1$

However, dynamical times can be of order T_2

$$\tau_D^{-2} \sim \frac{4\pi d^2 \omega \Delta N}{\hbar}; \Omega_R = \frac{dE}{\hbar}$$

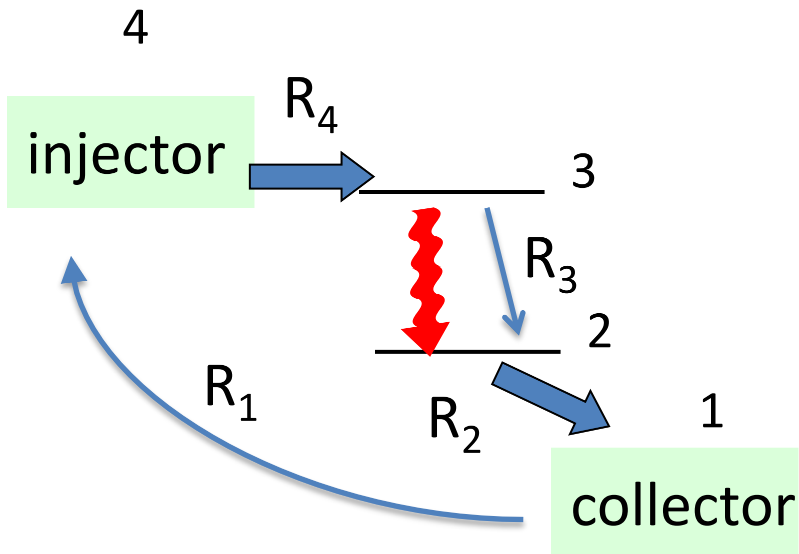
Resonant tunneling:

$$J = \frac{e\Omega^2\gamma}{\hbar(\Delta^2+\gamma^2)}\left(n_g e^{-|\Delta|/k_B T} - n_u\right)$$

$\gamma = 1/T_2 \sim 10^{13}\ s^{-1}$

- Before trying mode locking …
- Why not try something simpler:
  - gain switching or Q-switching?

For a quick check we can use a two-level model



$R_2 >> R_{1,3,4}$

Injector stays undepleted:

$N_1 \sim N_0 >> N_{2,3}$

$N_2 << N_3$

If we put $N_2 = 0$ (crude approximation)…

Reduces to two-level equations for population inversion $\Delta = N_3 - N_2$ and coherence

$$\frac{\partial \Delta}{\partial t} \approx -\frac{\Delta}{T_1} + R_1 - \frac{2\,\mathrm{Im}\left(dE\sigma^*\right)}{\hbar}$$

$$\frac{\partial \sigma}{\partial t} + \left(\frac{1}{T_2} + i(\omega_0 - \omega)\right) = -\frac{idE}{\hbar}\Delta$$

$$r_{32}(t) = s(t)\exp[-i w_0 t]$$

Effective gain recovery time:

$T_1 \sim 1/R_3 \sim 1$ ps

Single-mode laser
Small-signal modulation of gain or loss

$$\frac{\partial E}{\partial t} + \cancel{c\frac{\partial E}{\partial z}} + (\alpha/2)E = 2\pi i \omega N_0 d\sigma$$

Mean field (long pulses)

$$\cancel{\frac{\partial \sigma}{\partial t}} + \frac{\sigma}{T_2} = -\frac{idE}{\hbar}\Delta$$

Very short T_2

$$\frac{\partial \Delta}{\partial t} = r(\Delta_p - \Delta) - \frac{2\,\mathrm{Im}\left(dE\sigma^*\right)}{\hbar} \qquad r = \frac{1}{T_1} \qquad r\Delta_p \approx R_1 \propto j/e$$

Injection current

Rate equations for normalized number of photons M and inversion N normalized to CW lasing threshold:

$$\frac{dM}{dt} = -\alpha M + \alpha MN$$

$$\frac{dN}{dt} = r(N_p - N) - \alpha MN$$

Only three parameters are left:

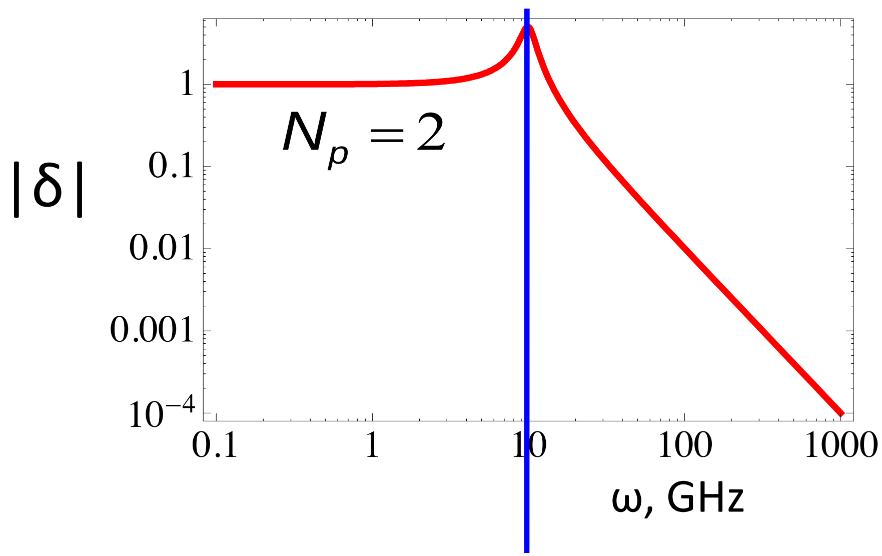
- Decay rate of photons α
- Relaxation rate of inversion *r*
- Inversion supported by pumping N_p

QCLs vs. other lasers

Diode lasers and other class B lasers: $r = \frac{1}{T_1} \sim 10^3 - 10^9 \ \mathrm{s}^{-1}; \ r << a$

Normalized amplitude of gain modulation:

$$d = \frac{ar(N_p - 1)}{ar(N_p - 1) + irN_p w - w^2}$$



$$w_{\max}^2 \approx w_r^2$$

Relaxation oscillations at

$$w_r^2 \equiv ar(N_p - 1)$$

Diode lasers: $w_r^2 = ar \frac{\partial g}{\partial n}\left(\frac{n}{n_{tr}} - 1\right)$

$$d_{\max} \sim \sqrt{\frac{a}{r}}$$

For loss modulation δ is higher:

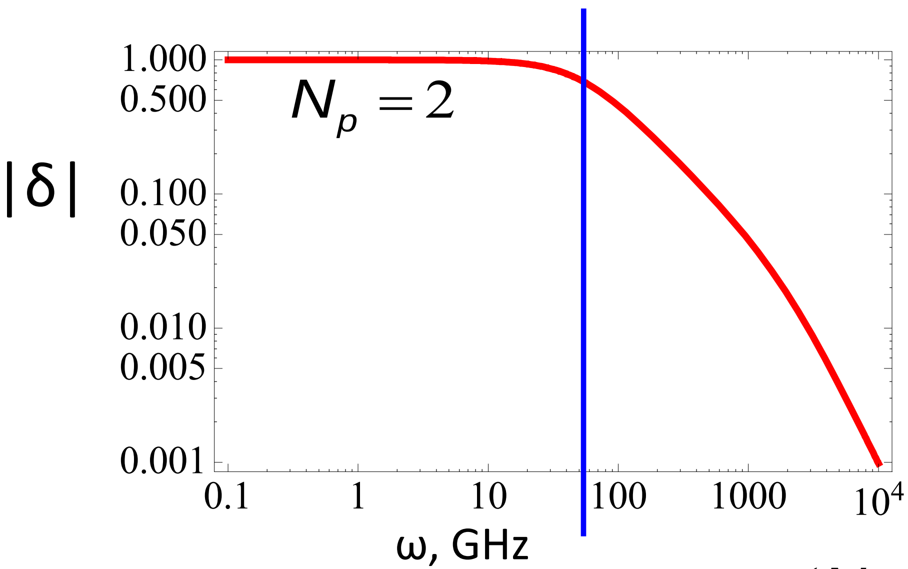
$$d_{\max} \sim \frac{a}{r}$$

QCLs vs. other lasers

$$\delta = \frac{\alpha\rho(N_p - 1)}{\alpha\rho(N_p - 1) + i\rho N_p \omega - \omega^2}$$

QCLs: $\rho \sim 10^{12}\ \mathrm{s}^{-1} >> \alpha \sim 10^{11}\ \mathrm{s}^{-1}$

Overdamped relaxation oscillations

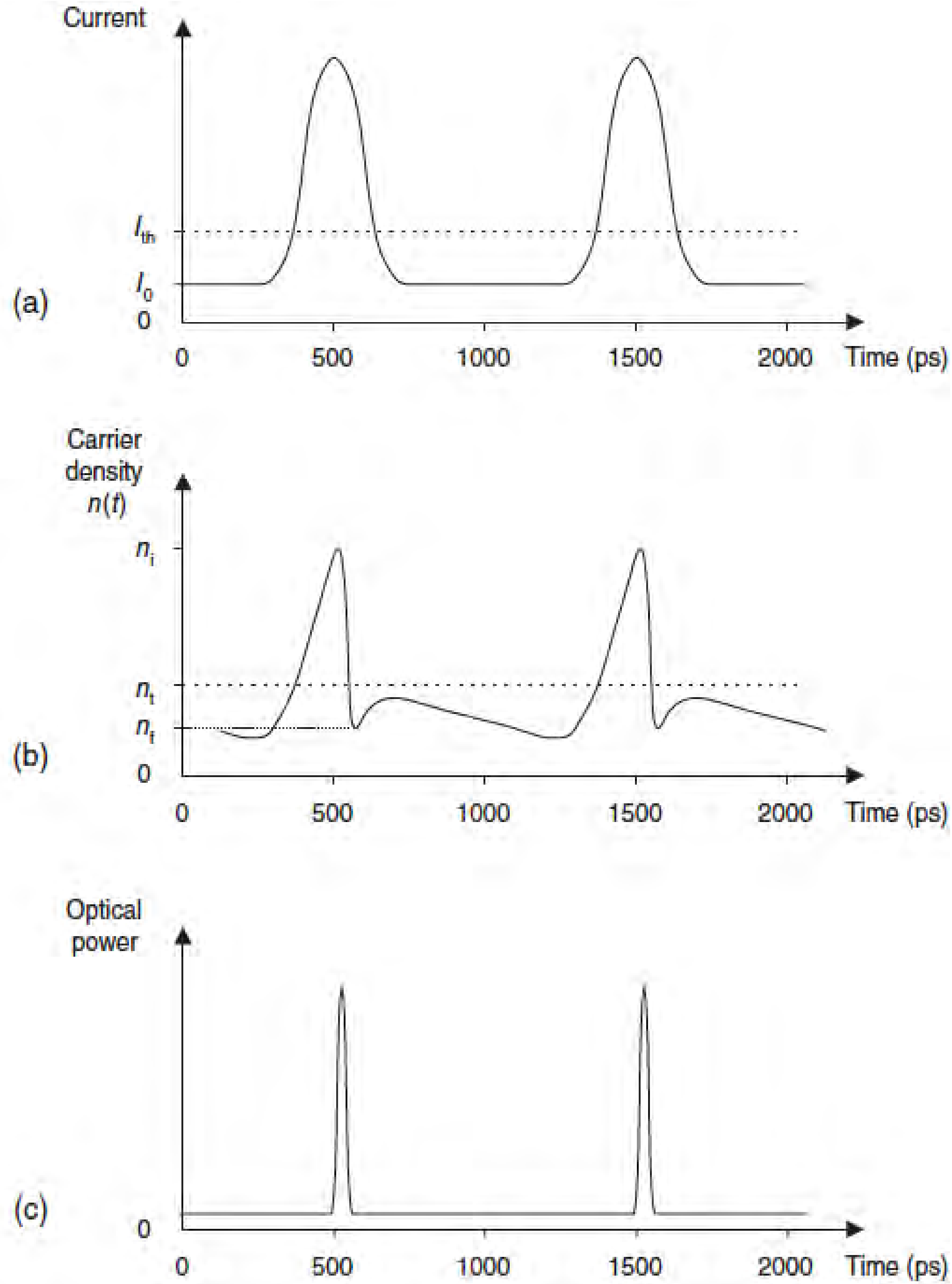


$$\omega_{\max} \approx \alpha(N_p - 1)/N_p$$

Inertia is mostly due to photon decay

Gain modulation is no problem

Maximum modulation rate ~ 10^{11} s^{-1}



Large-amplitude gain modulation

It works for diode lasers

It won’t work in QCLs

Gain won’t overshoot CW value by much

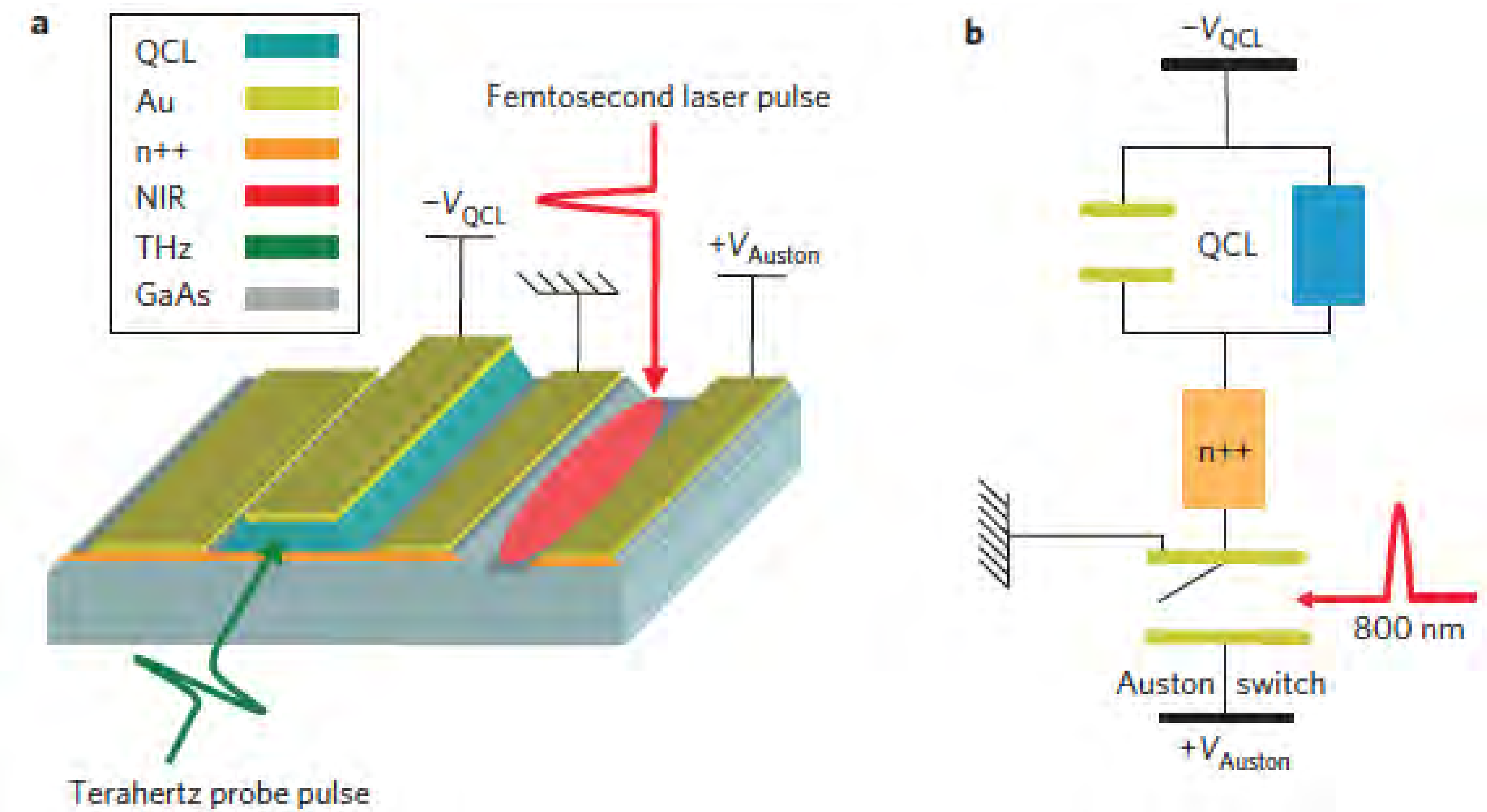
Peak power will be low

Optical pulses will be as long as current pulses

Pumping with ps current pulses??

Picture: P. Vasiliev, Rep. Prog. Phys. 2000

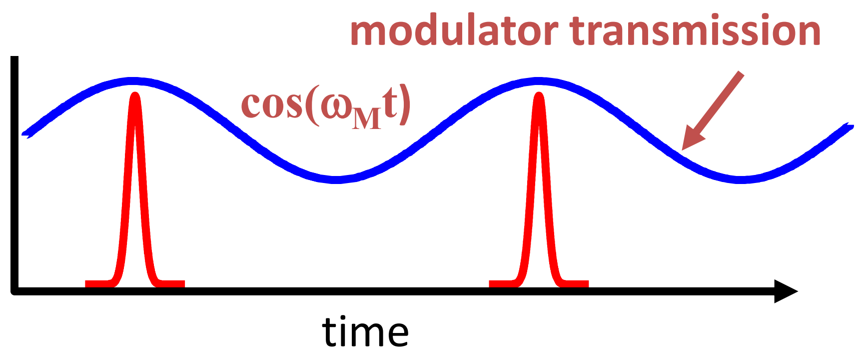
Generation of THz transients using integrated Auston switch in THz QC amplifiers



Jukam et al. Nature Phot. 2009

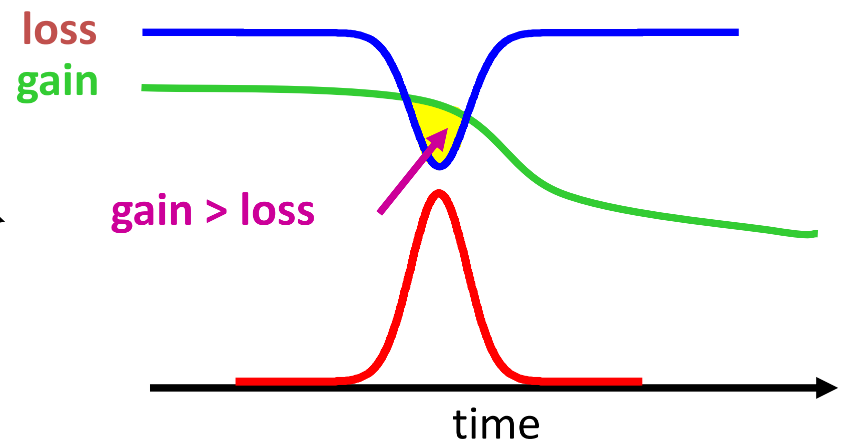
Mode locking

Resonantly or parametrically pumps energy into the laser pulse by periodic (self-) modulation of some parameter



Active mode-locking

Passive mode-locking

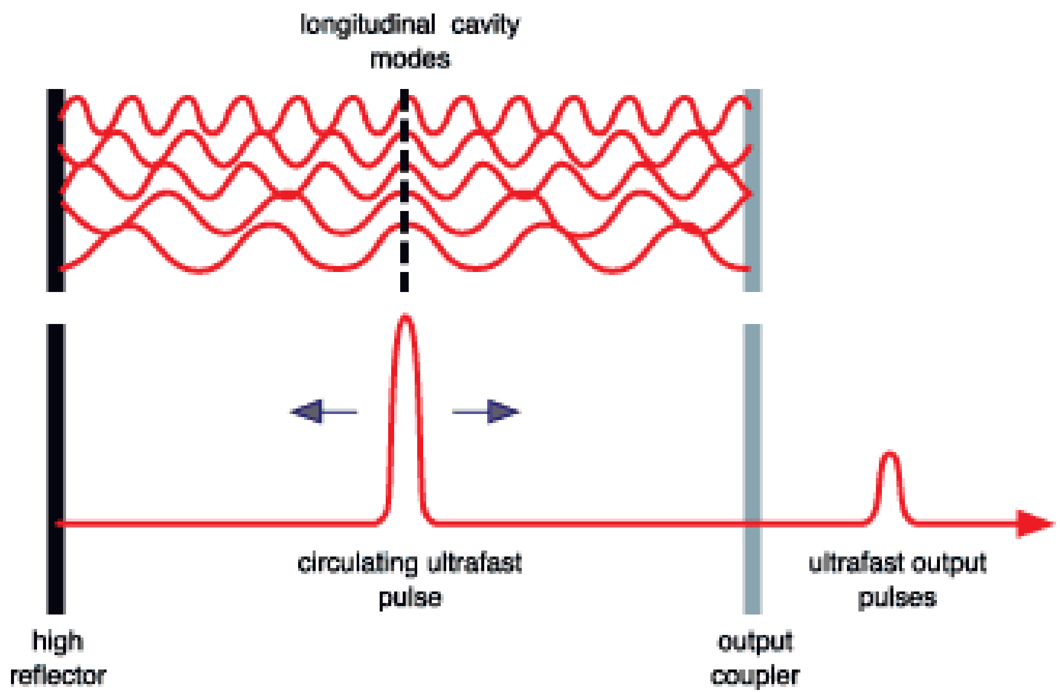


Pictures from Rick Trebino slide

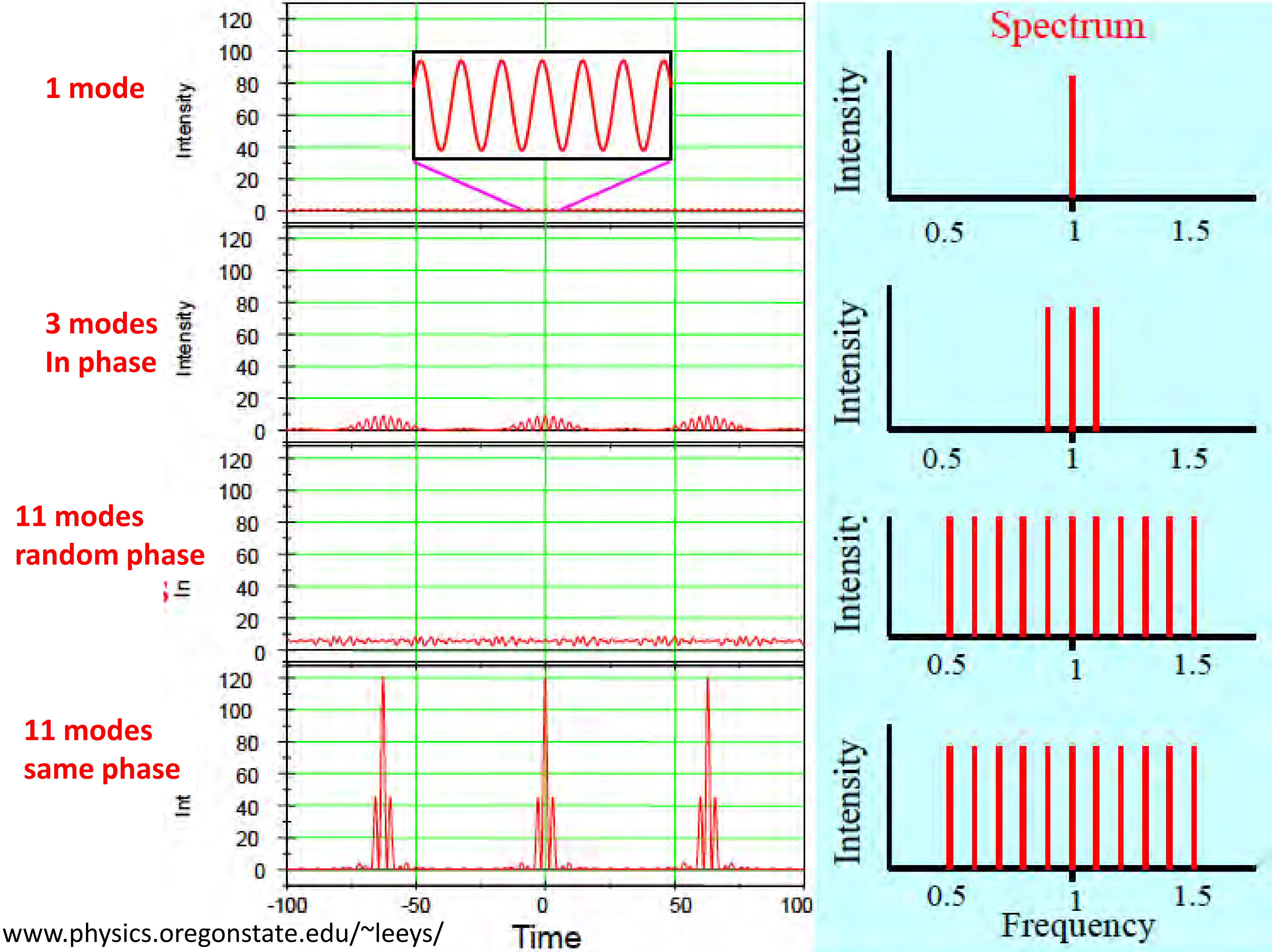
Space-time approach: circulating ultrashort pulse *E(t,z)*

Spectral (modal) approach: field as superposition of modes with equidistant frequencies and deterministic phase relationship

$$E(t,z)=\sum_m E_m(z)e^{i(\omega_m t+\phi_m)}+\text{c.c.}$$



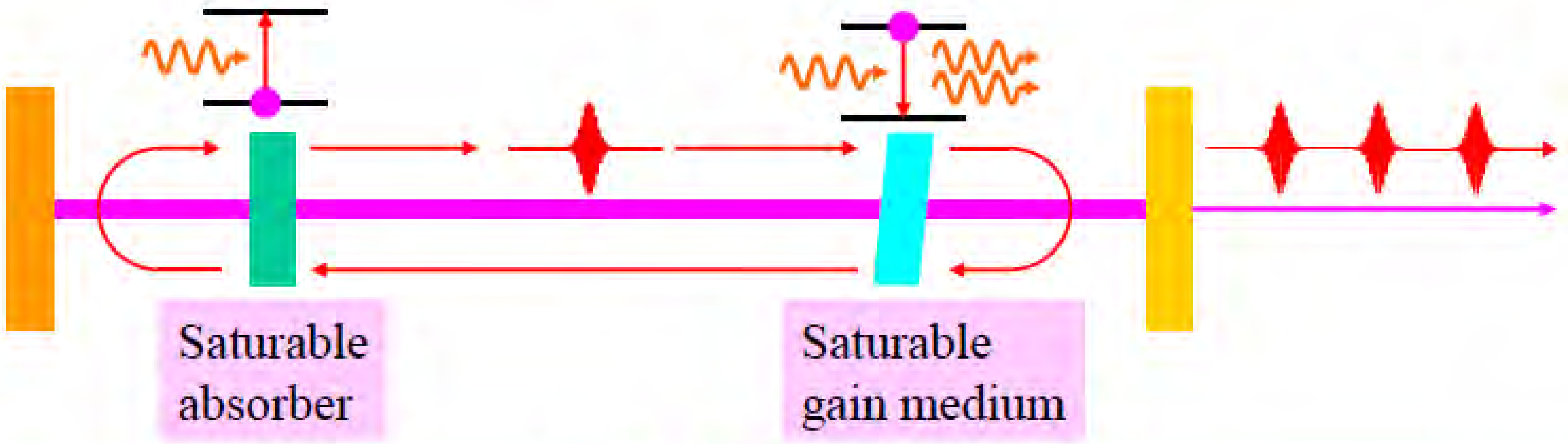
http://spie.org/x17070.xml

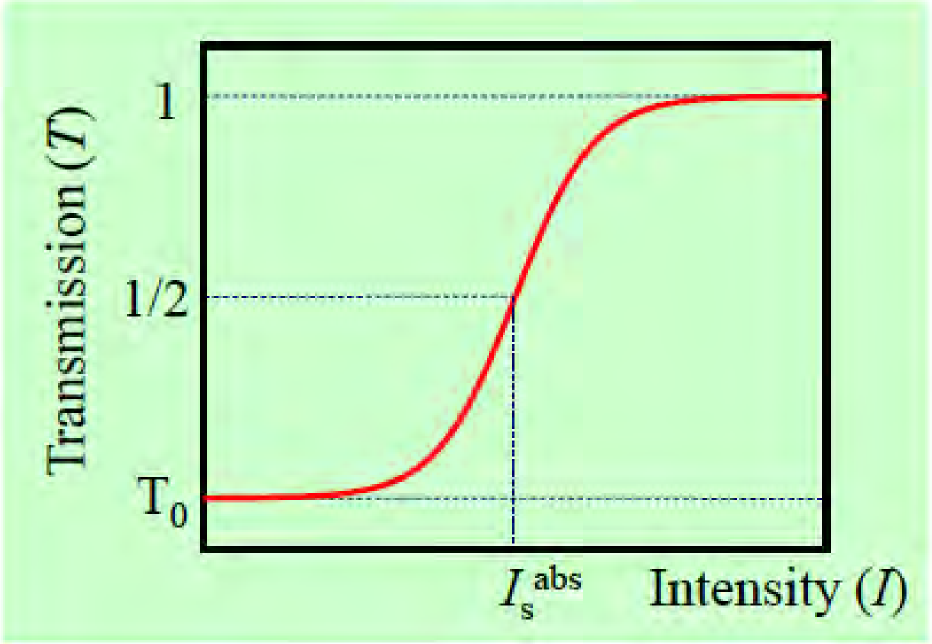


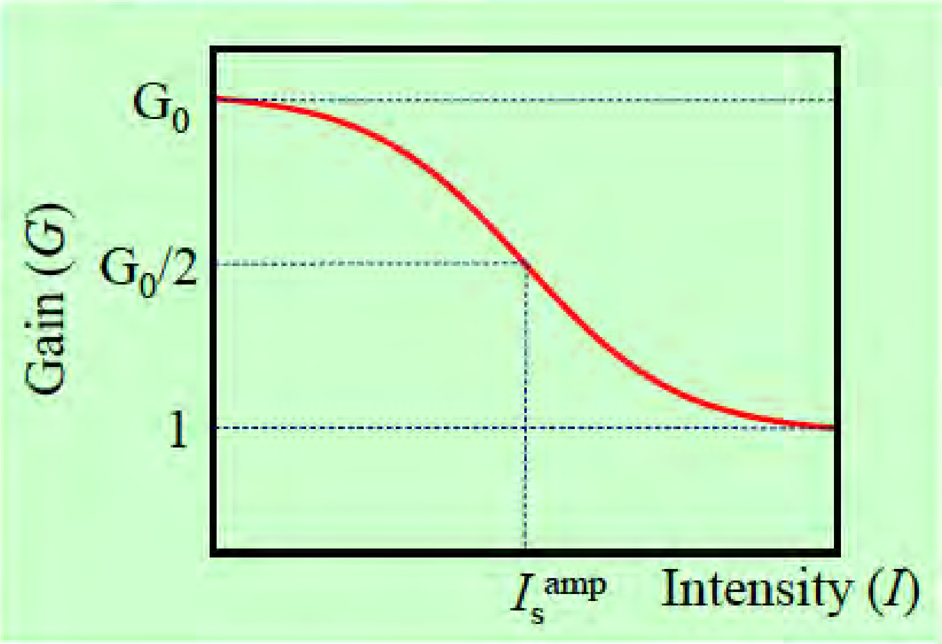
www.physics.oregonstate.edu/~leeys/

- How to achieve *stable* mode locking and pulse formation?
- How to make pulsed operation self-starting?
- Is it possible to get mode-locked pulses from QCLs?

Passive mode-locking







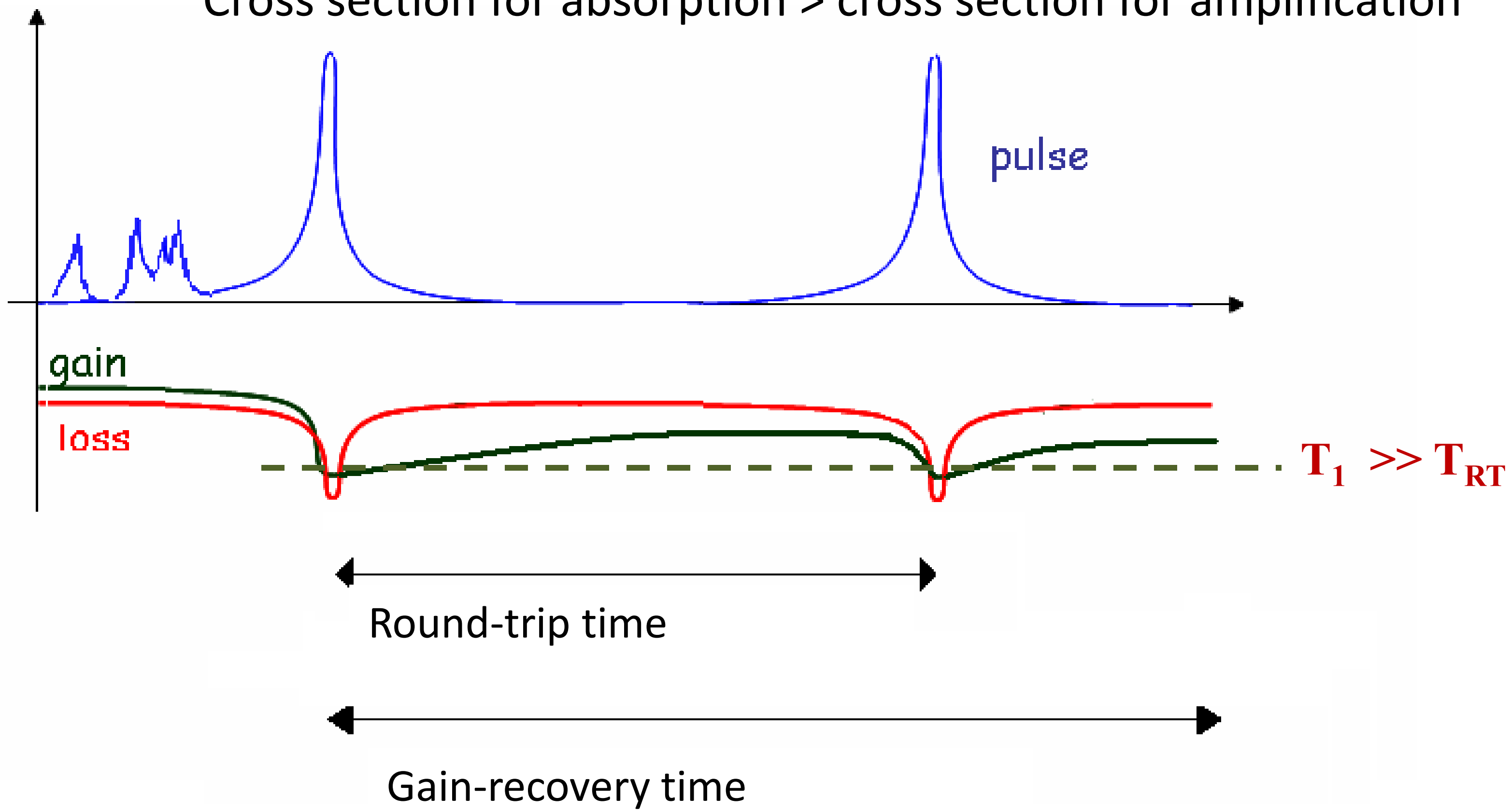
www.physics.oregonstate.edu/~leeys/

Conditions for stable passive mode locking:

gain recovery time $T_1 \gtrapprox T_{RT} = 2nL_c/c$

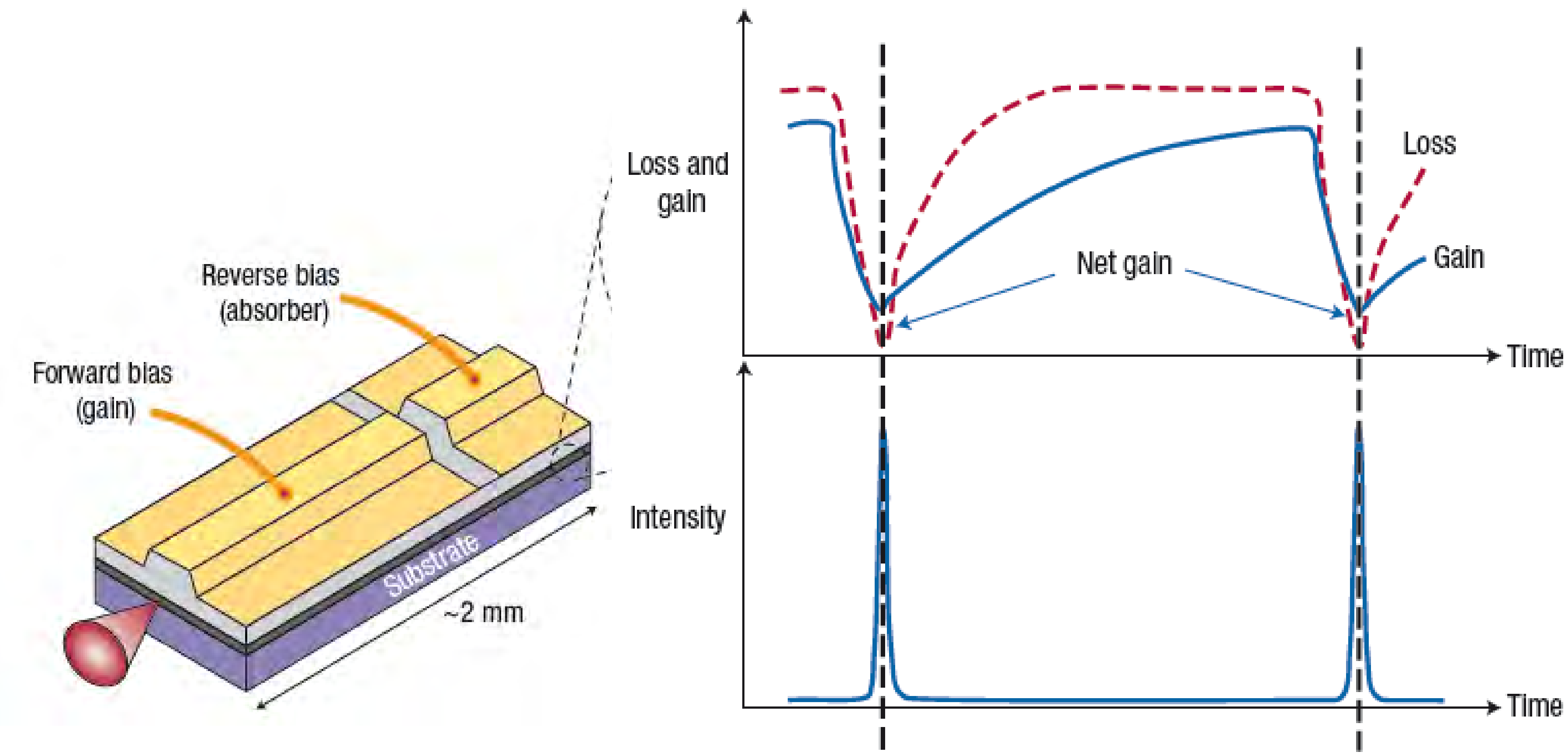
Gain should stay saturated below losses except the peak of the pulse when absorption is saturated

Cross section for absorption > cross section for amplification



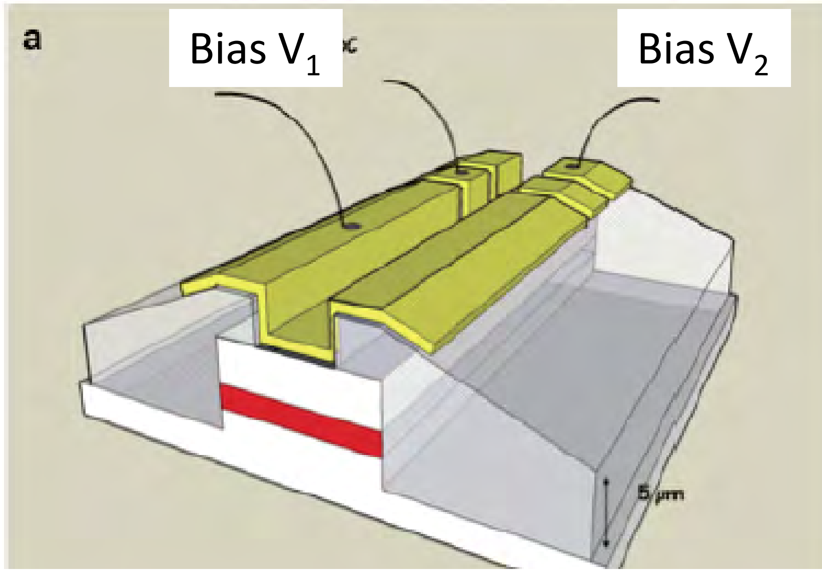
Picture from Pietro Malara's slide

Passive mode locking works well in diode lasers



Rafailov Nature Phot. 2007

Saturable absorption in QCLs



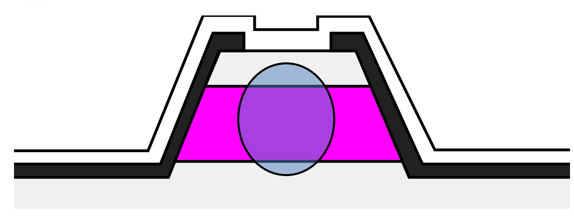
Multi-section cavity

One section serves as saturable absorber

However all of this does not matter …

Loss self-modulation due to Kerr effect:

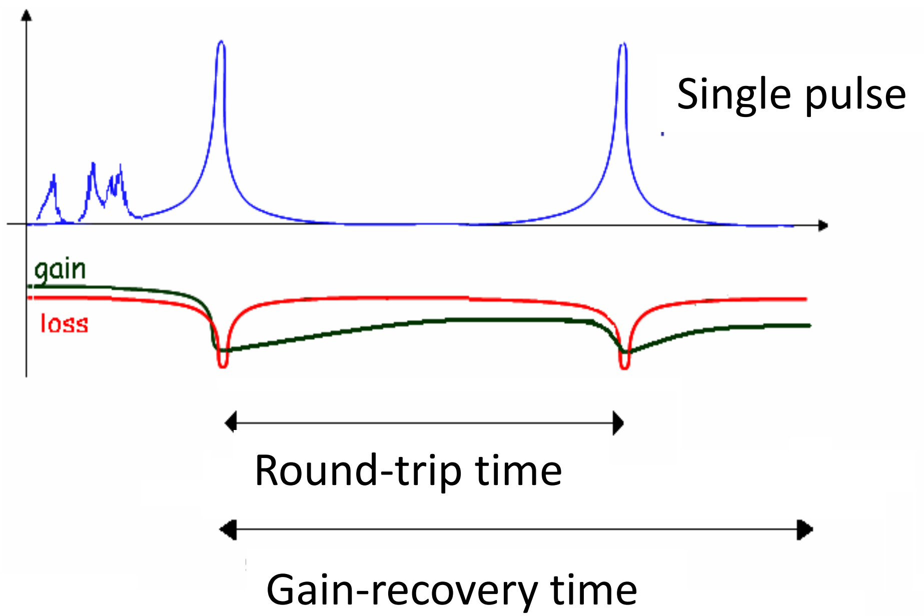
$n = n_0 + n_2 I$

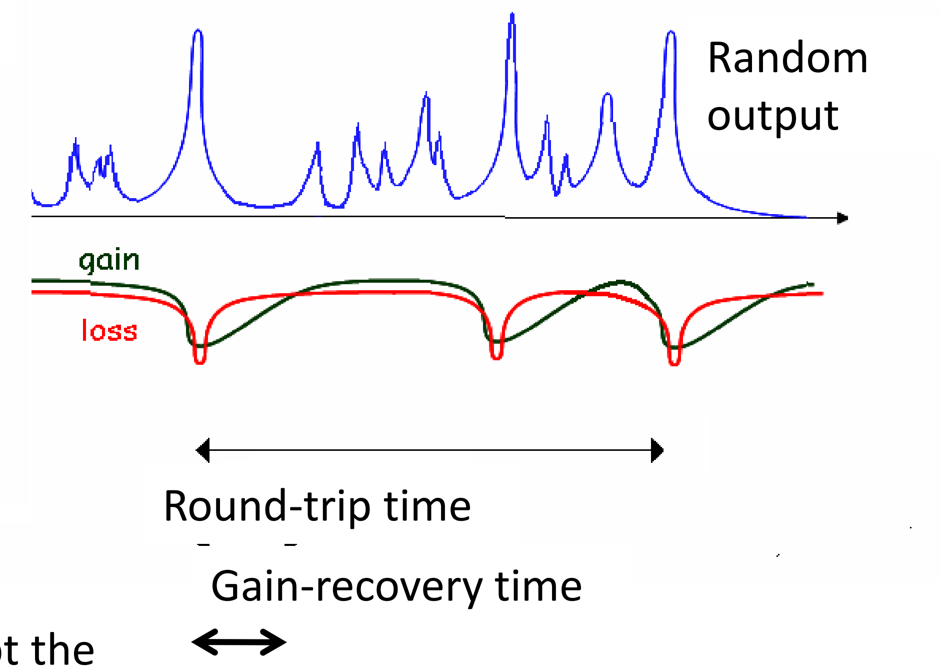


To achieve stable mode locking:

gain recovery time > roundtrip time = $2nL_c/c$

In QCLs this condition is not fulfilled



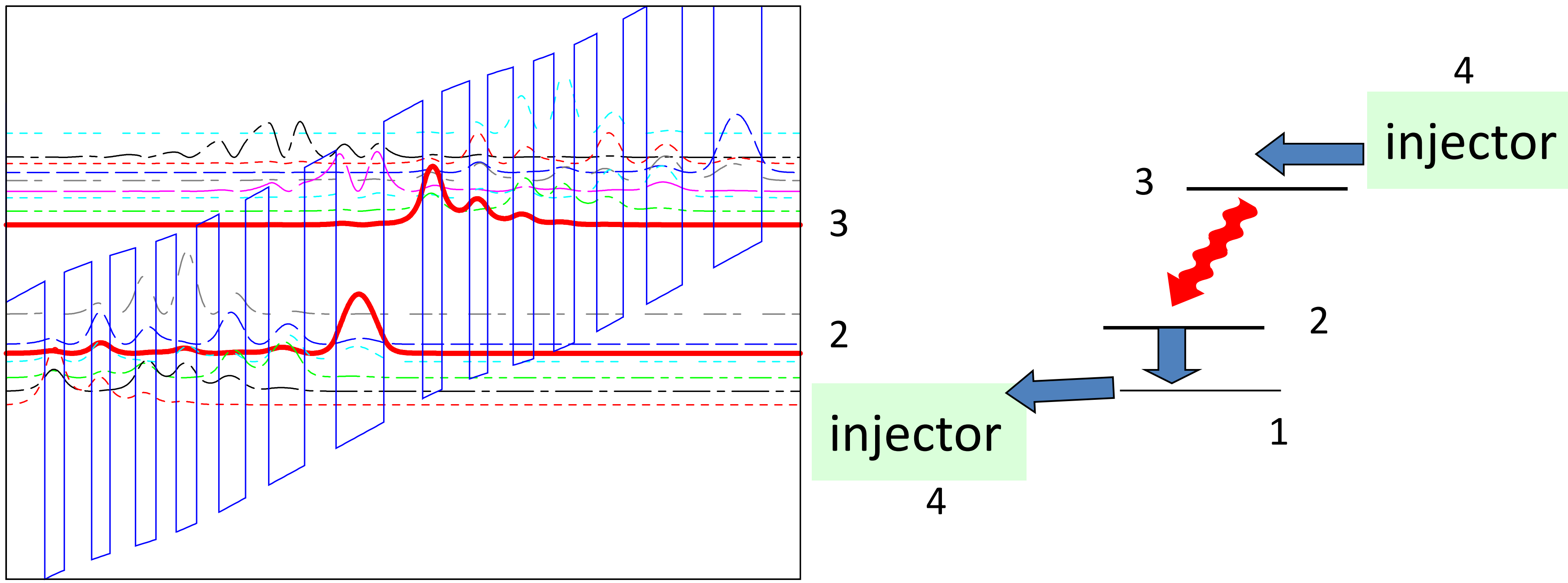


Gain should stay saturated below losses except the peak of the pulse when absorption is saturated

Picture from Pietro Malara’s slide

Making T_1 longer

Laser transition: superdiagonal



Calculated upper state lifetime ~50 ps
Confirmed by T. Norris measurements

No passive mode locking observed so far

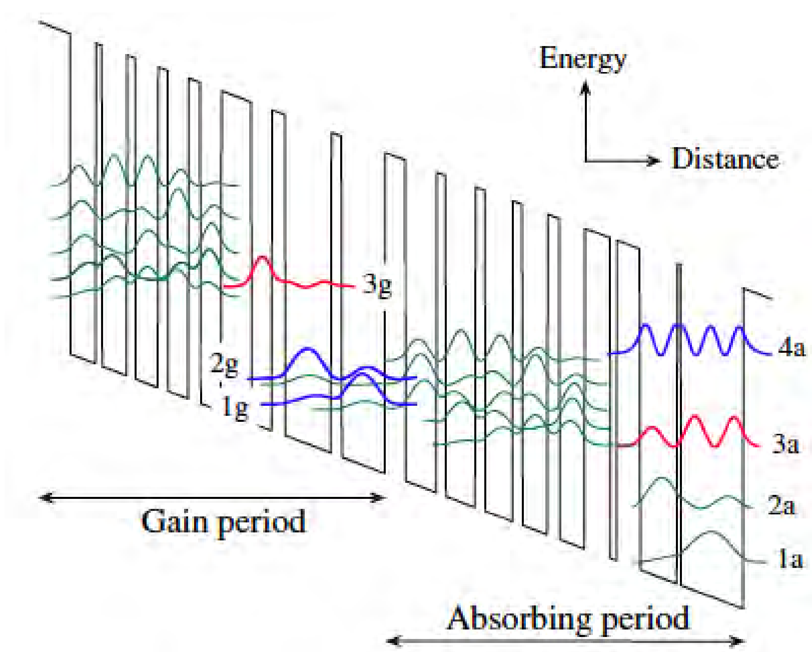
Fast components in gain recovery?

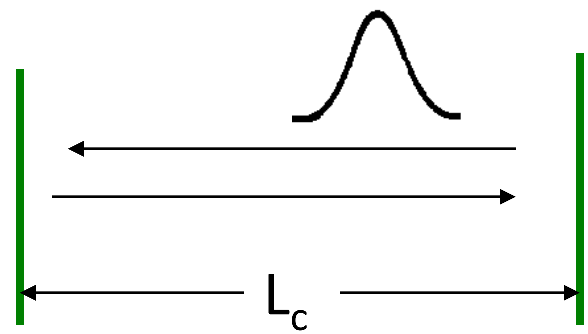
Not enough saturable absorption?

Capasso group 2008

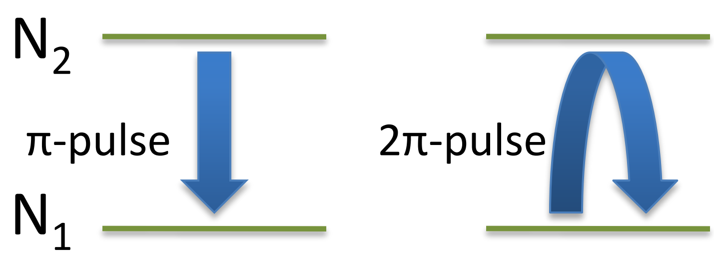
Self-induced transparency mode locking

Short T_1 is an advantage!





Mode-locked pulse is a π-pulse in the gain region and 2π-pulse in the absorbing region

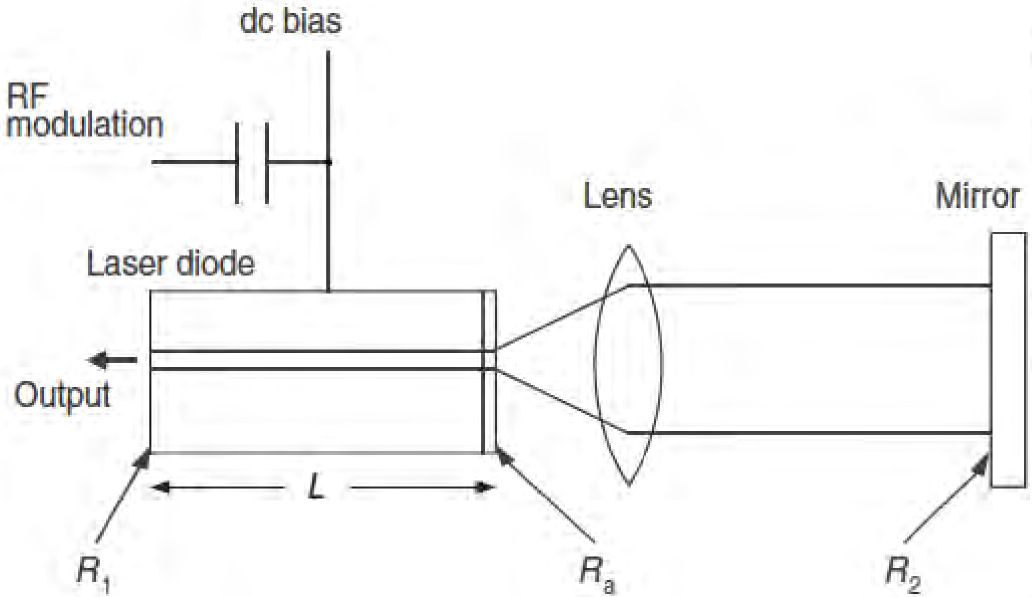


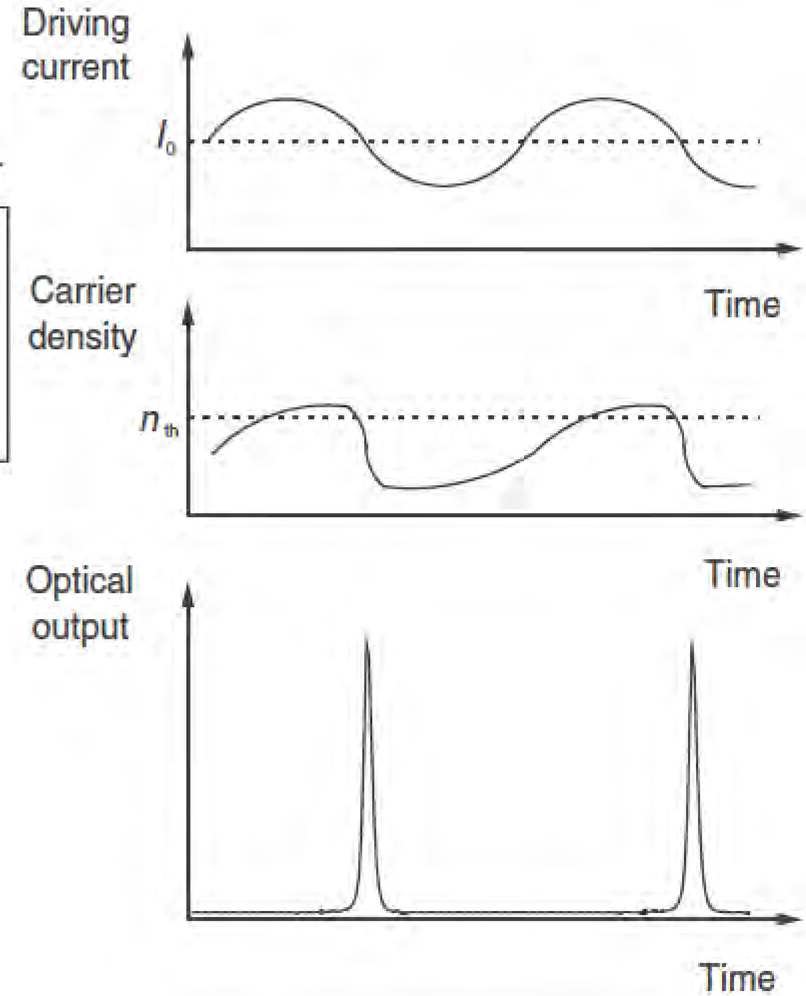
Letokhov 1969, Kozlov PRA 1997
Menyuk et al. PRL 2009

Laser does not self-start; requires injection of ~ 1 ps pulse

So we are left with active mode locking

Typical active mode locking scheme of diode lasers





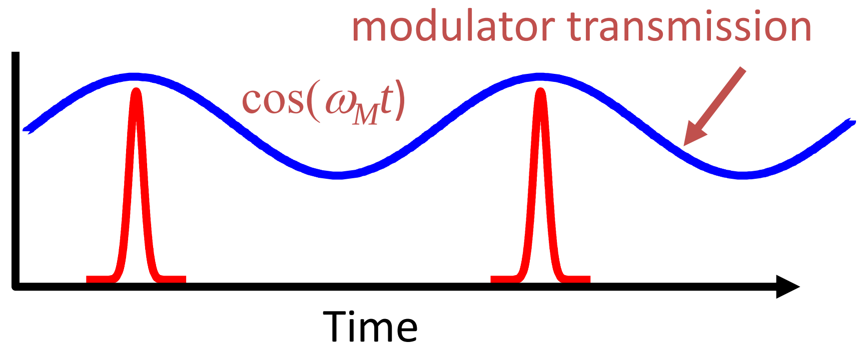
Modulation of gain at the round-trip frequency

Gain window is opened for a short time

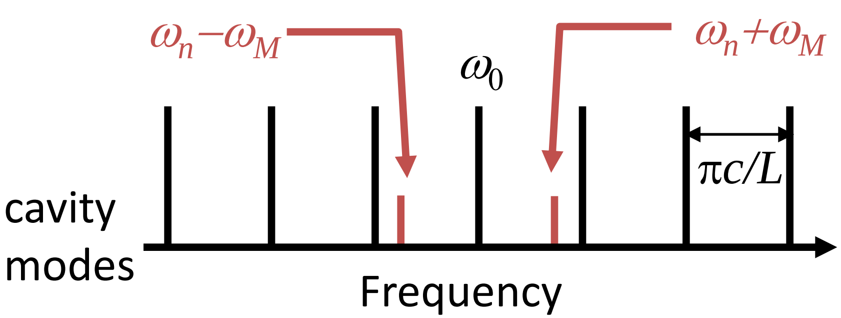
Shortest pulse duration ~ 0.1 ps

P. Vasiliev, Rep. Prog. Phys. 2000

Active mode-locking



In the frequency domain, a modulator introduces side-bands of every mode.



For mode-locking, make sure that ω_M is close to mode spacing.
This means that:
ω_M = 2π/cavity round-trip time
= $2\pi/(2nL/c) = \pi c/nL$

Modes proliferate until dispersion moves them out of resonance
In a multi-mode regime each mode competes for gain with adjacent modes and is phase-coupled to them.
Can they be phase locked with favorable phases to form stable pulses?

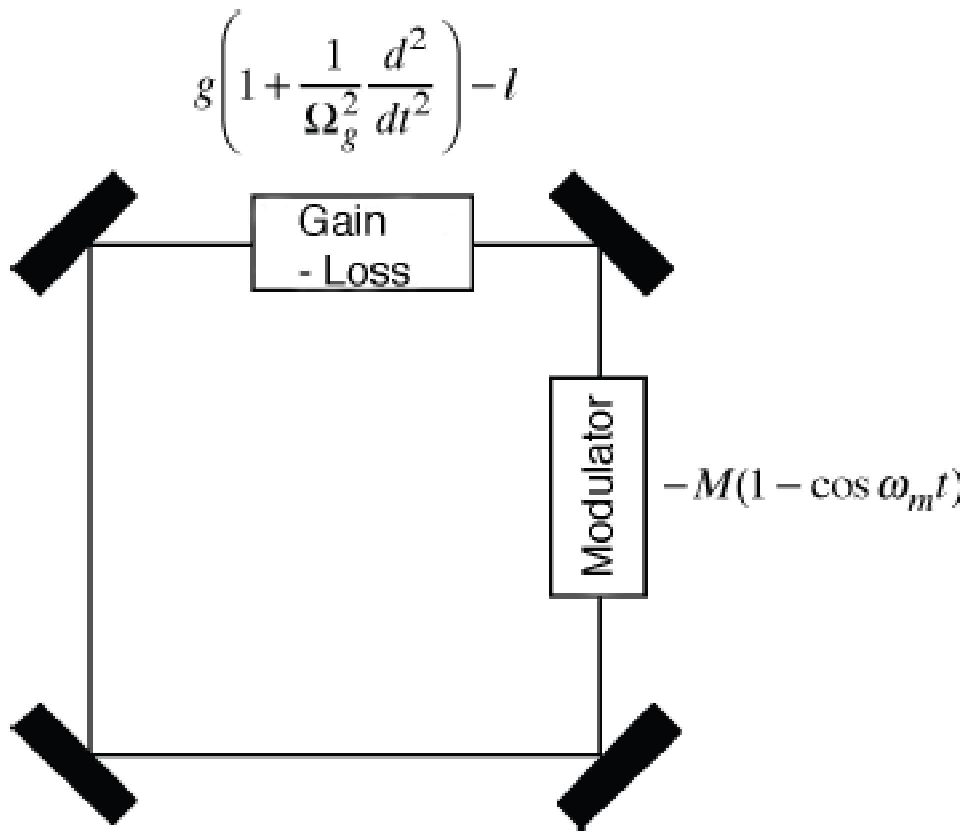
Pictures from Rick Trebino slides

Simplest model in the time domain: Haus’ master equation

1) Assumes small change in gain, loss, and modulation per round-trip
2) Very short gain, loss, etc. elements: no propagation effects
Poor assumptions for semiconductor lasers

No change per round-trip:

$$T_R \frac{\partial A(T,t)}{\partial T} = \sum_i \Delta A_i = 0$$



Picture and formulas (originally by Haus) from U. Keller’s lecture:
http://www.ulp.ethz.ch/education/ultrafastlaserphysics/7_Active_modelocking.pdf

Gain element

$$g(\omega) = \frac{g(z)L_g}{1 + \left[{2(\omega - \omega_0)}/{\Delta\omega_g} \right]^2} = \frac{g}{1 + \left[{(\omega - \omega_0)}/{\Omega_g} \right]^2} \approx g\left(1 - \frac{(\omega - \omega_0)^2}{\Omega_g^2}\right)$$

$$\exp\left[g(\omega)\right]\tilde{A}(\omega) \approx \left[1 + g\left(1 - \frac{\Delta\omega^2}{\Omega_g^2}\right)\right]\tilde{A}(\omega) = \left[1 + g - \frac{g}{\Omega_g^2}\Delta\omega^2\right]\tilde{A}(\omega)$$

$$\Delta A_1 = g\left(1 + \frac{1}{\Omega_g^2}\frac{d^2}{dt^2}\right)A(T,t)$$

http://www.ulp.ethz.ch/education/ultrafastlaserphysics/7_Active_modelocking.pdf

Modulator

$$A_{out}(t) = \exp\left[-M\left(1-\cos\omega_m t\right)\right]A_{in}(t)$$

$$A_{out}(t) \approx \left[1-M\left(1-\cos\omega_m t\right)\right]A_{in}(t)$$

$$\Rightarrow\ \Delta A_2 = A_{out}(t) - A_{in}(t) \approx -M\left(1-\cos\omega_m t\right)A_{in}(t)$$

http://www.ulp.ethz.ch/education/ultrafastlaserphysics/7_Active_modelocking.pdf

Master equation

$$T_R \frac{\partial A(T,t)}{\partial T} = \left[g\left(1 + \frac{1}{\Omega_g^2}\frac{d^2}{dt^2}\right) - l - M\left(1 - \cos\omega_m t\right)\right] A(T,t)$$

parabolic approximation:

$$M\left(1 - \cos\omega_m t\right) \approx M\frac{\omega_m^2 t^2}{2}$$

Schrödinger equation for harmonic oscillator

Solution: $$A_n(t) = \sqrt{\frac{W_n}{2^n\sqrt{\pi}\,n!\,\tau}} H_n\left(\frac{t}{\tau}\right) e^{-t^2/2\tau^2}$$

Hermite polynomial of grade *n*, $H_0 = 1$:

$$\tau = \sqrt[4]{\frac{D_g}{M_s}} \longrightarrow \tau_p = 1.66\tau = 1.66 \times \sqrt[4]{\frac{2g}{M}}\sqrt{\frac{1}{\omega_m \Omega_g}} = 0.445 \times \sqrt[4]{\frac{g}{M}}\sqrt{\frac{1}{f_m \Delta f_g}}$$

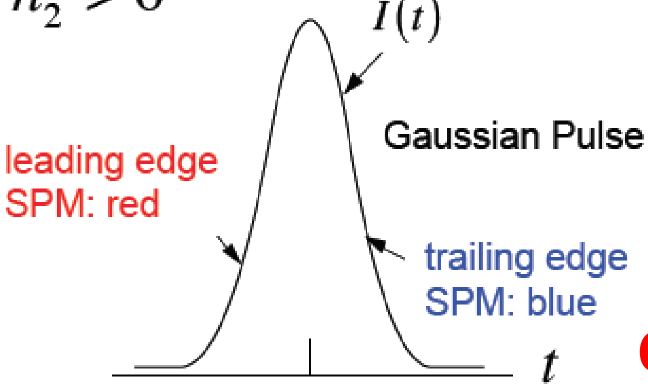
gain dispersion parameter: $D_g = \frac{g}{\Omega_g^2}$

curvature of the loss modulation: $M_s = \frac{M\omega_m^2}{2}$

There is nothing in this solution which requires a long gain relaxation time

Adding self-phase modulation

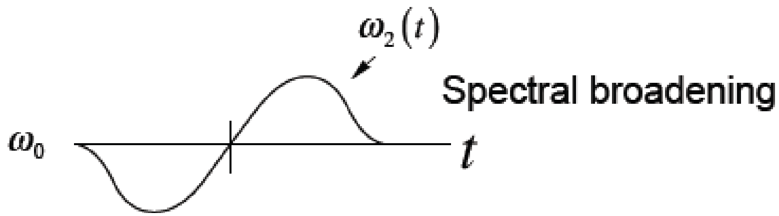
$n_2 > 0$



$$\phi_2(t) = -kn_2 I(t) L_K = -kn_2 L_K |A(t)|^2 \equiv -\delta |A(t)|^2$$

$$\delta \equiv kn_2 L_K$$

Chirped Gaussian pulse



$$\omega_2(t) = \frac{d\phi_2(t)}{dt} = -\delta \frac{dI(t)}{dt}$$

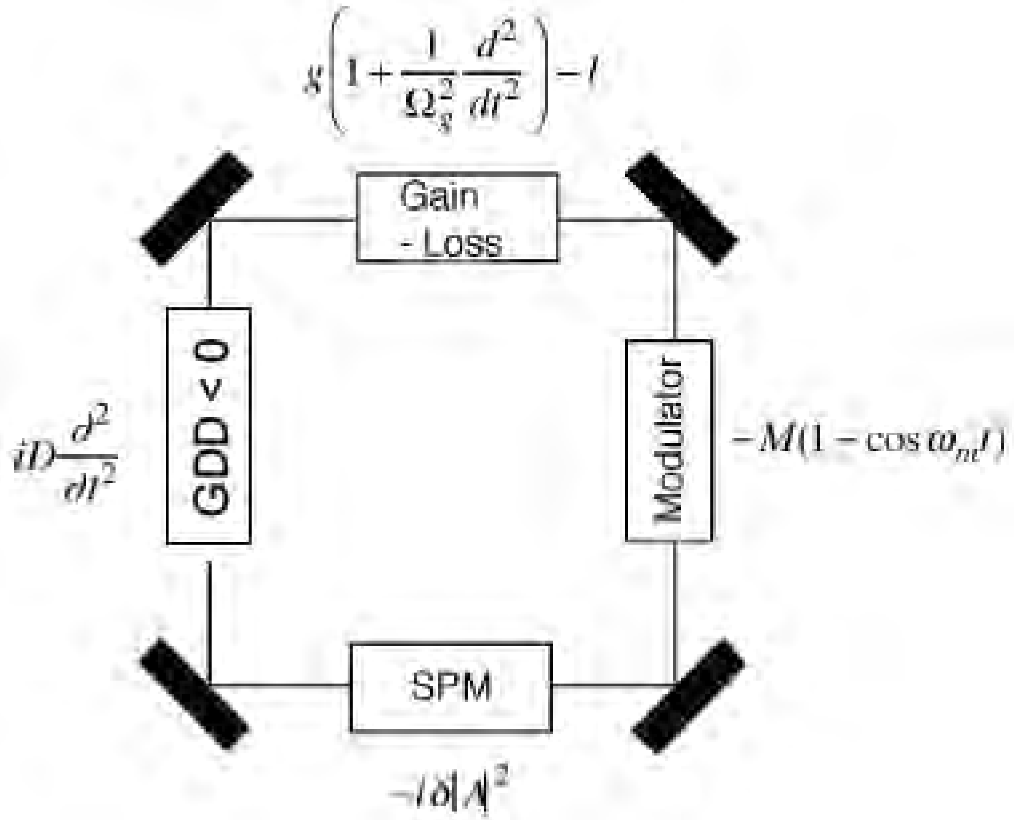
$$E(L_K, t) = A(0,t)\exp\left[i\omega_0 t + i\phi(t)\right] = A(0,t)\exp\left[i\omega_0 t - ik_n(\omega_0)L_K - i\delta|A(t)|^2\right]$$

$$A(L_K, t) = e^{-i\delta|A|^2} A(0,t) e^{-ik_n(\omega_0)L_K} \xrightarrow{\delta|A|^2 \ll 1} \approx \left(1 - i\delta|A(t)|^2\right) A(0,t) e^{-ik_n(\omega_0)L_K}$$

$$\Delta A_{SPM} \approx -i\delta|A(T,t)|^2$$

http://www.ulp.ethz.ch/education/ultrafastlaserphysics/7_Active_modelocking.pdf

Adding second-order (group-delay) dispersion



$$T_R\frac{\partial}{\partial T}A(T,t)=\left(iD\frac{\partial^2}{\partial t^2}-i\delta|A(T,t)|^2\right)A(T,t)+\left(g-l+D_g\frac{\partial^2}{\partial t^2}-M(1-\cos\omega_m t)\right)A(T,t)=0$$

nonlinear Schrödinger equation

http://www.ulp.ethz.ch/education/ultrafastlaserphysics/7_Active_modelocking.pdf

Group delay dispersion

$$\tilde{A}(z,\Delta\omega) = \tilde{A}(0,\Delta\omega)\, e^{-i\Delta k_n z} = \tilde{A}(0,\Delta\omega)\, e^{-i[k_n(\omega_0+\Delta\omega)-k_n(\omega_0)]z}$$

$$k_n(\omega) - k_n(\omega_0) \cong +k_n'\Delta\omega + \frac{1}{2}k_n''\Delta\omega^2 + \dots$$

$$\tilde{A}(z,\Delta\omega) \cong \tilde{A}(0,\Delta\omega)\, exp\left(-i\frac{1}{2}k_n''\Delta\omega^2\right) \xrightarrow{k_n''\Delta\omega^2 << 1} \approx \tilde{A}(0,\Delta\omega)\left[1 - i\frac{1}{2}k_n''\Delta\omega^2\right]$$

$$\Delta\tilde{A}_{GDD}(\Delta\omega) \approx -i\frac{1}{2}k_n''\Delta\omega^2\tilde{A}(\Delta\omega) \equiv -iD\Delta\omega^2\tilde{A}(\Delta\omega)$$

$$D \equiv \frac{1}{2}k_n''$$

$$\omega \Leftrightarrow -i\frac{\partial}{\partial t}$$

$$\omega^2 \Leftrightarrow -\frac{\partial^2}{\partial t^2} = \left(-i\frac{\partial}{\partial t}\right)^2$$

Fourier transformation: $-\Delta\omega^2 \rightarrow \frac{\partial^2}{\partial t^2}$

$$\Delta A_{GDD} \approx iD\frac{\partial^2}{\partial t^2}$$

Leads to pulse spreading
Can be compensated by nonlinearity
Stable solitons are possible

$$\tau = \frac{4|D|}{\delta \cdot e_p}$$

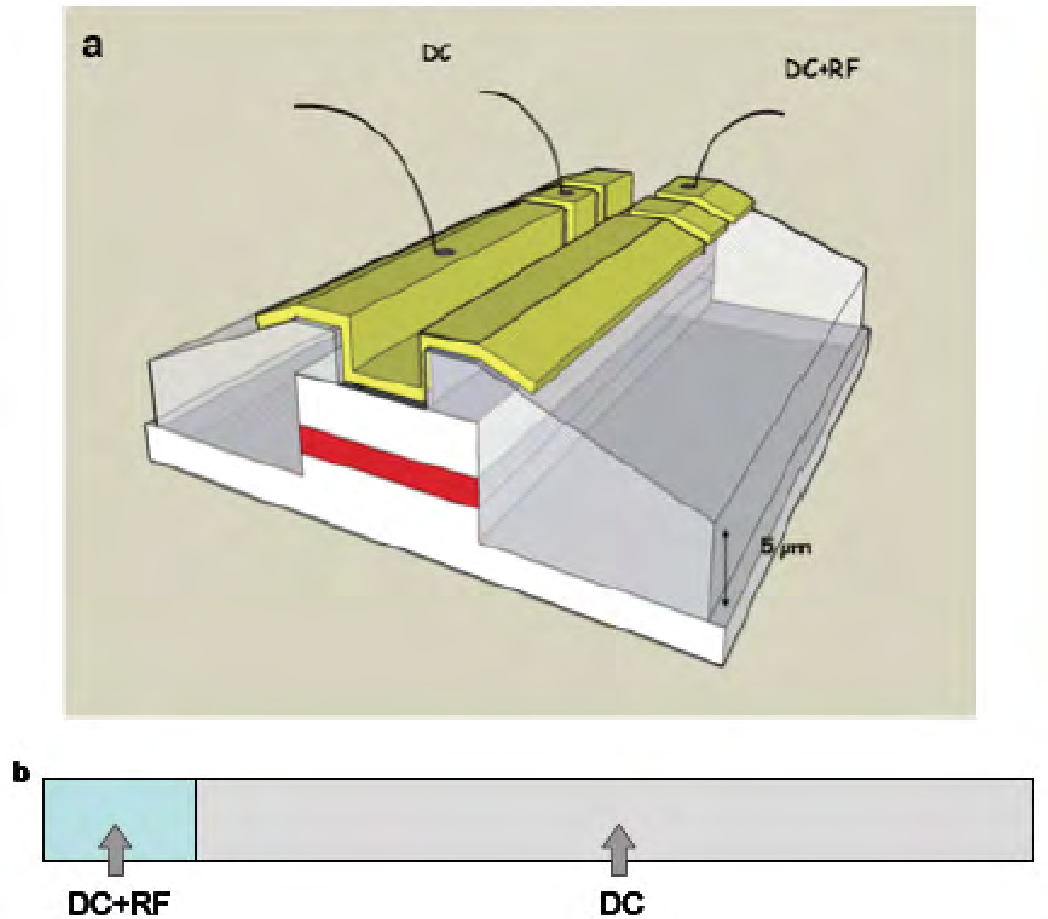
http://www.ulp.ethz.ch/education/ultrafastlaserphysics/7_Active_modelocking.pdf

QCLs: beyond Haus’ equation

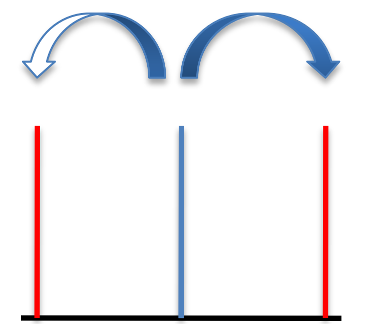
- Strong gain and loss
- Significant propagation effects: spatial hole burning, group delay, etc.
- Short gain relaxation time: gain will adiabatically follow the modulation of voltage
  - How to make short isolated pulses?

- Modulate a short section of a QCL cavity
- Put QCL in an external cavity
  - Both Fabry-Perot and ring cavity would work

Active mode locking in a multi-section cavity



$$P = P_0 + A\sin(2\pi f t)$$

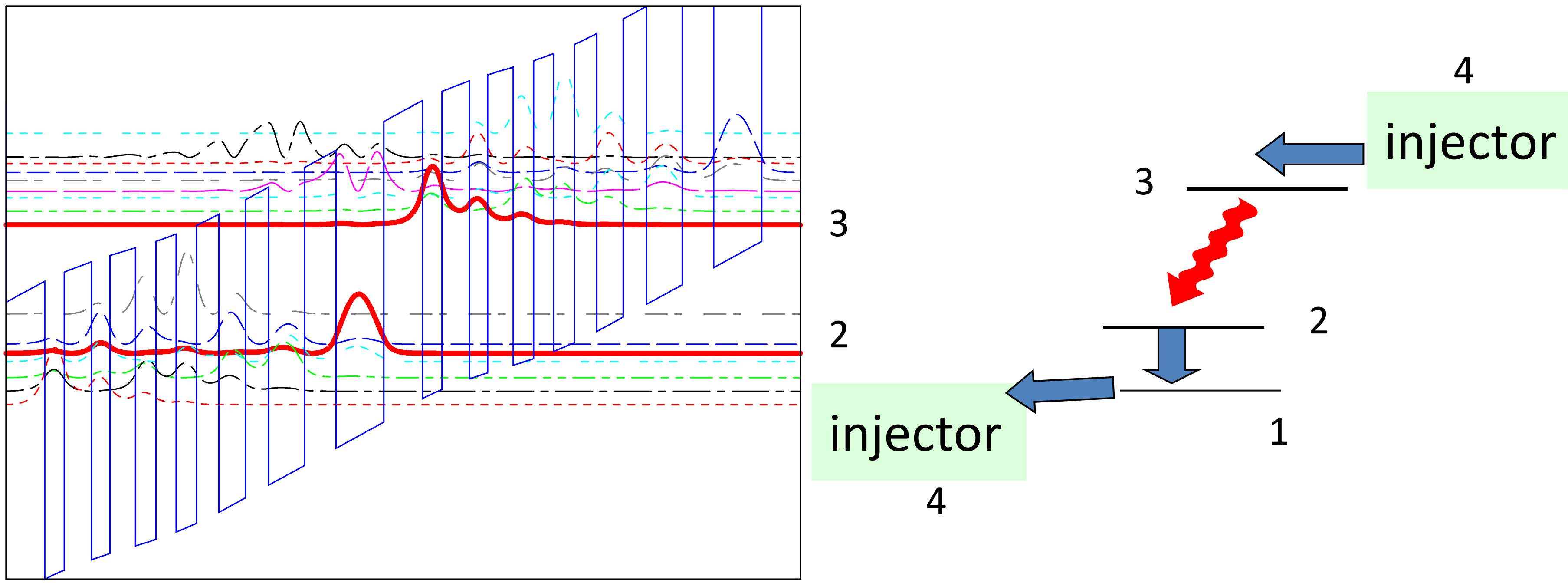


Superdiagonal lasers

Gain is modulated in a short section at the round-trip frequency f = $1/T_{RT}$

Capasso group, Optics Express 2009, 2010

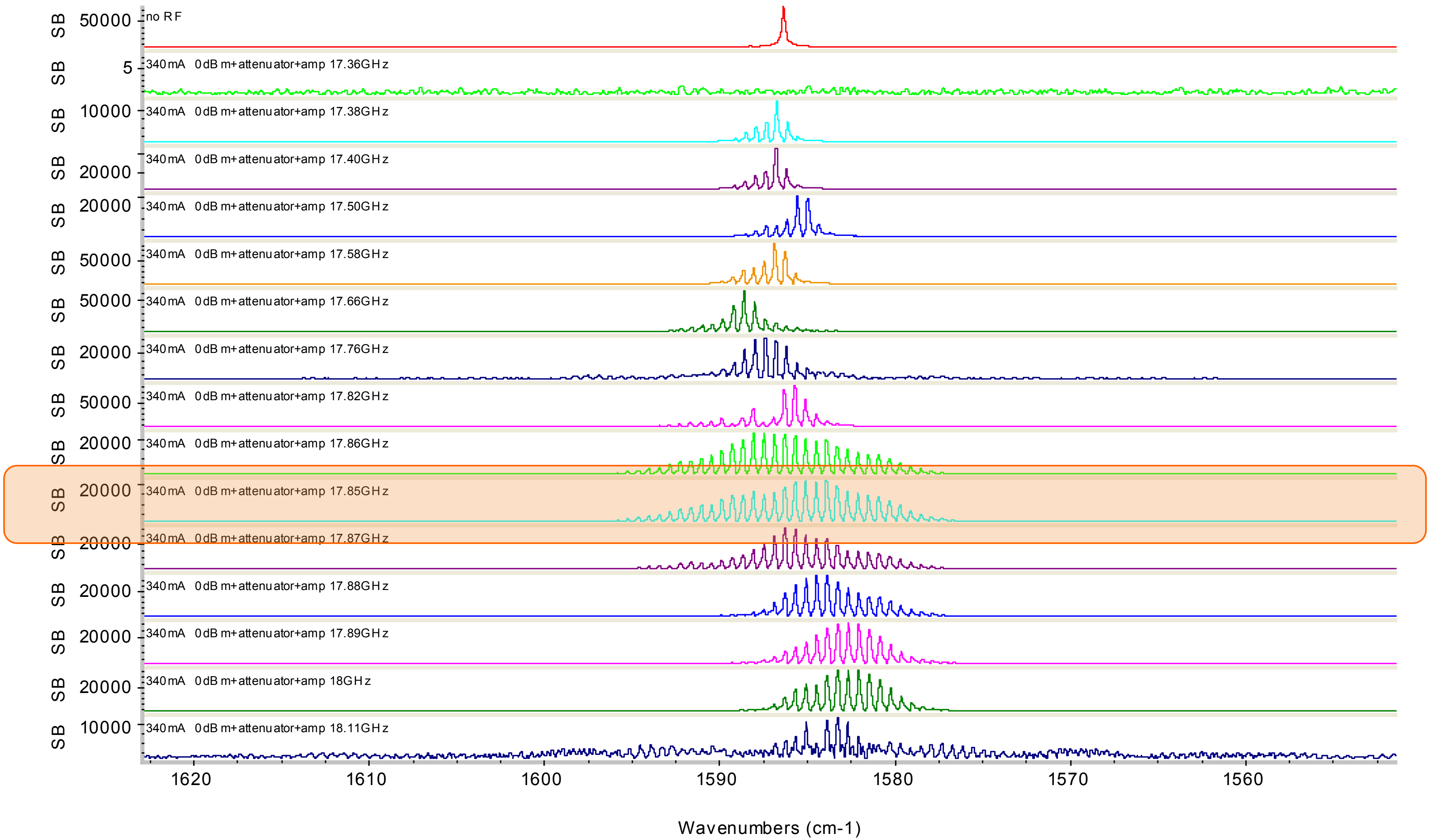
Super-diagonal lasers



Calculated upper state lifetime ~50 ps
Confirmed by T. Norris measurements

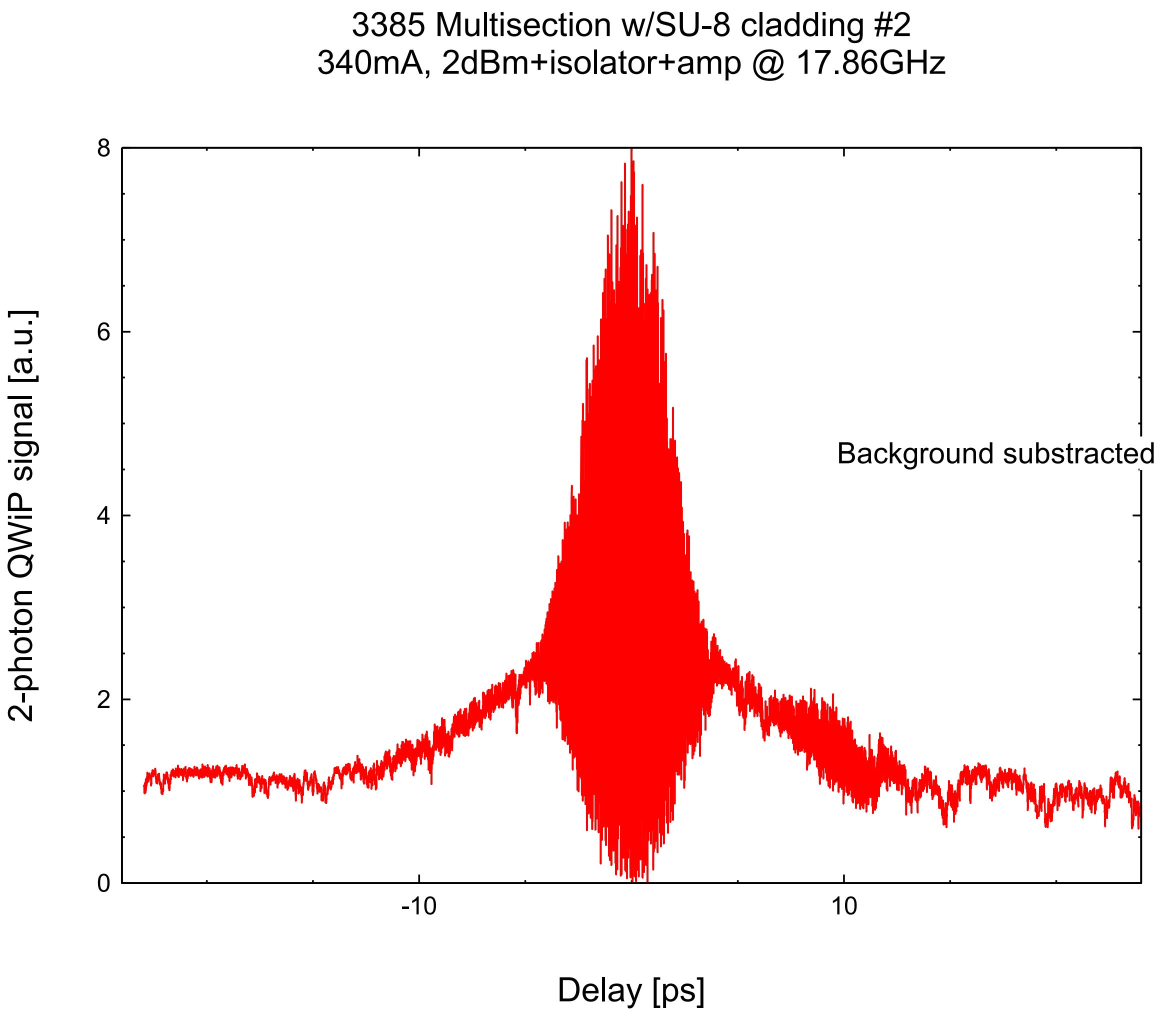
Capasso group 2008

I=340mA, with 35dBm RF power



Resonance @ 17.86 GHz
Power ~ 10 mW

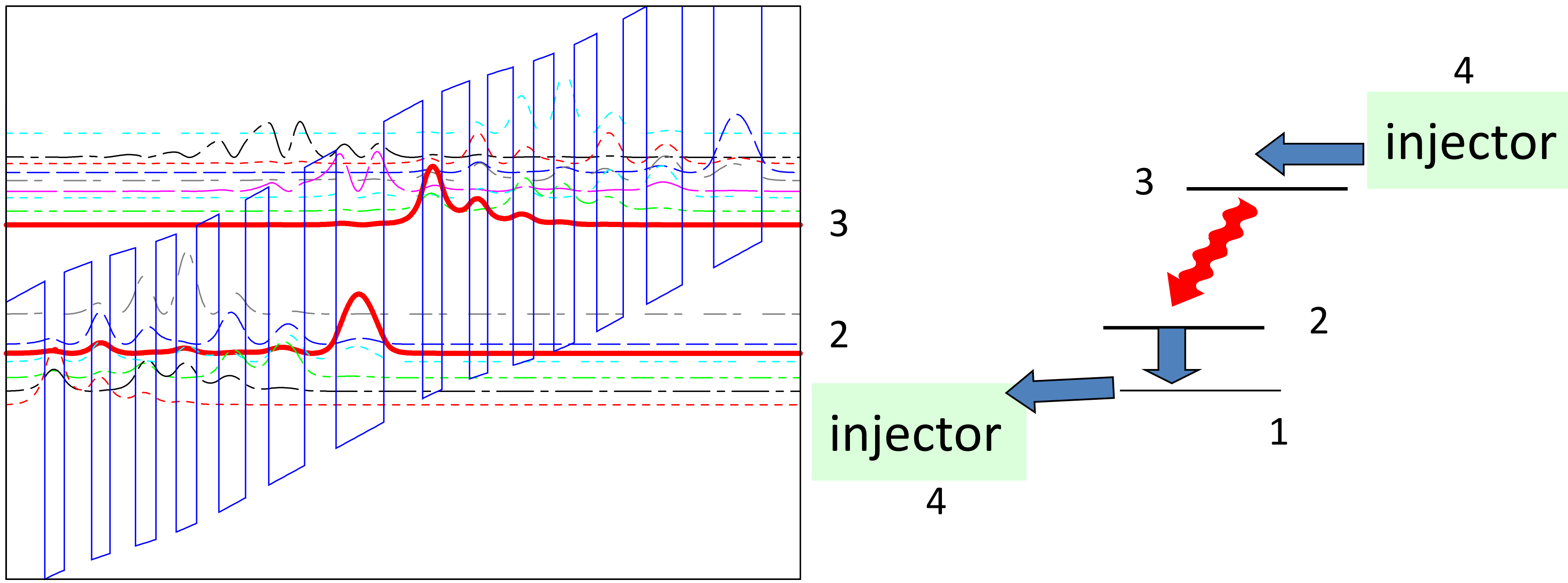
2-Photon Autocorrelation shows 3-ps pulses



Wang et al. OE 2009

Mode locking exists only close to laser threshold

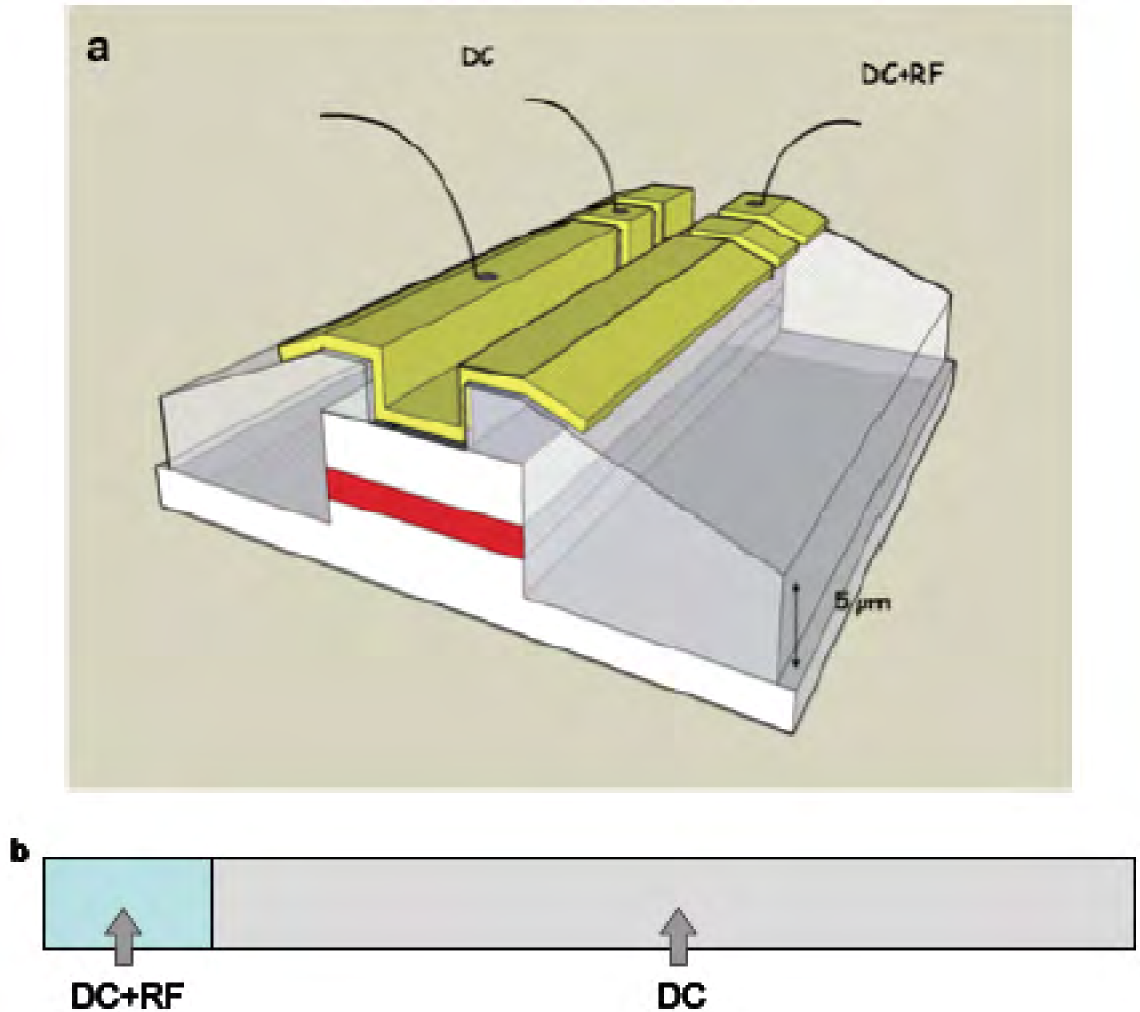
Problems with superdiagonal lasers



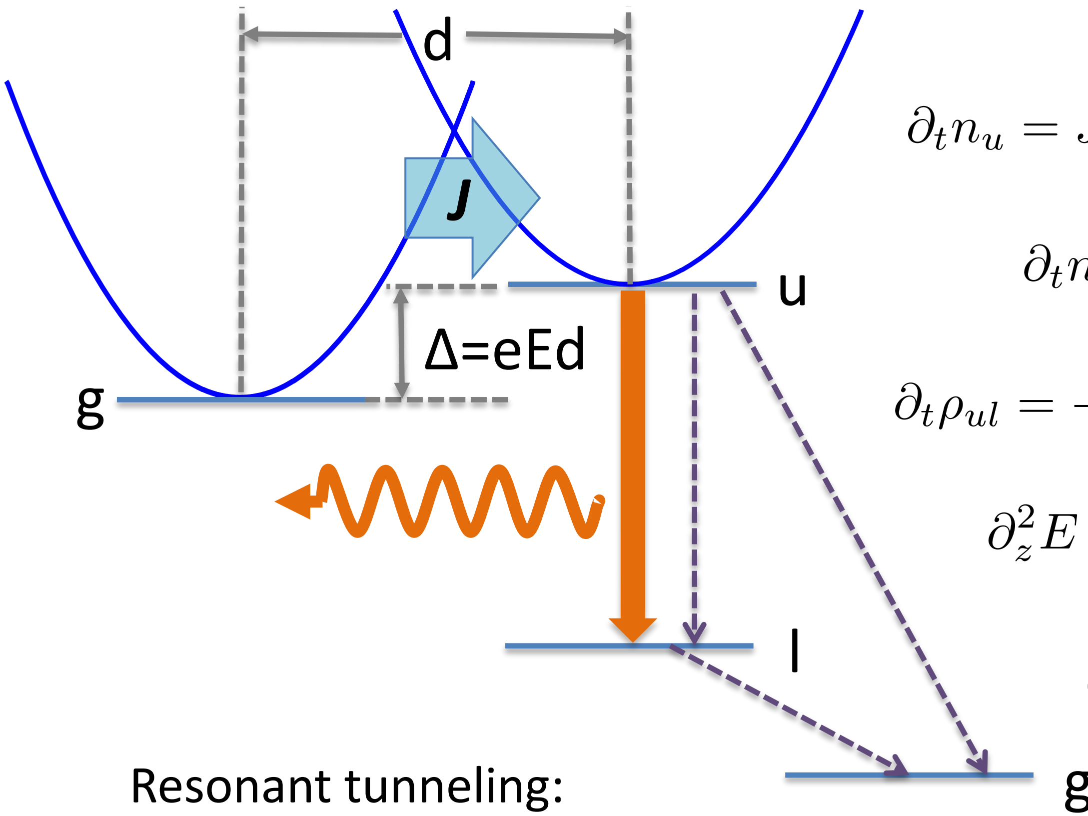
Population inversion is not affected much by modulation.
Main effect comes from varying transition frequency and wave-function overlap.
Gain suppression is likely too small

Wang et al. 2009

Modulation of multi-section lasers with short gain relaxation time



Modeling of space-time dynamics with coherent effects



$$\partial_t n_g = \frac{n_u}{T_{ug}} + \frac{n_l}{T_{lg}} - J$$

$$\partial_t n_u = J - \frac{n_u}{T_{ul}} - \frac{n_u}{T_{ug}} - i\frac{dE}{\hbar}(\rho_{ul} - \rho_{ul}^*)$$

$$\partial_t n_l = \frac{n_u}{T_{ul}} - \frac{n_l}{T_{lg}} + i\frac{dE}{\hbar}(\rho_{ul} - \rho_{ul}^*)$$

$$\partial_t \rho_{ul} = -(i\omega + 1/T_2)\rho_{ul} - i\frac{dE}{\hbar}(n_u - n_l)$$

$$\partial_z^2 E - \frac{n^2}{c^2}\partial_t^2 E = \frac{\Gamma d}{\epsilon_0 c^2 L_p}\partial_t^2(\rho_{ul} + \rho_{ul}^*)$$

Resonant tunneling:

$$J = \frac{e\Omega^2\gamma}{\hbar(\Delta^2 + \gamma^2)}\left(n_g e^{-|\Delta|/k_B T} - n_u\right)$$

Wang & Belyanin, to be submitted

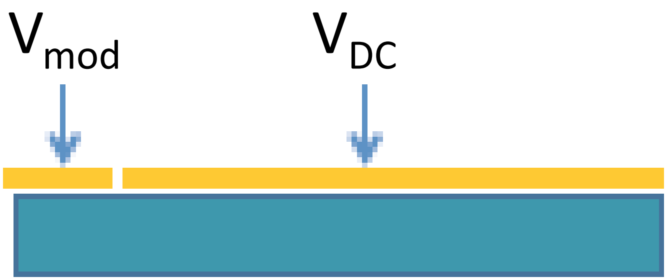
Coherent effects are very important if

$$\frac{dE}{\hbar} > \frac{1}{T_2}$$

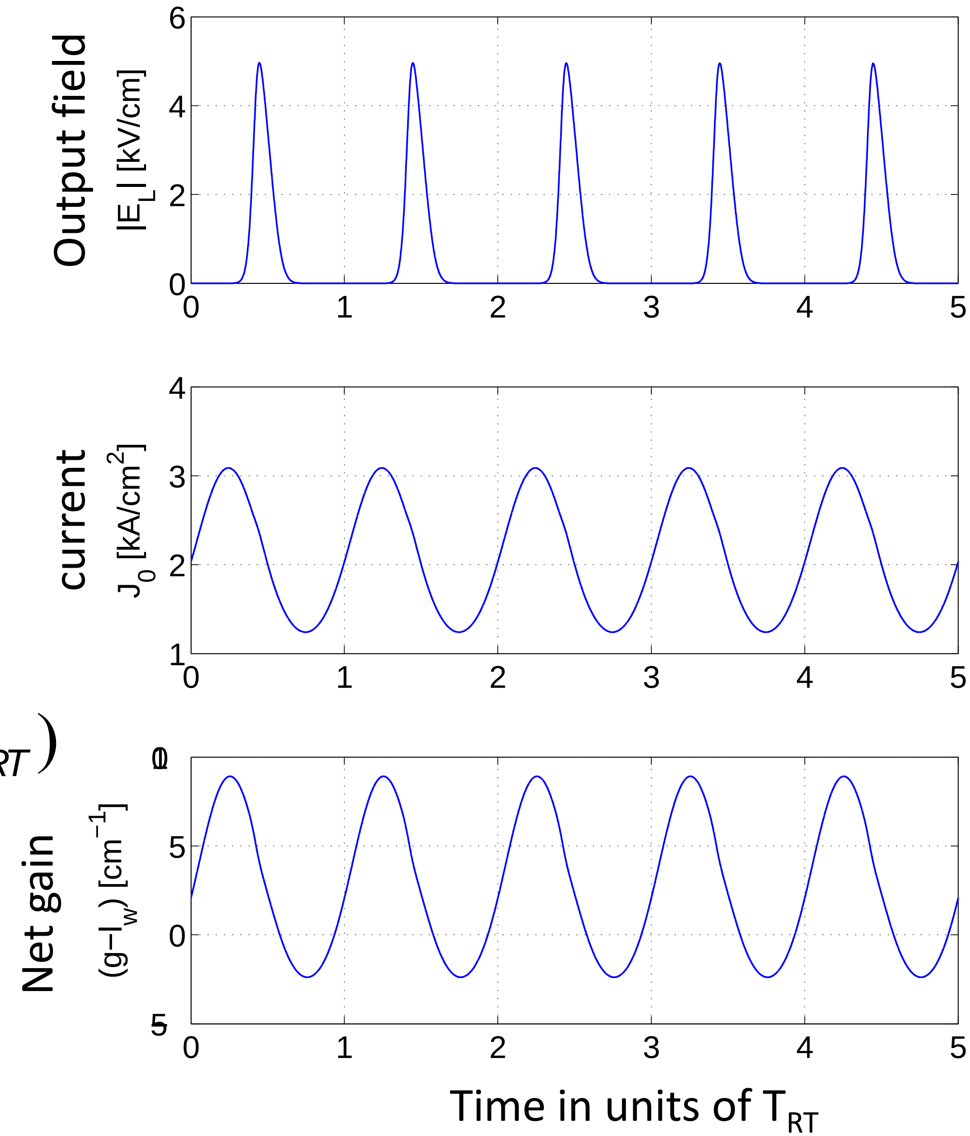
Or if dynamic timescales < T_2 .

They are noticeable in our case.

Assume sinusoidal modulation of bias in the short section:

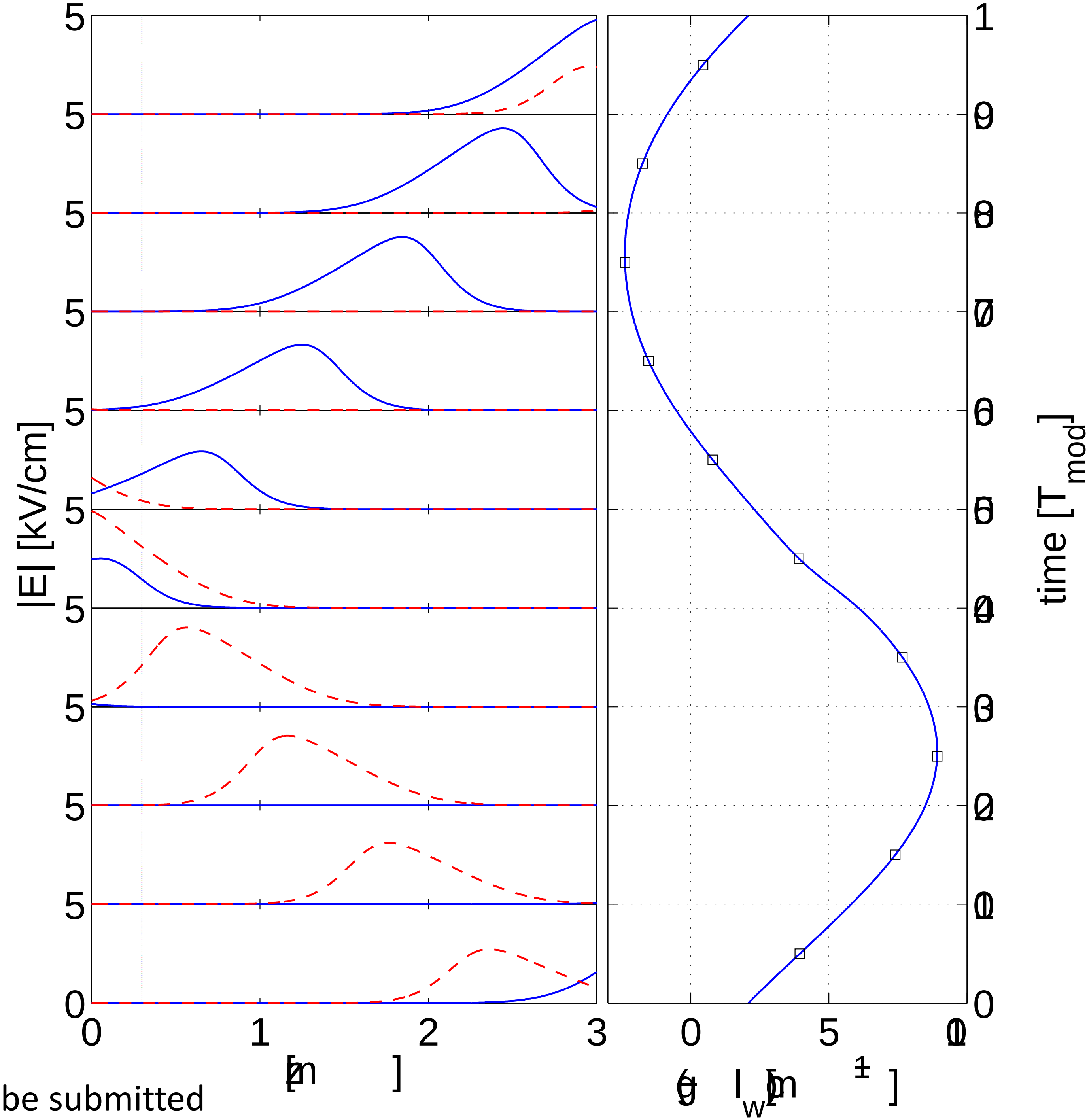


$$V_{\mathrm{mod}} = V_{\mathrm{mod},DC} + V_{amp} \cos(2pt / T_{RT})$$



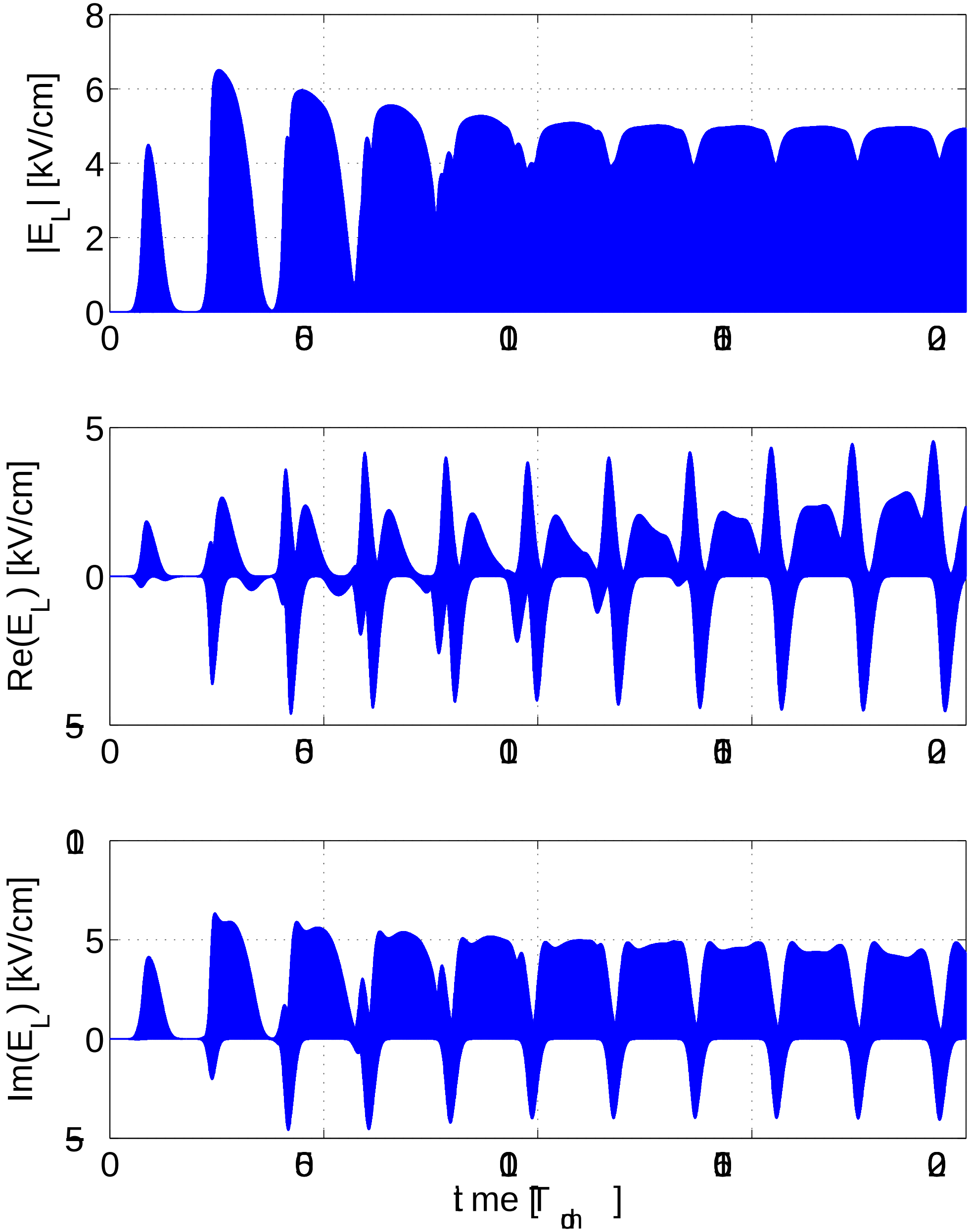
Weakly nonlinear response of gain to bias modulation

Wang & Belyanin, to be submitted



Wang & Belyanin, to be submitted

Dynamics over 2000 round-trips



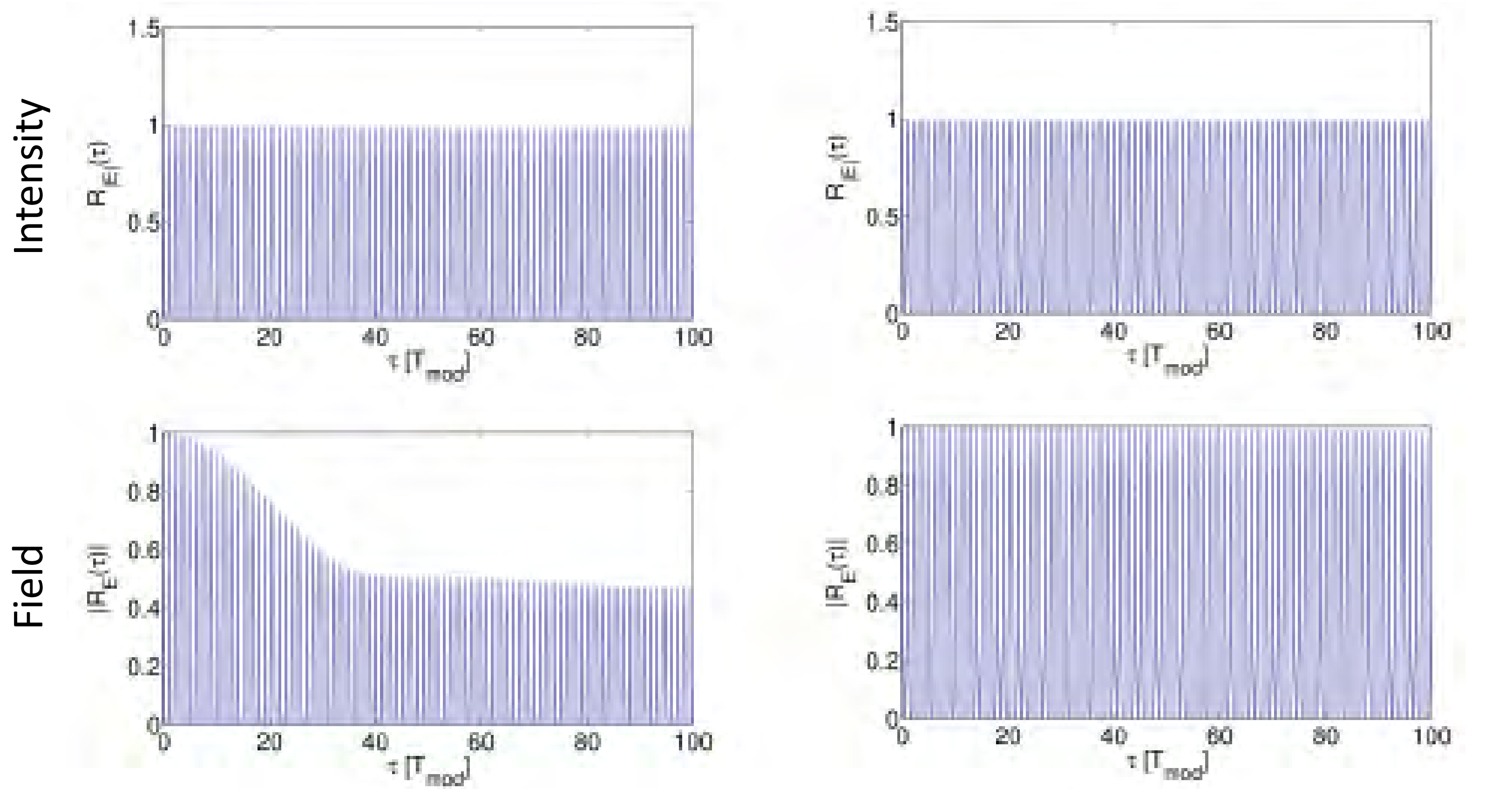
Intensity is strictly periodic …

But the field is not.

Initial offset phase (CE phase) is not stabilized

Autocorrelation function of the intensity and the field

$$R_E(\tau) = \int_{t_1}^{t_2} E^*(t)E(t+\tau)dt \Big/ \int_{t_1}^{t_2} E^*(t)E(t)dt$$



$T_{mod} = 1.000\ T_{RT}$

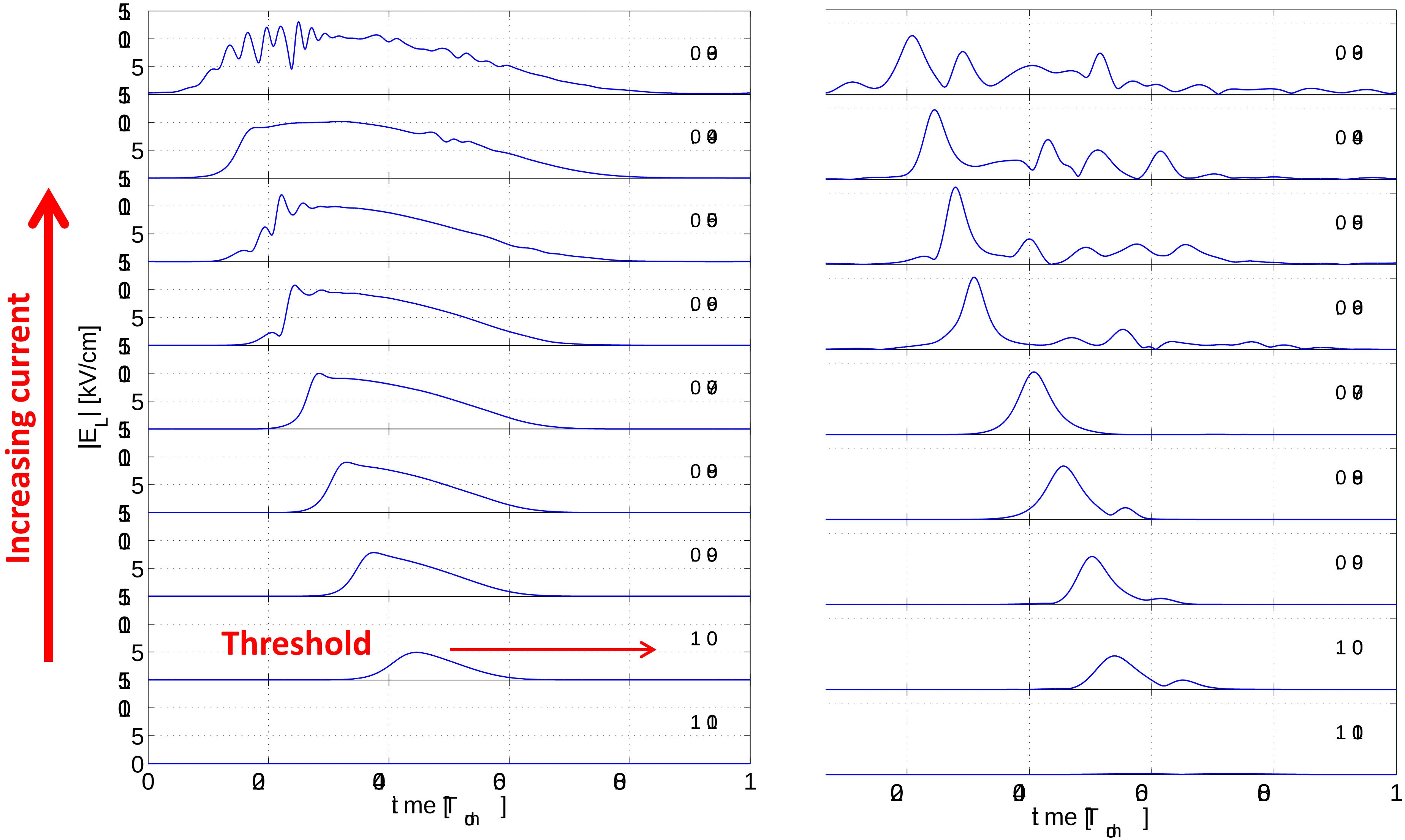
Intensity is periodic, field is not

$T_{mod} = 1.005\ T_{RT}$

Both intensity and field are periodic

Wang & Belyanin, to be submitted

Dependence of the output on DC bias



T_{UL} = 1 ps

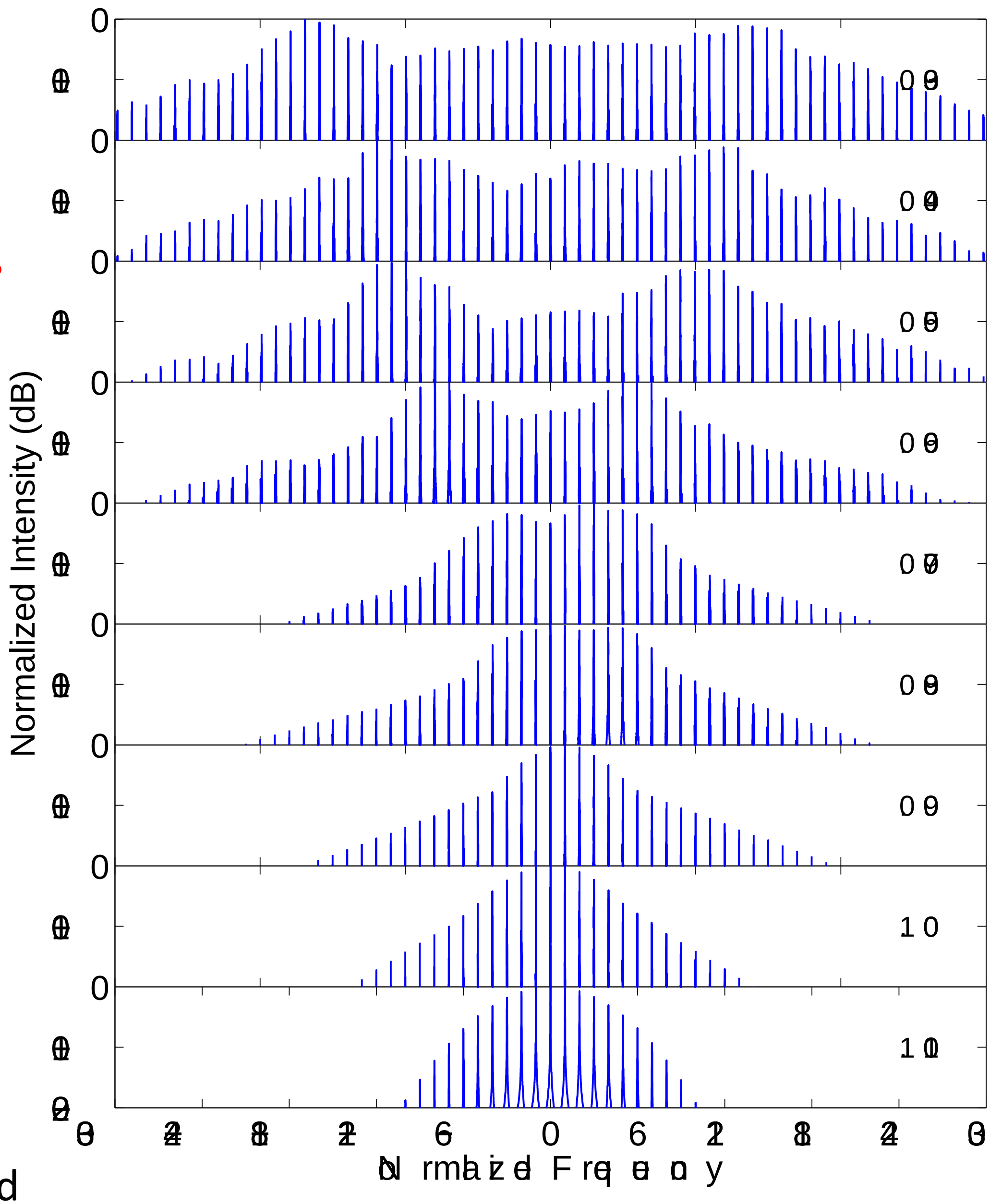
T_{UL} = 50 ps

Pulses broaden but survive until higher current and power

Spectra with increasing current for T_{UL} = 1 ps

Spectrum broadens although pulses broaden too

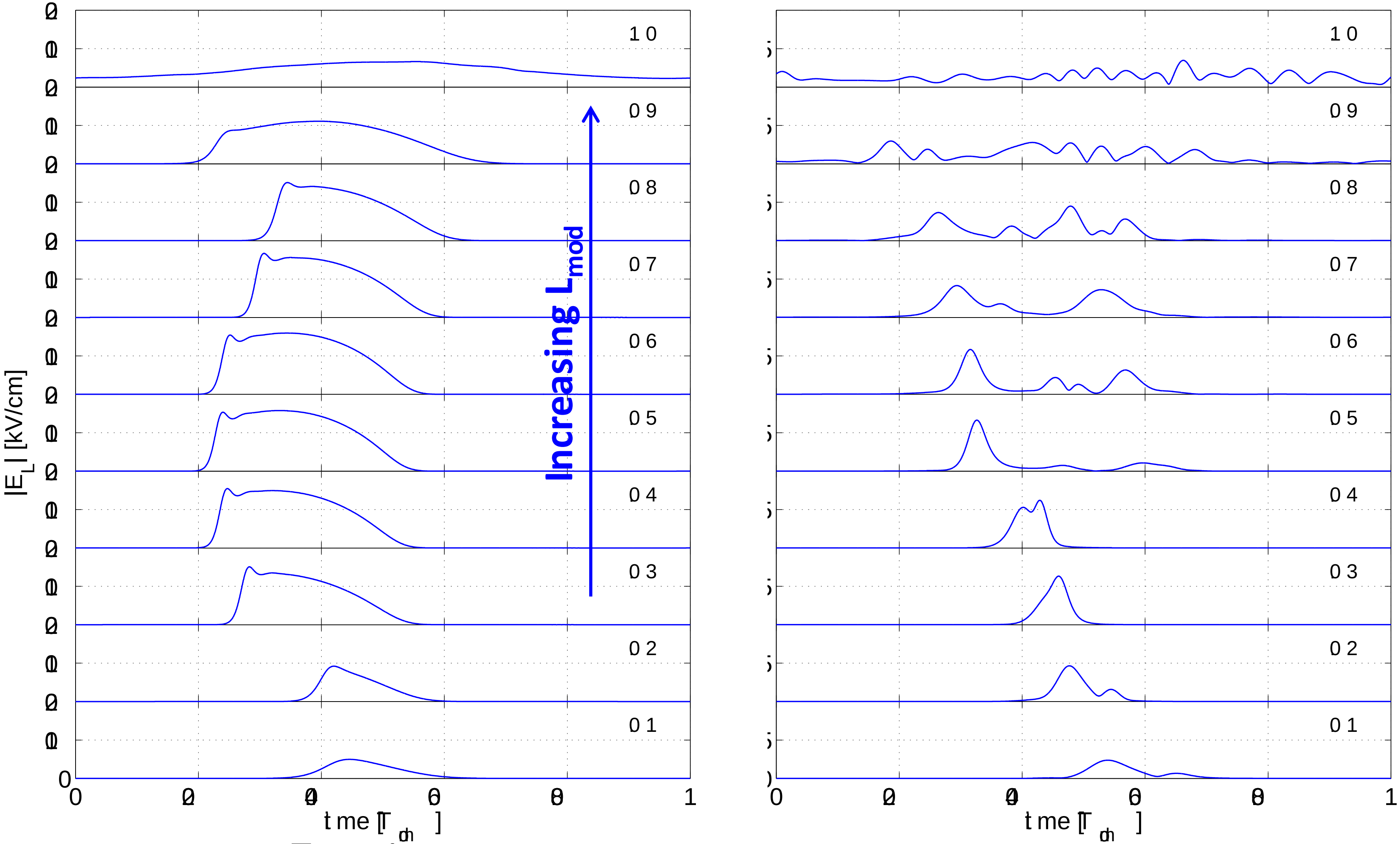
Increasing current



Wang & Belyanin, to be submitted

Dependence of the output on the length of modulated section

Pulses broaden strongly as L_{mod} is extended to the whole cavity



T_{UL} = 1 ps

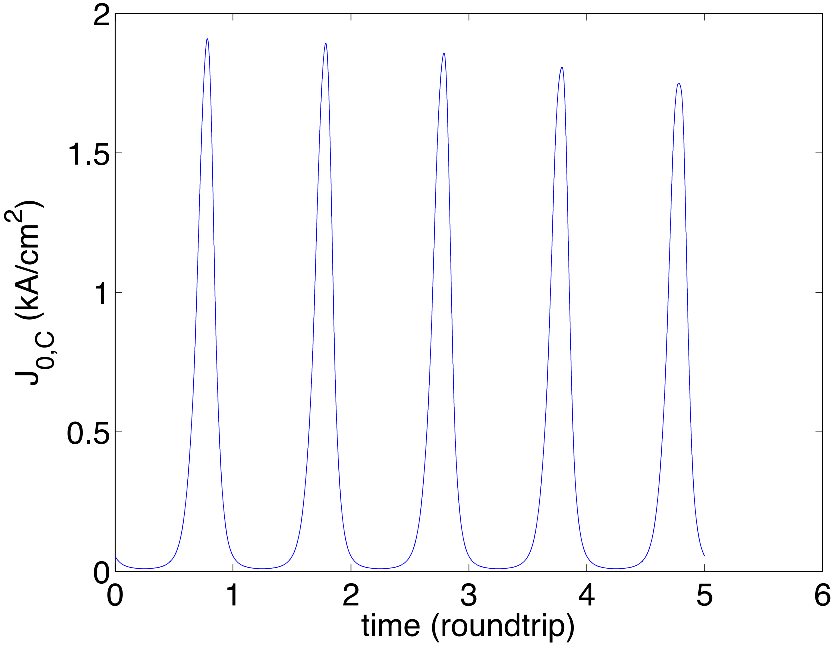
T_{UL} = 50 ps

Wang & Belyanin, to be submitted

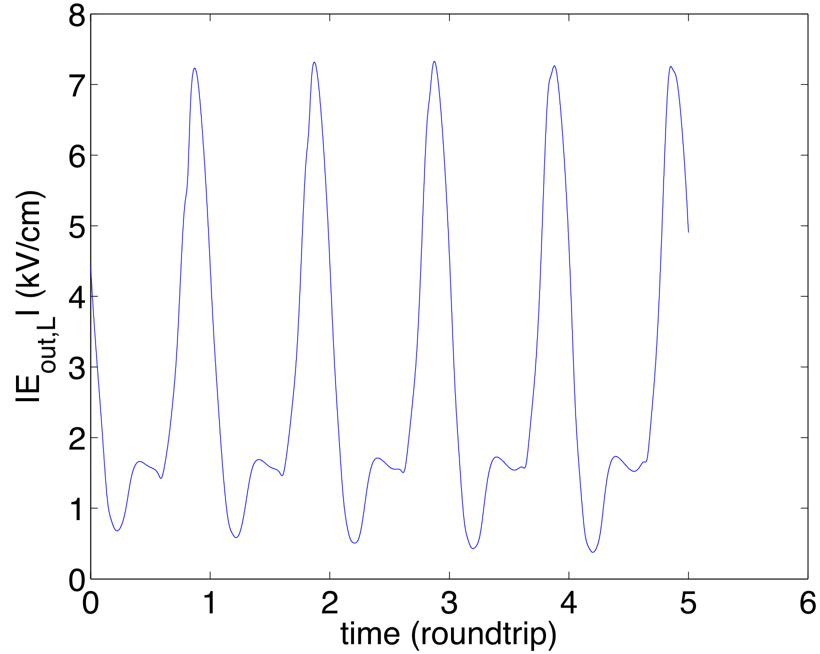
THz QCL: modulation of the whole cavity

Pronounced pulsations are observed only for very large modulation amplitude

Current in the modulated section

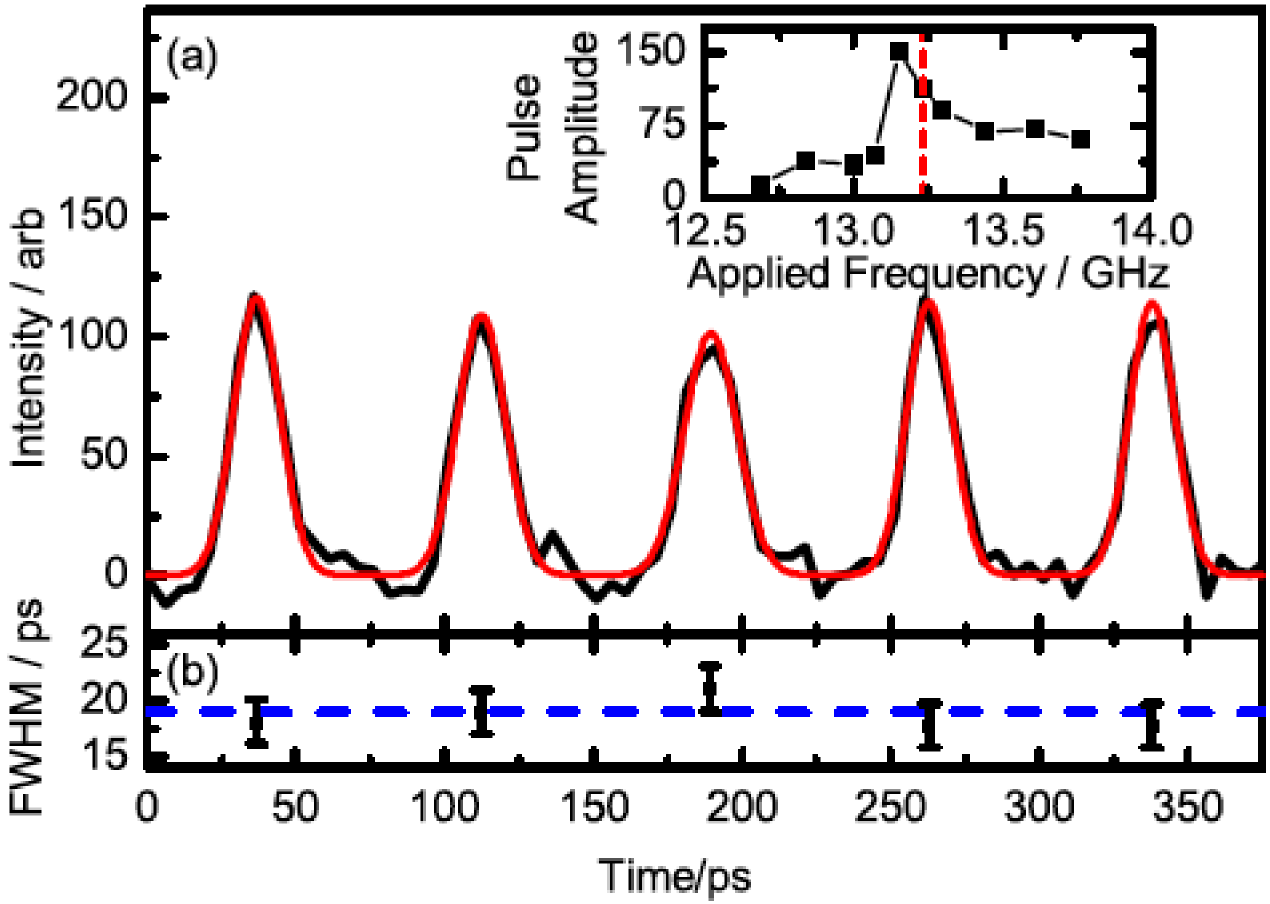


Output field amplitude



Disagreement with observations of mode-locked pulses in THz QCLs?
(Barbieri et al. 2011 and later development).

Active mode locking of THz QCLs

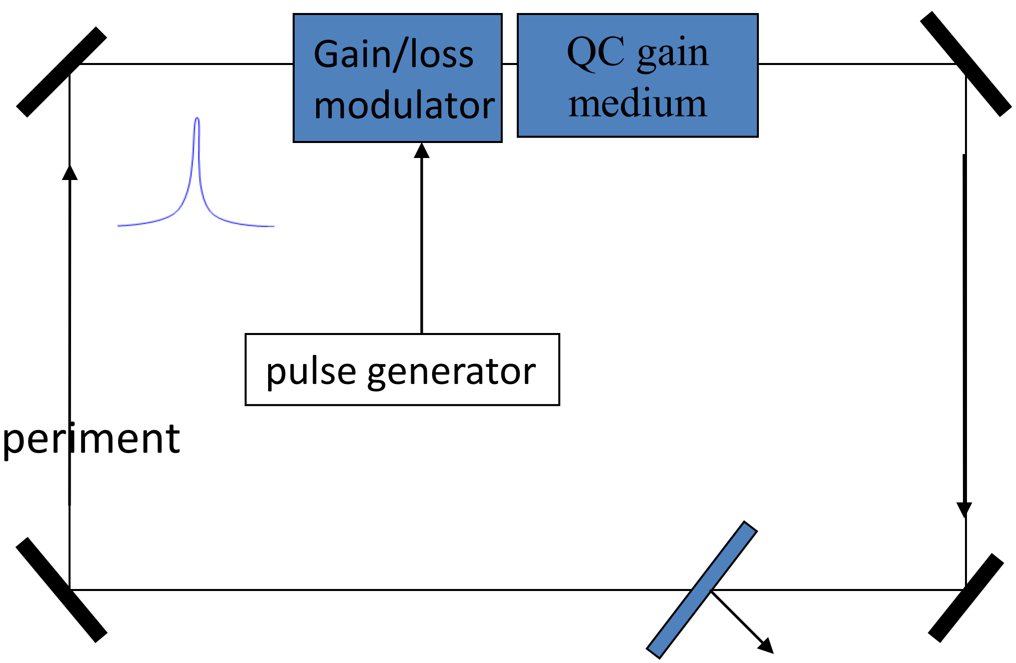


Effectively, modulation of only a small part of the cavity?

Freeman et al. APL 2012

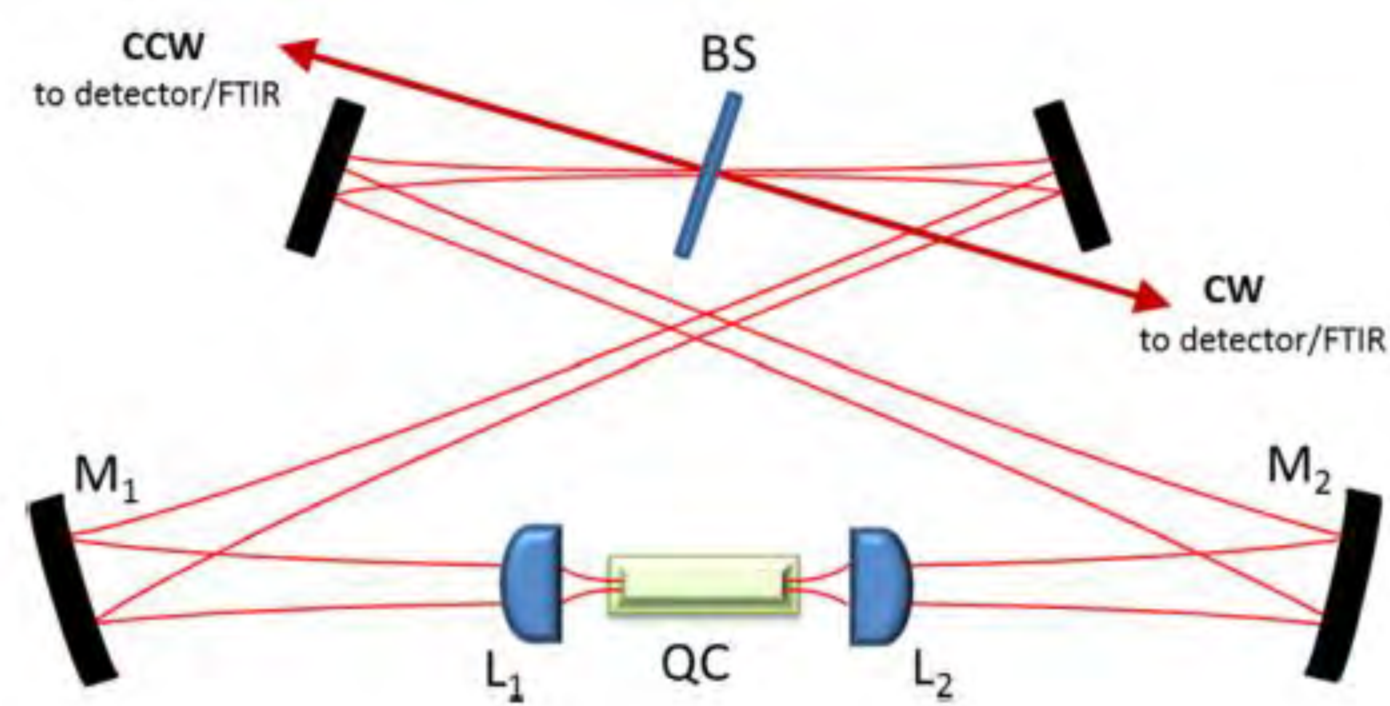
External cavity

- Round-trip frequency in the ~ 100 MHz range
- Easy to ensure single optical pulse in the cavity
- Easy to add nonlinear elements, feedback loops etc.
- Ring cavity: unidirectional emission, no spatial hole burning



Idea and ongoing experiment
Capasso group

External ring-cavity QCL



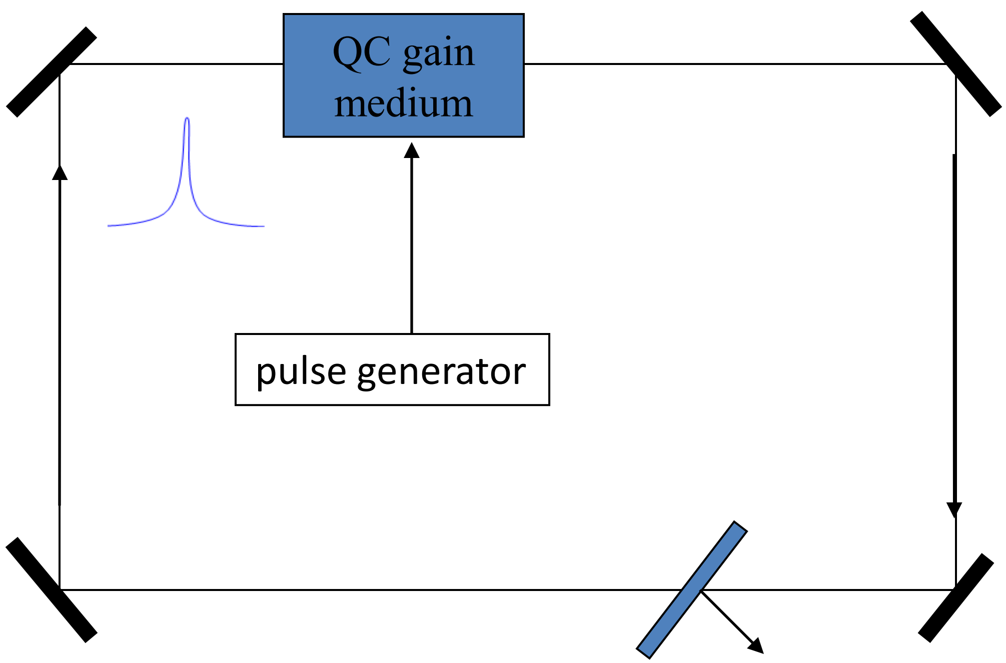
Single-mode operation in quasi-CW regime
Unidirectional lasing; switching between directions

Malara et al. 2013

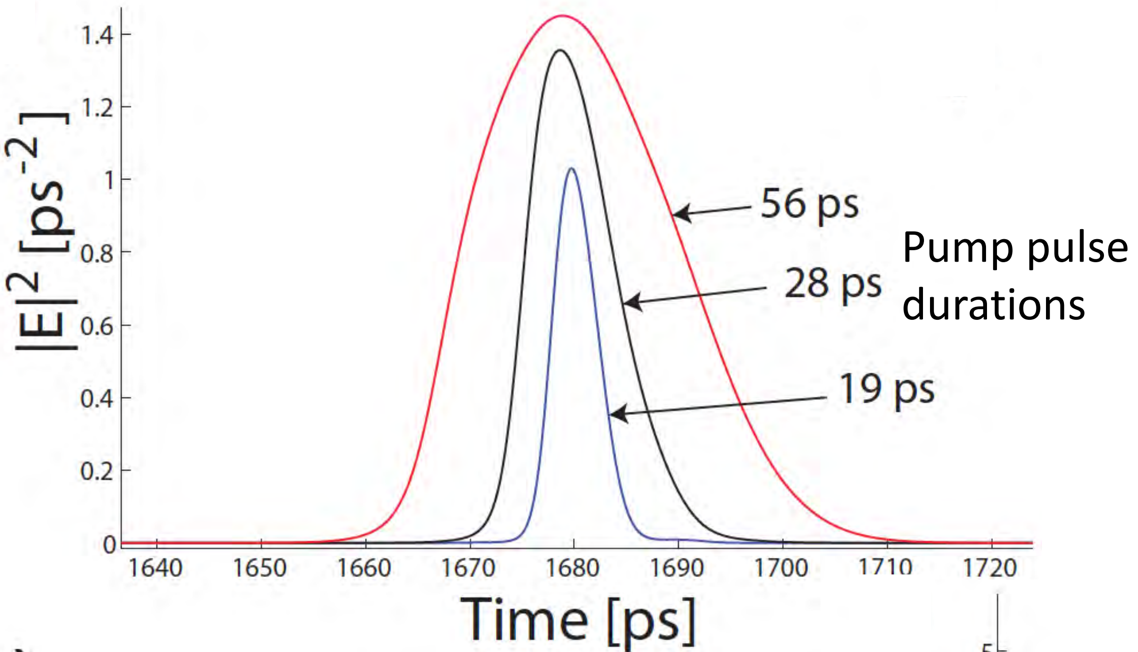
Modeling of active mode locking in a ring cavity

- Full set of Maxwell-Bloch equations with coherences
- Sinusoidal or short-pulse modulation of the gain

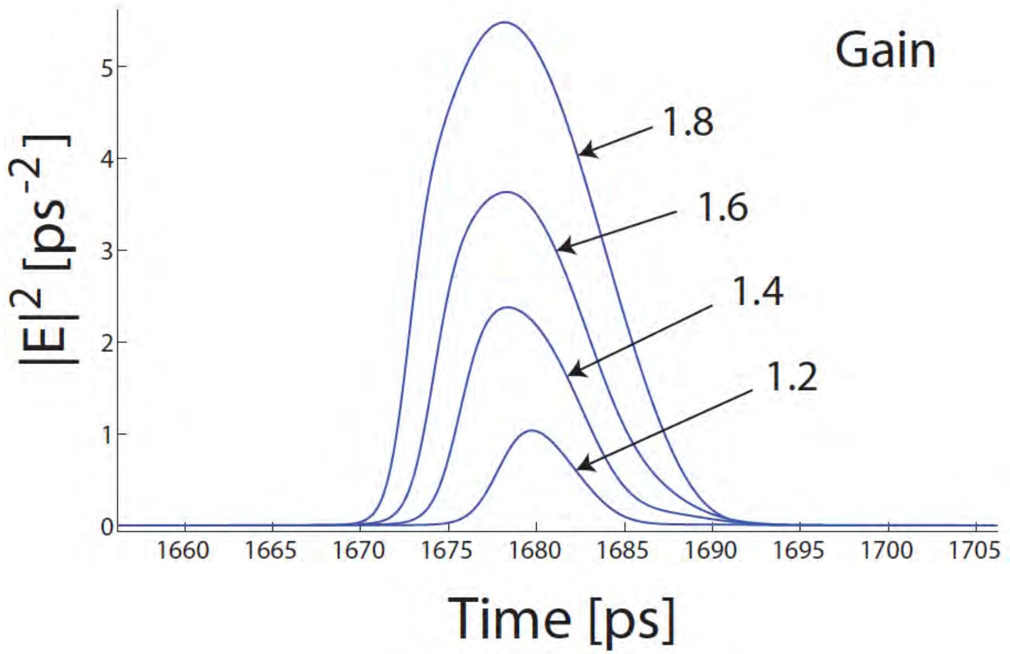
Cavity length L = 1 m, QC gain length = 1 mm
T_1 = 1 ps, T_2 = 0.1 ps, T_{rt} = L/c = 3.3 ns
Losses 10 cm^{-1} in the chip only; AR coating



Gain modulation with short Gaussian pulses



Output pulse duration ~ 5 ps
Many 1000s of modes are excited



Wojcik et al. APL 2013

Conclusions

- Passive mode locking of QCLs remains a challenge due to short gain recovery time
- Active mode locking of QCLs with short gain recovery time is feasible and is robust to changes in pumping and laser parameters
- Modulation has to be applied to a short section of a cavity
- Both monolithic two-section cavities and external cavities show similar performance