Instabilities and mode locking of quantum cascade lasers

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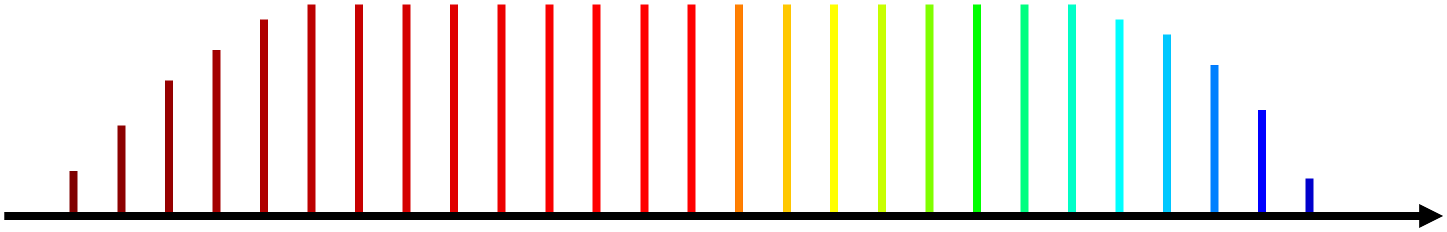
Outline

- Motivation and Experimental Observations
- What's different about QCLs compared to other Lasers?
- A simple two-level model for QCLs
- Multimode Instabilities:

    Spectral Hole Burning
    Risken-Nummedal-Graham-Haken Instability

- Actively Modelocked QCLs with Super Diagonal Gain
- Conclusion

MID-IR Frequency Comb Spectroscopy: 2-5μm and 8-14μm Finger Print Regions



covering one octave

- A frequency comb from a stabilized modelocked laser is equivalent to an enormous number (~100,000) of narrow band cw laser.
- Provides amplitude and phase across hundreds of nanometers, which can simultaneously probe multiple transitions.
- Offers a frequency resolution and accuracy > 10^{-15}

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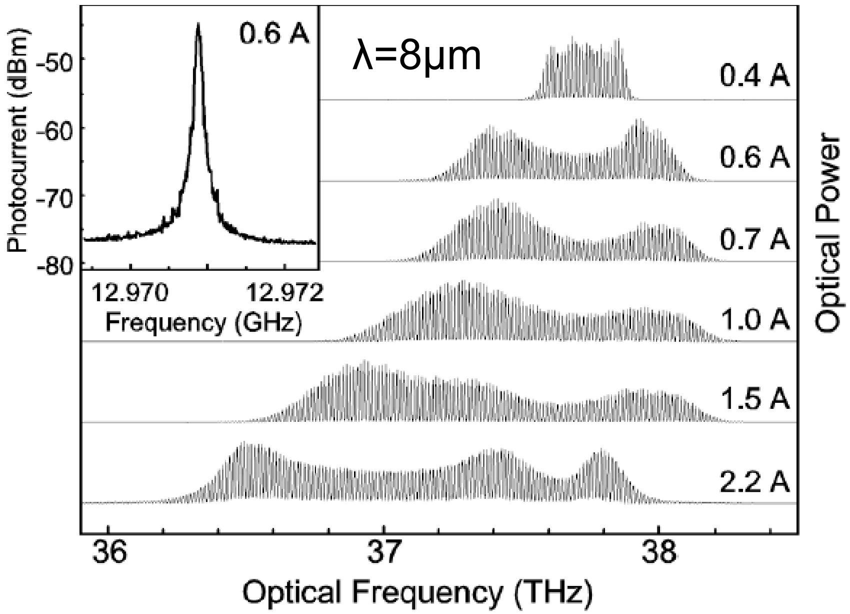
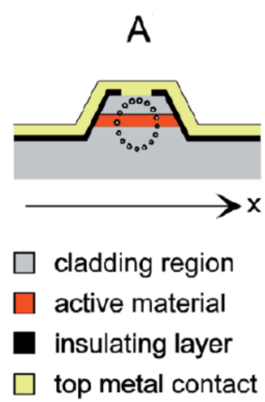
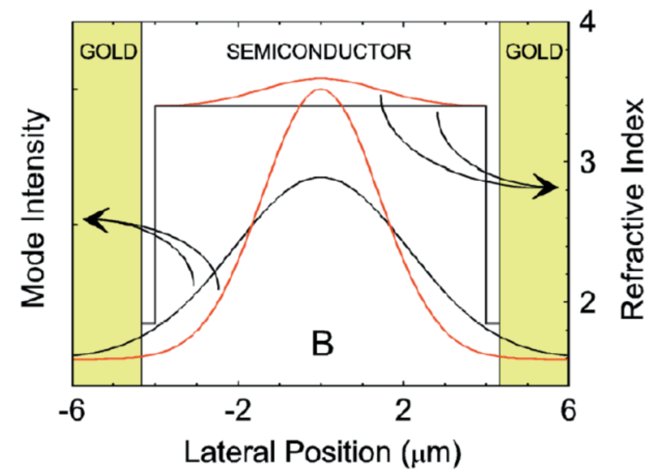
First Evidence of Self Pulsation in QCLs

RF spectrum **Optical spectrum**



Kerr-lensing mechanism for saturable absorption





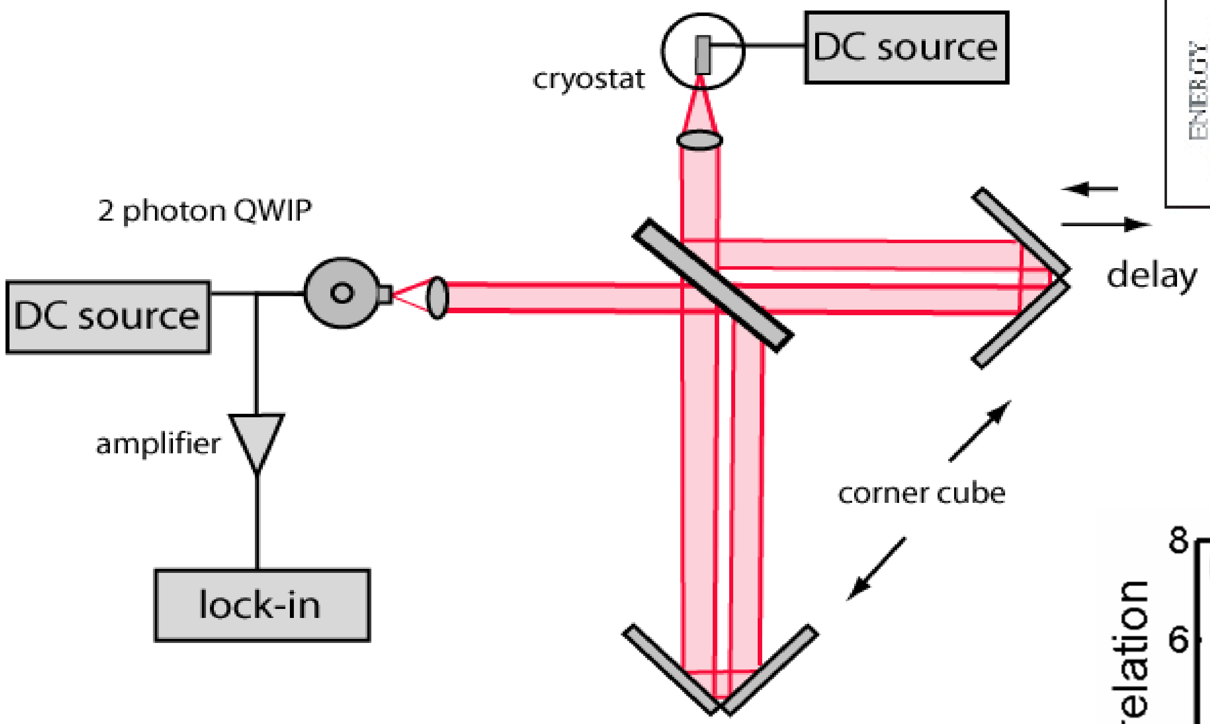
What can we learn from the data?

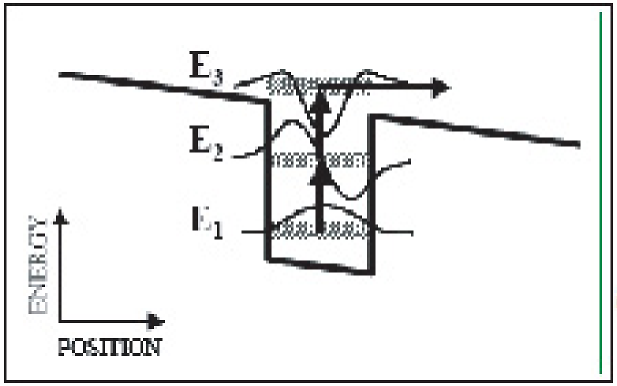
1. Many modes are lasing
2. The modes maintain coherence for ~1000th roundtrips.

R. Paiella *et al.*, Science 290, 1793 (2000)

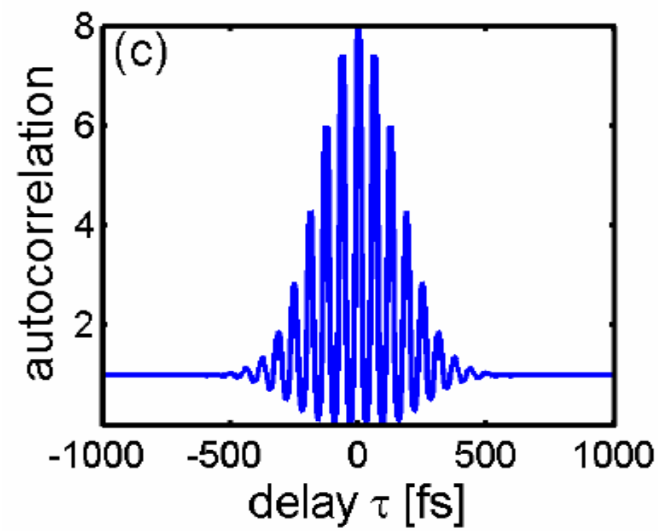
Isolated Single Pulses ?

Interferometric Autocorelation



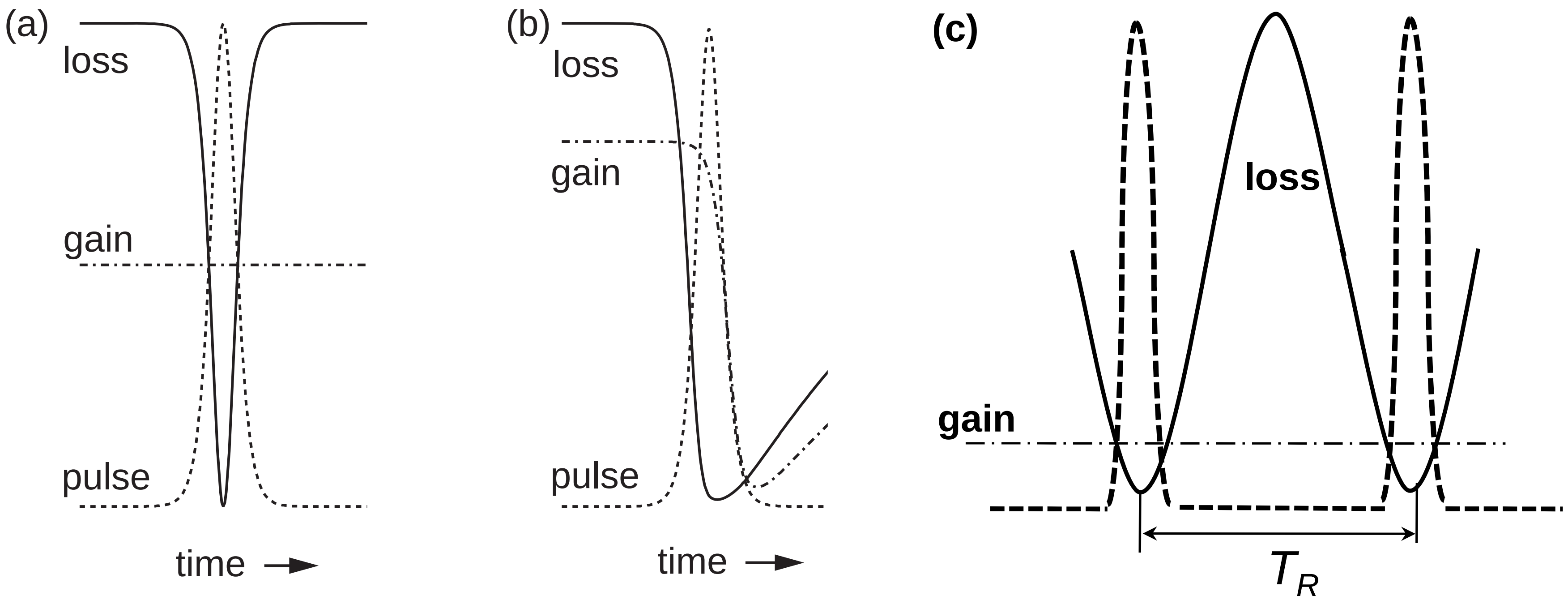


For isolated pulses
Ratio < 8:1



QWIPs from H.C. Liu and H. Schneider

Stable Modelocking Needs Net Gain Window



Solid-State Lasers

Semiconductor or Dye Lasers

Active Modelocking

Typical QCLs have 1ps-type gain recovery

Super-Diagonal QCLs → 50ps gain recovery

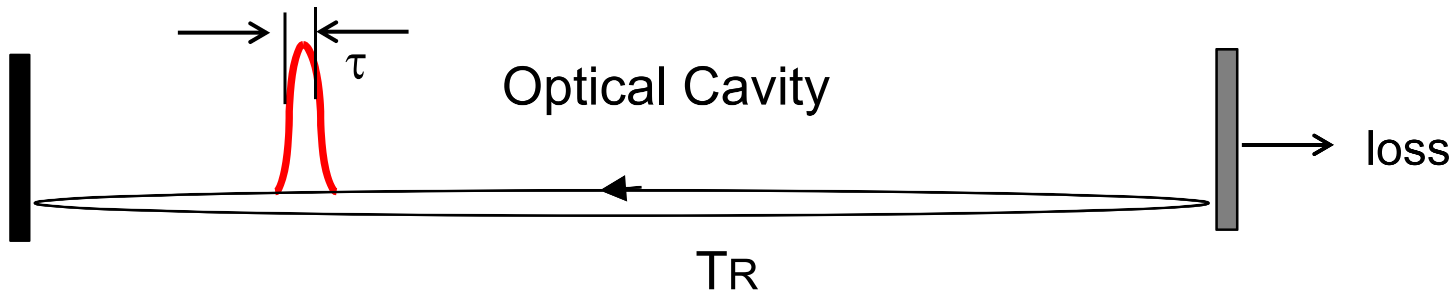
Comparison of Different Laser Media

Medium	Upper State Lifetime T_1	Dipole Decay T_2	Gain sat. Intensity $I_s \sim T_1 \cdot T_2 \left|\mu\right|^2$	Rabi Frequency $\Omega_{\text{Rabi}} = \frac{\mu E}{2\hbar}$	Mode Spacing $1/T_R$
Solid State	1 μs-1 ms	10fs-1ps	~kW/cm^2	10-100 MHz	10-100 MHz
Semi-con-ductor	>1 ns	50 fs	~kW/cm^2	10 GHz	10-100 GHz
QCL	0.5 – 50 ps	100 – 500 fs	~100 kW/cm^2	1THz	10-20 GHz

Dipole dynamics important

Dipole dynamics couples many longitudinal modes

Maxwell – Bloch Equations



Polarization

$$\dot{\rho}_{ab} = i\omega\rho_{ab} + i\frac{\mu E}{\hbar}\Delta - \frac{\rho_{ab}}{T_2},$$

Inversion **Diffusion**

$$\dot{\Delta} = -2i\frac{\mu E}{\hbar}\left(\rho_{ab}^{*} - \rho_{ab}\right) - \frac{\Delta_p - \Delta}{T_1} + D\frac{\partial^2 \Delta}{\partial z^2}$$

Field

$$\partial_z^2 E - \frac{n^2}{c^2}\partial_t^2 E = \frac{N\Gamma\mu}{\varepsilon_0 c^2}\partial_t^2\left(\rho_{ab} + \rho_{ab}^{*}\right).$$

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Inversion Grating

$$E(z,t) = \frac{1}{2}\left[E_+^*(z,t)e^{-(\mathrm{i}\omega t-kz)} + E_+(z,t)e^{\mathrm{i}(\omega t-kz)}\right] + \frac{1}{2}\left[E_-^*(z,t)e^{-(\mathrm{i}\omega t+kz)} + E_-(z,t)e^{\mathrm{i}(\omega t+kz)}\right]$$

$$\rho_{ab}(z,t) = \eta_+(z,t)e^{\mathrm{i}(\omega t-kz)} + \eta_-(z,t)e^{\mathrm{i}(\omega t+kz)}$$

$$\Delta(z,t) = \Delta_0(z,t) + \Delta_2(z,t)e^{2ikz} + \Delta_2^*(z,t)e^{-2ikz},$$

$$k = \frac{2\pi}{\lambda_L}$$

[illegible]

[illegible]

[illegible]

Inversion grating

[illegible]

Saturable Absorber Effects

$$\ell = \gamma|E|^2$$

Inversion Grating Decay Time

$$\frac{1}{T_G} = \frac{1}{T_1} + 4k^2 D$$

Grating Strength

$$\sim \frac{1}{1+4k^2 D T_1}$$

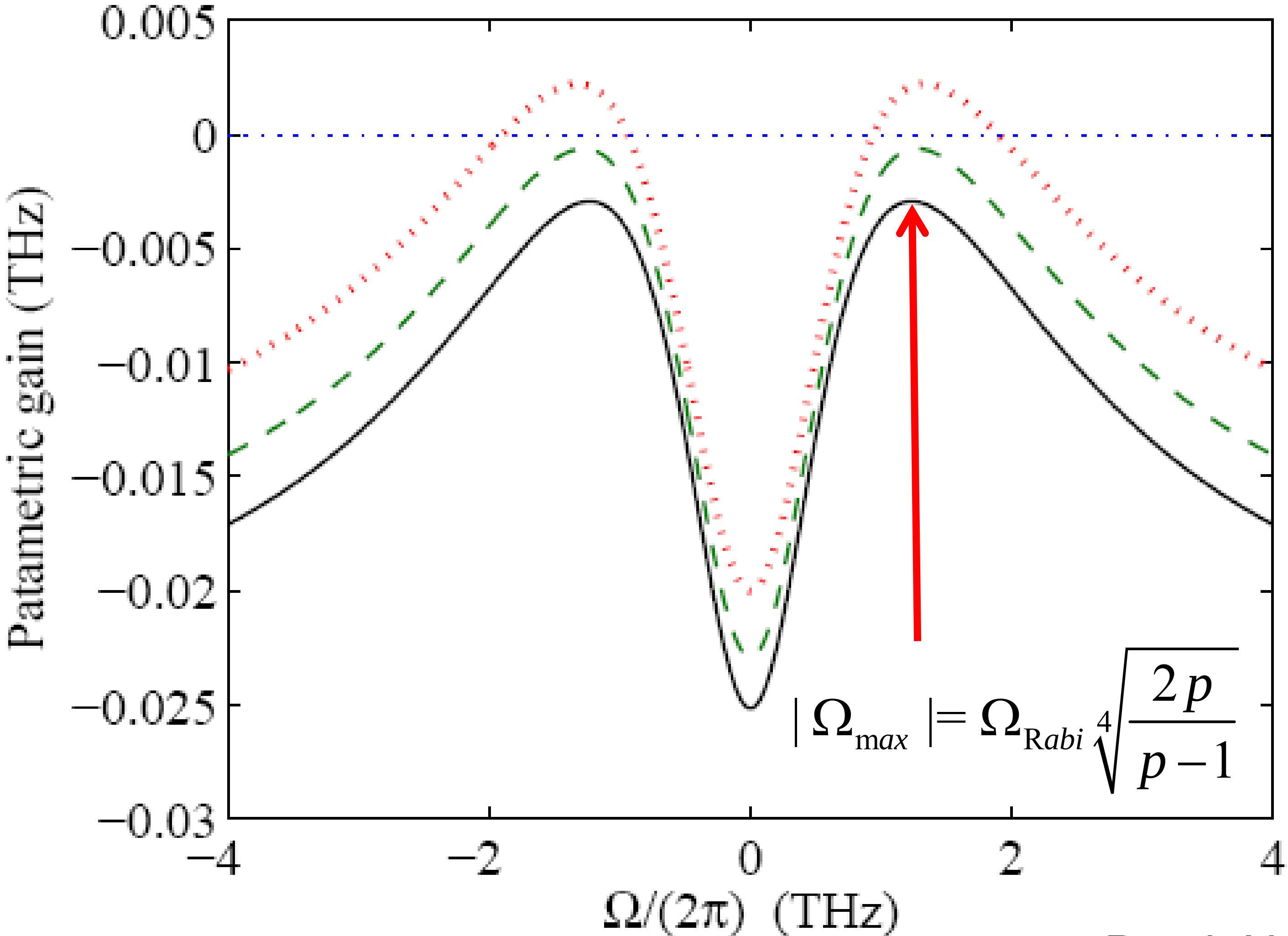
+ Boundary Conditions

Spatial Hole Burning Effects

Strong in QCLs

Ring Cavity: (Risken Nuhmedal Grahem & Haken Only)

- No Standing Waves → No Spatial Holeburning



Offset Frequency

Pump Parameter

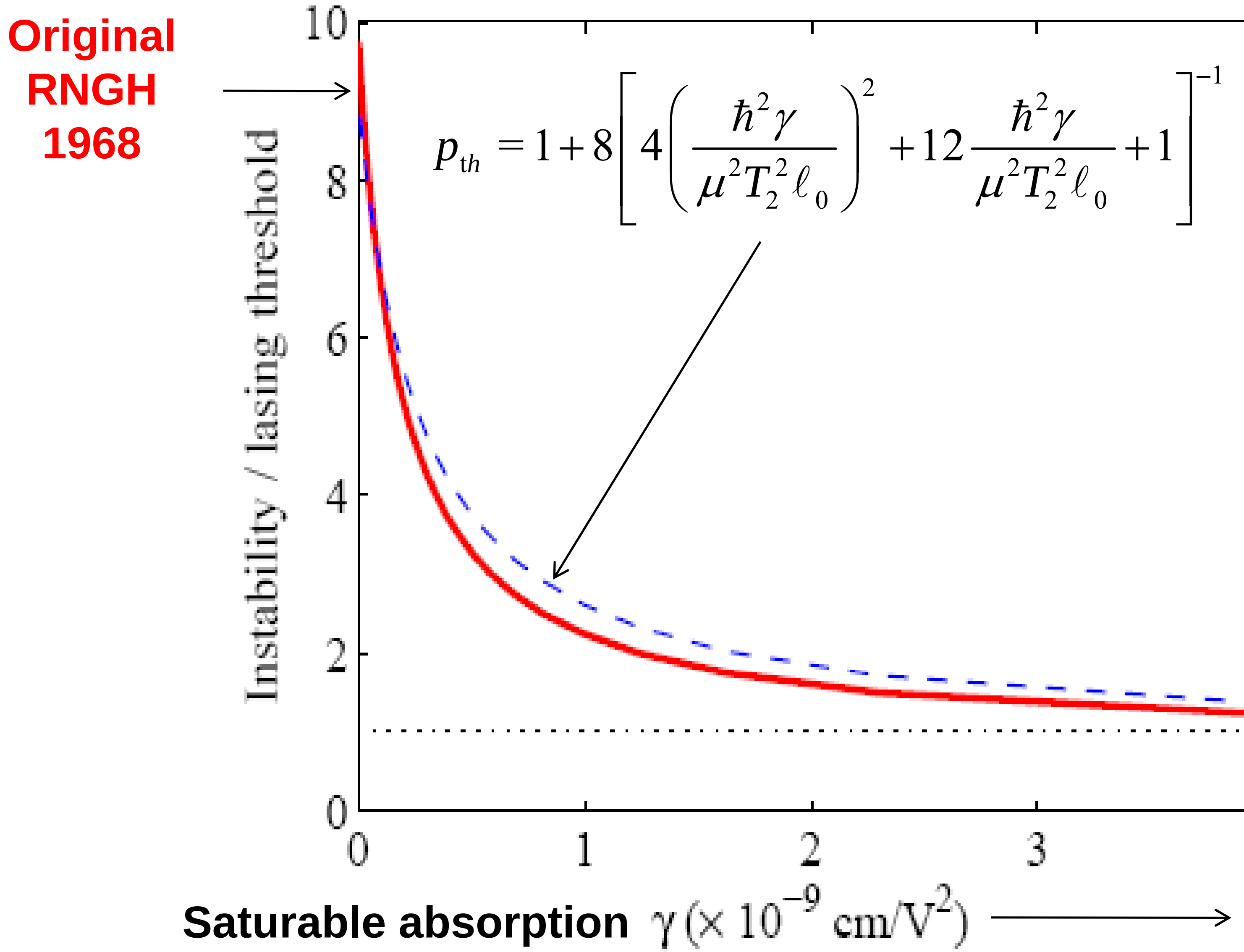
$$p \equiv \frac{\Delta_p}{\Delta_{th}}$$

CW- Rabi Frequency

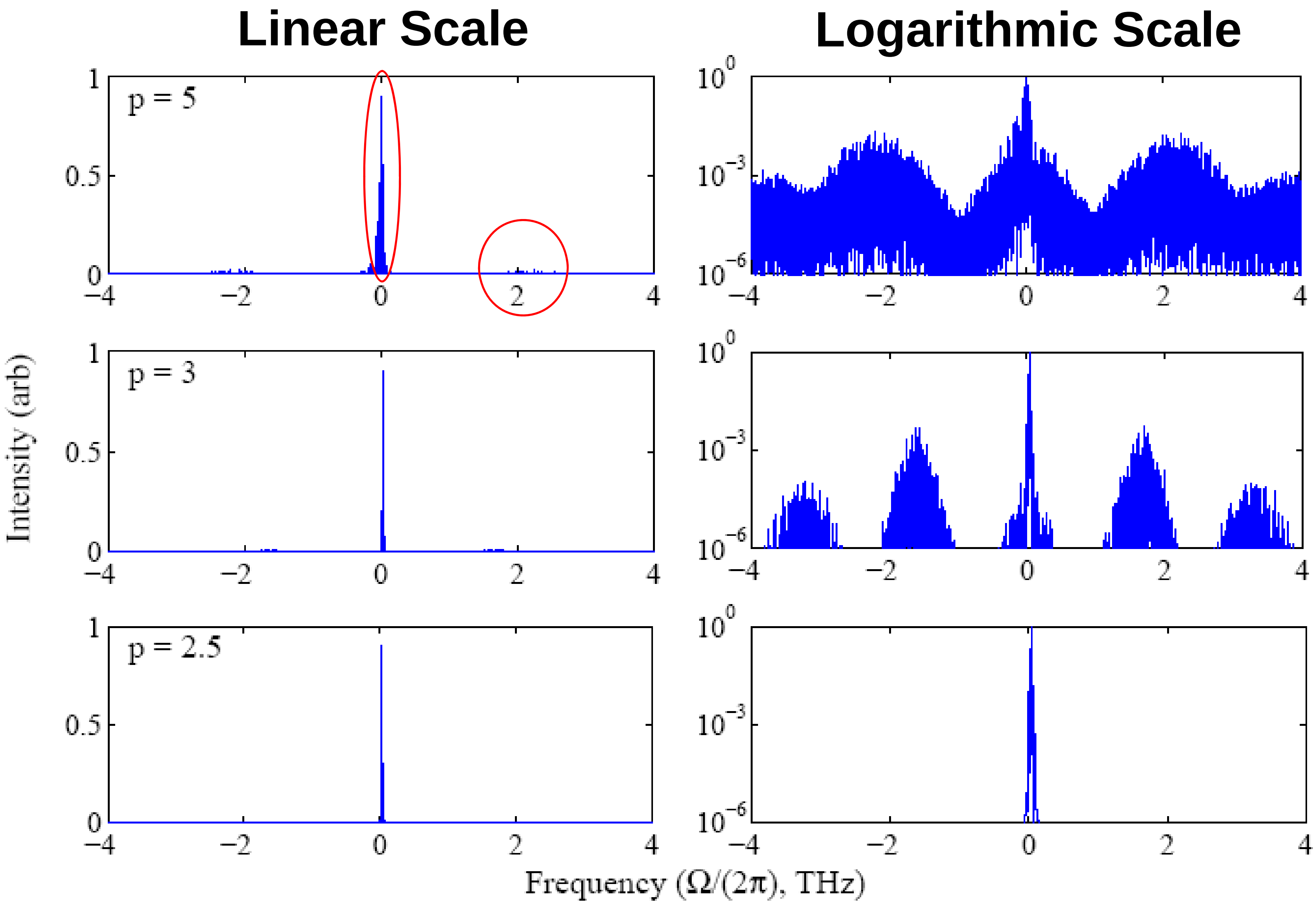
$$\Omega_{Rabi} = \sqrt{\frac{p-1}{T_1 T_2}}$$

Boyd: Nonlinear Optics

RNGH Instability Threshold

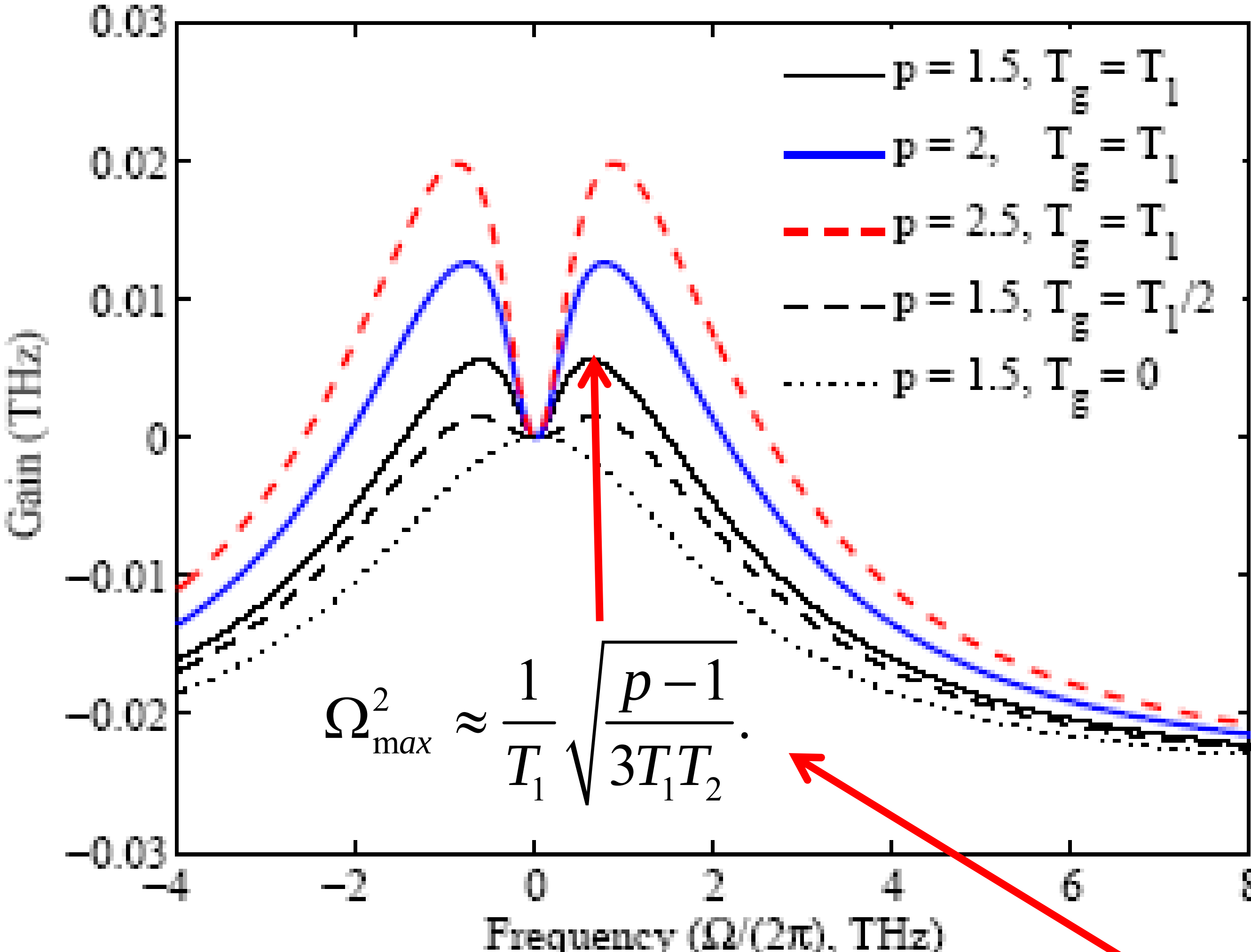


Numerical Simulations



A. Gordon et al., PRA 77, 053804 (2008)

Linear (Standing Wave) Cavity (SHB)



$$\Omega_{max}^2 \approx \frac{1}{T_1}\sqrt{\frac{p-1}{3T_1T_2}}.$$

$$\sim \sqrt{\frac{1}{T_1}\cdot\Omega_{Rabi}}$$

Inversion Grating Decay Time

$$\frac{1}{T_g} = \frac{1}{T_1} + 4k^2D$$

AlInAs-nGaAs heterost.

$D = 400\,cm^2/sec$

$k = 3.7\times10^4\ cm^{-1}$

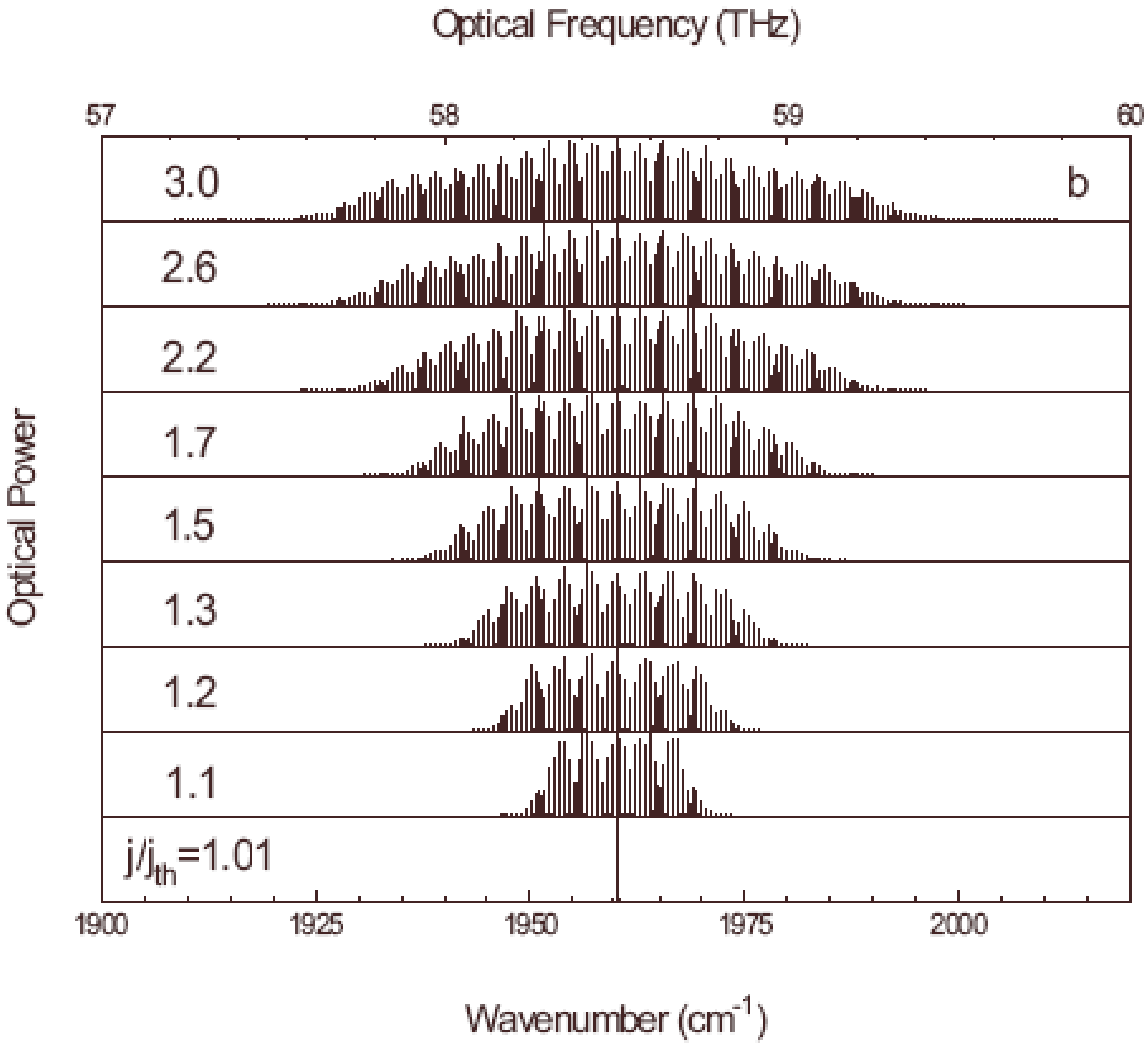
$4k^2D \approx 2THz$

A. Gordon et al., PRA 77, 053804 (2008)

Parameter Values

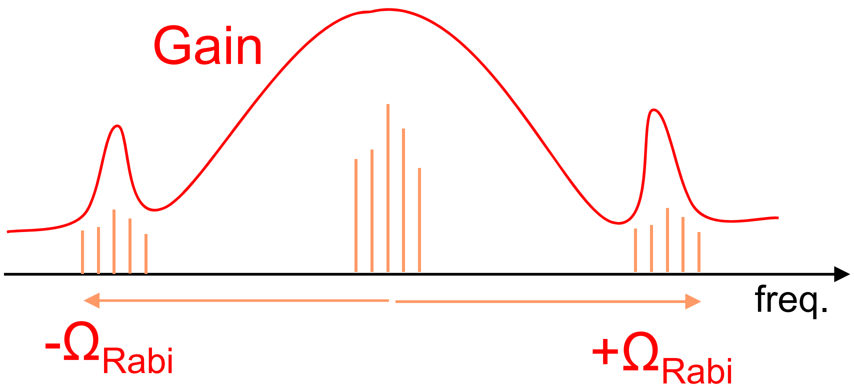
Quantity	Symbol	Value
Gain recovery time	T_1	0.5 ps
Dephasing time	T_2	0.067 ps
Linear cavity loss	l_0	5 cm^{-1}
Transition dipole element	μ	2.54 nm $\times e$
Background refractive index	n	3
Cavity length	L	3 mm
Saturable absorber coefficient	γ	$10^{-8}\,\frac{cm}{V^2}$

Numerical Sim.: SHB, RNGH but no saturable absorber

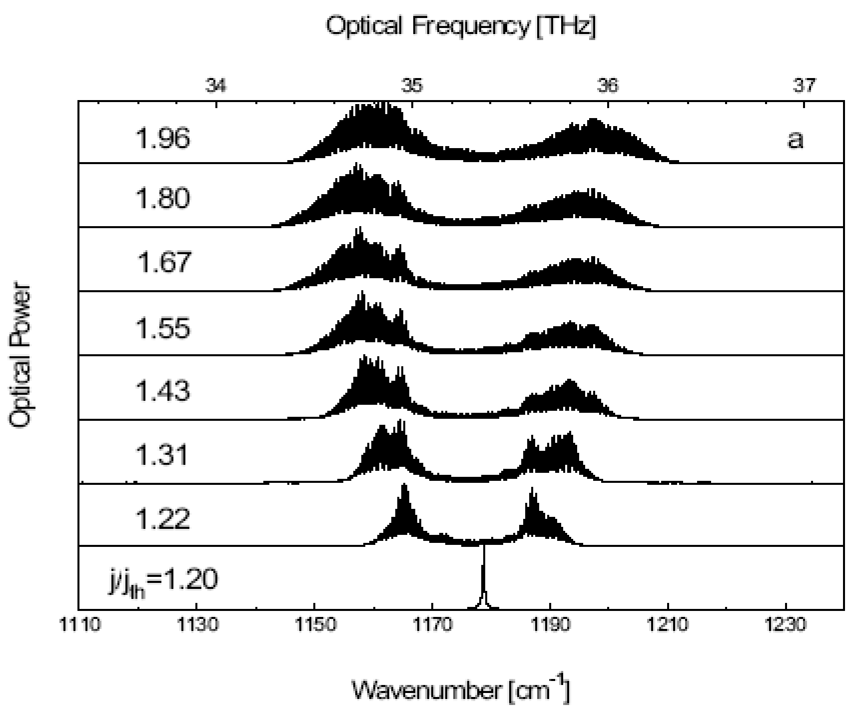


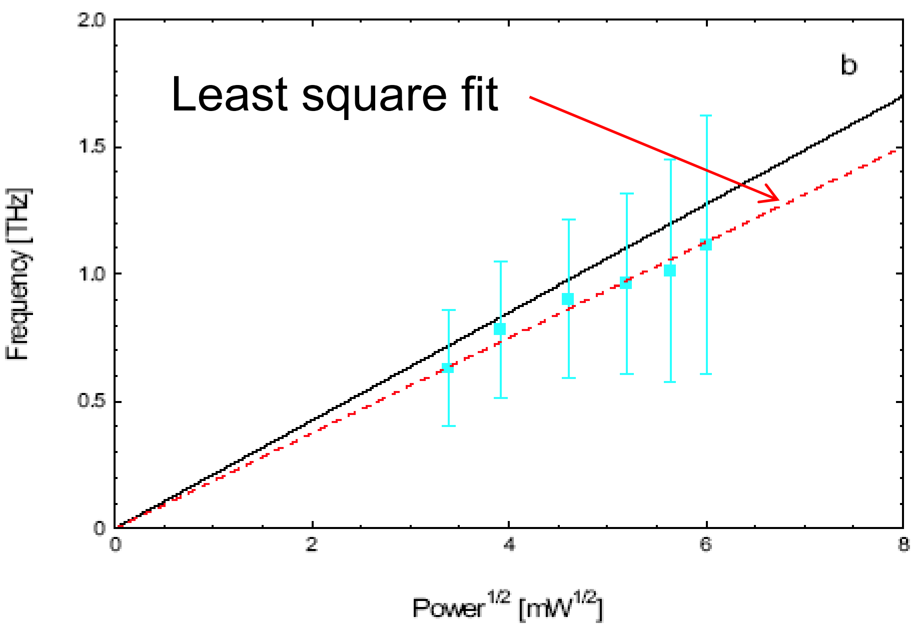
A. Gordon et al., PRA 77, 053804 (2008)

Including Saturable Absorber



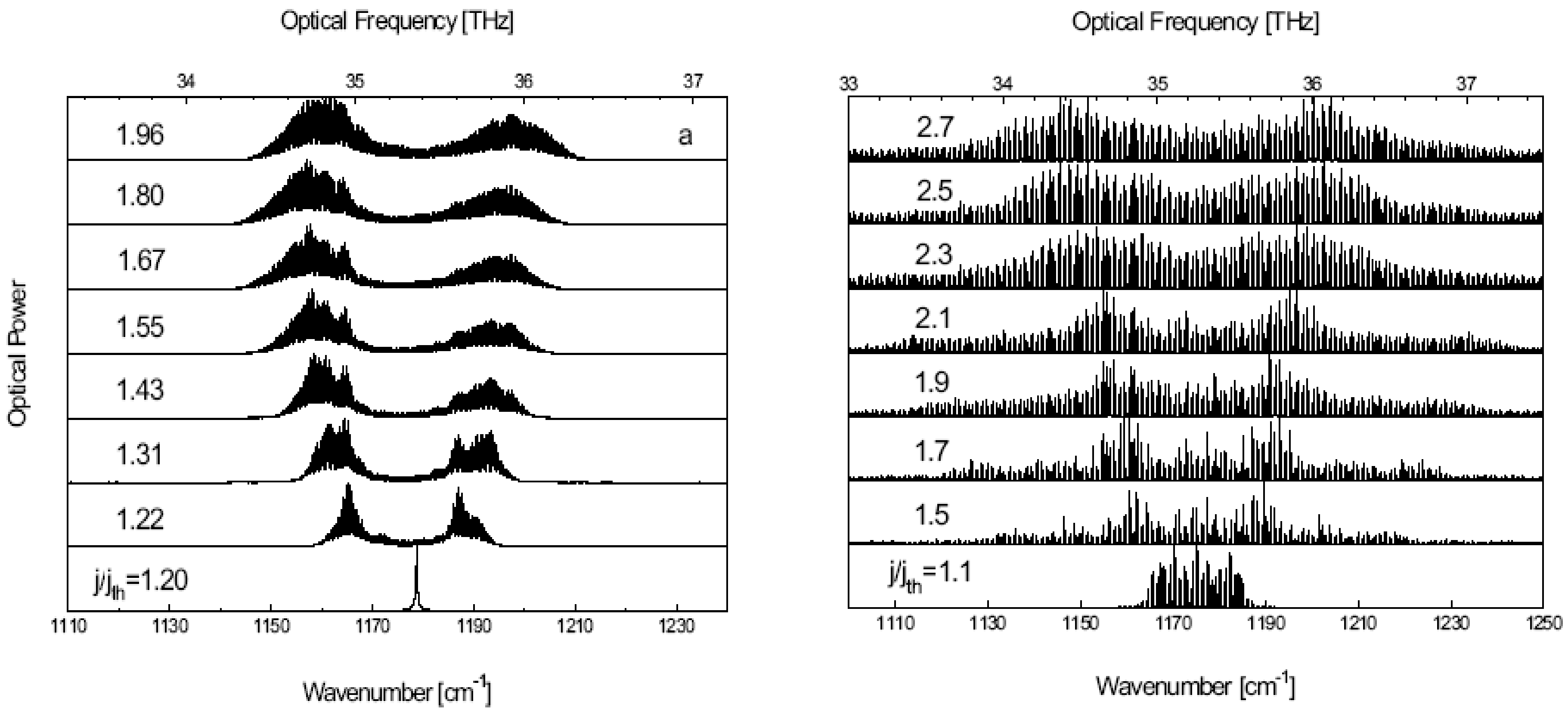
3μm wide buried heterostructure laser at 8.38 μm.





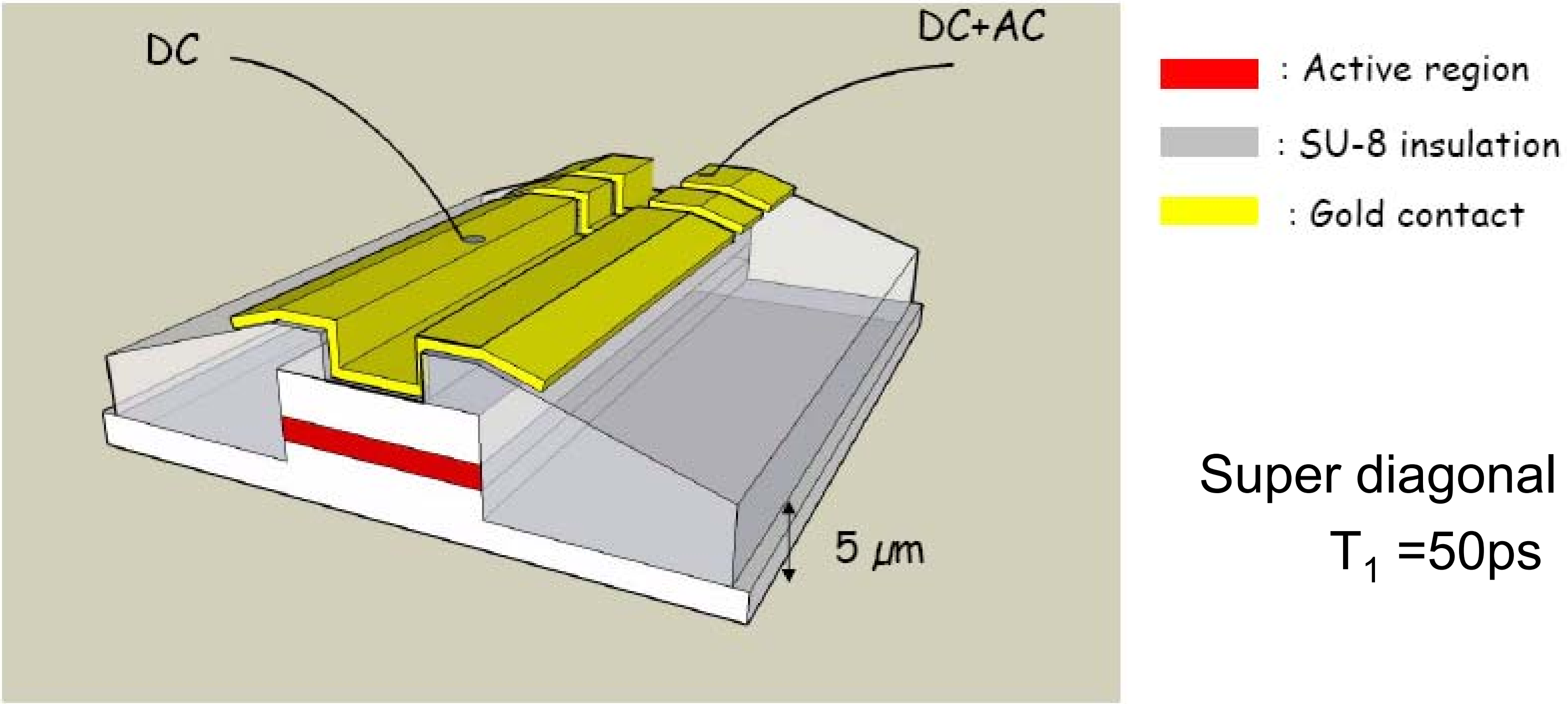
A. Gordon et al., PRA 77, 053804 (2008)

Maxwell-Bloch Simulations



A. Gordon et al., PRA 77, 053804 (2008)

Actively Modelocked QCL



Super diagonal gain

T_1 =50ps

Thick insulation is used to reduce the parasitic capacitance.

Pumping of small section: $\lambda = p*\lambda_{th} + m*\lambda_{th}*\sin(\omega_R * t)$

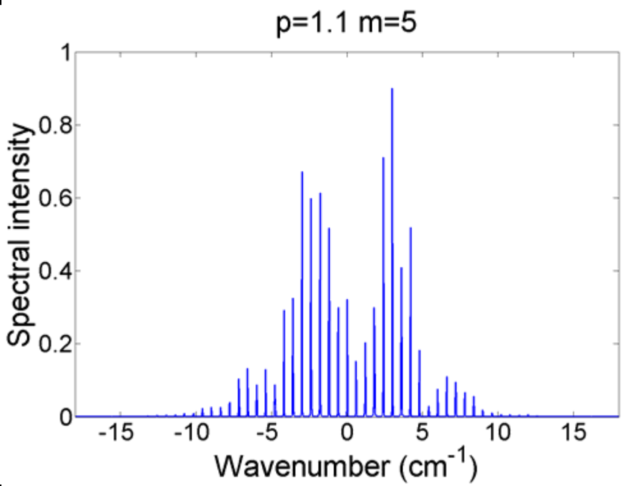
Pumping of long section: $\lambda = p*\lambda_{th}$

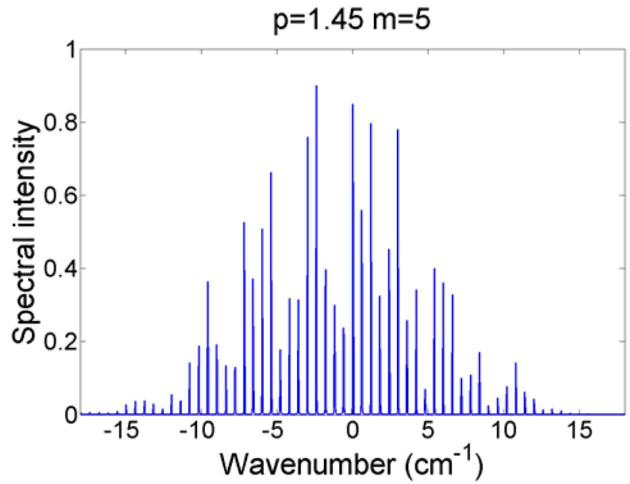
Ch. Wang, et al. CLEO 2008

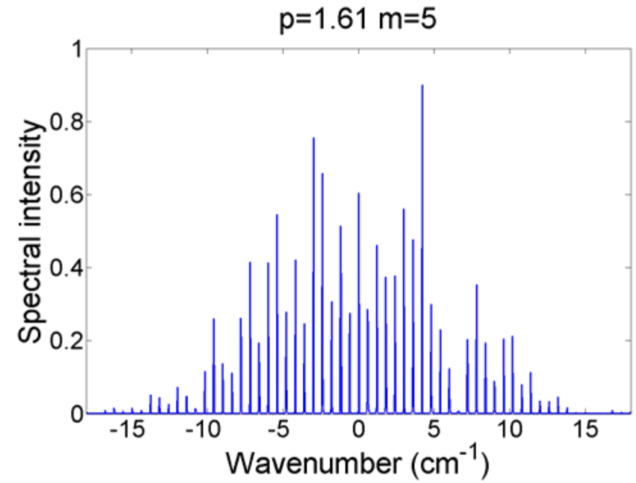
Parameter values

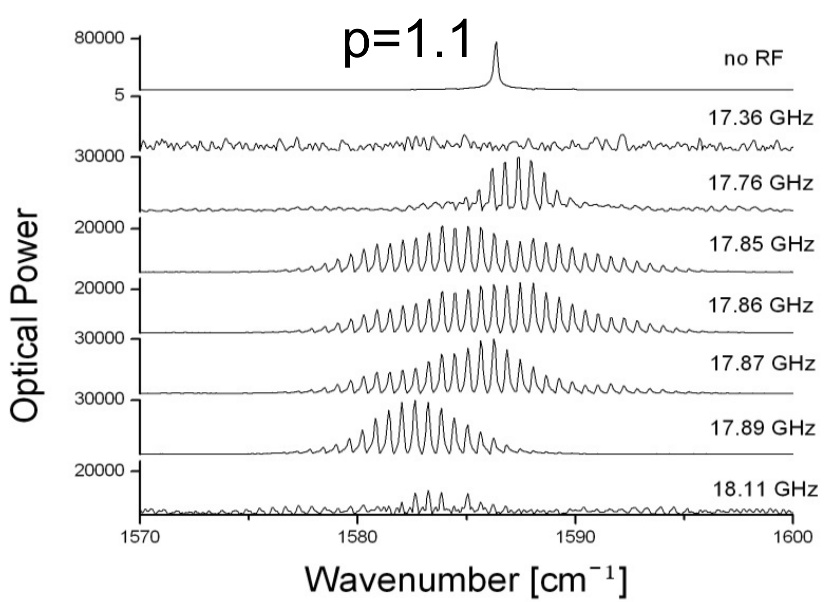
Quality	Symbol	Value
Gain Recovery Time	T_1	50 psec
Dephasing time	T_2	0.05 psec
Linear cavity loss	l_0	10 cm^{-1}
Mirror reflectivity	R	0.53
Transition dipole element	μ	2.54 nm × *e*
Background refractive index	*n*	3.2
Cavity length	*L*	2.6 mm
Modulator section length	L_s	0.24 mm

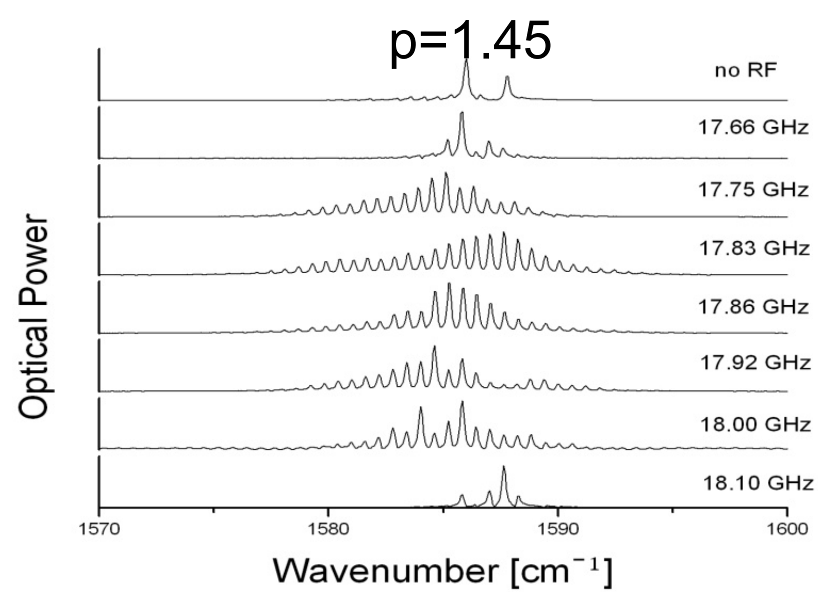
Spectra





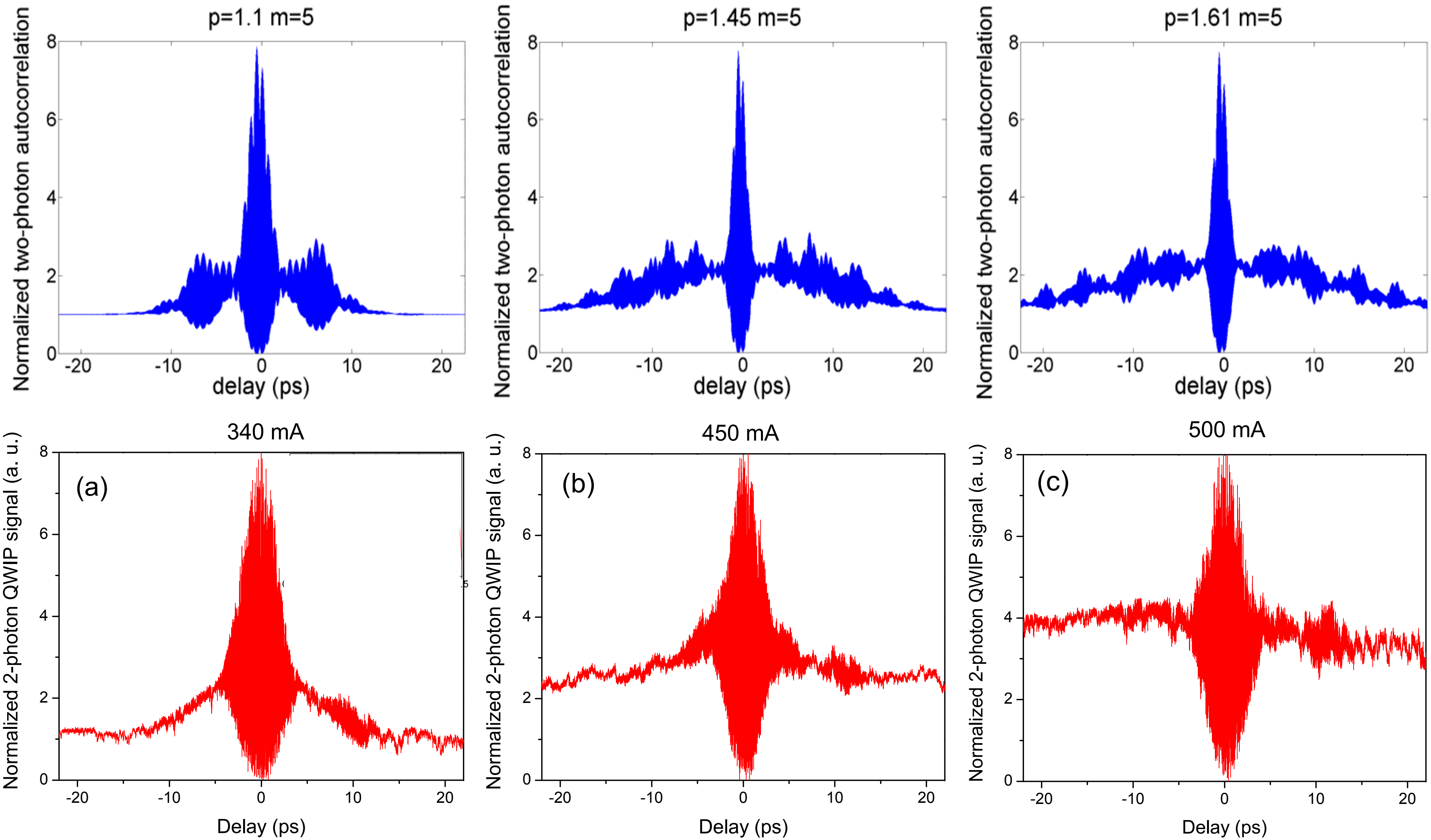






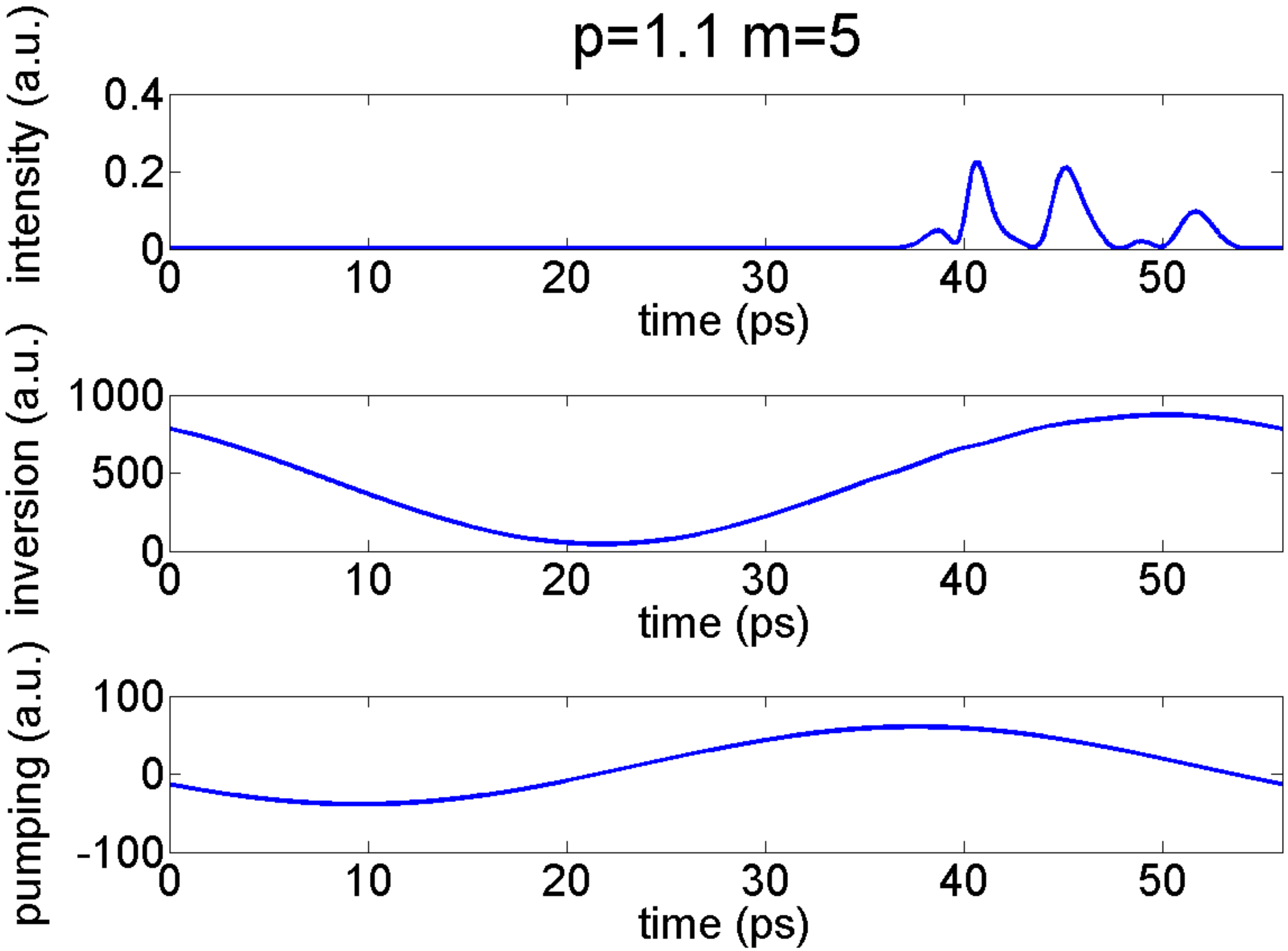
Ch. Wang, CLEO 2008

Autocorrelation plots including SHB



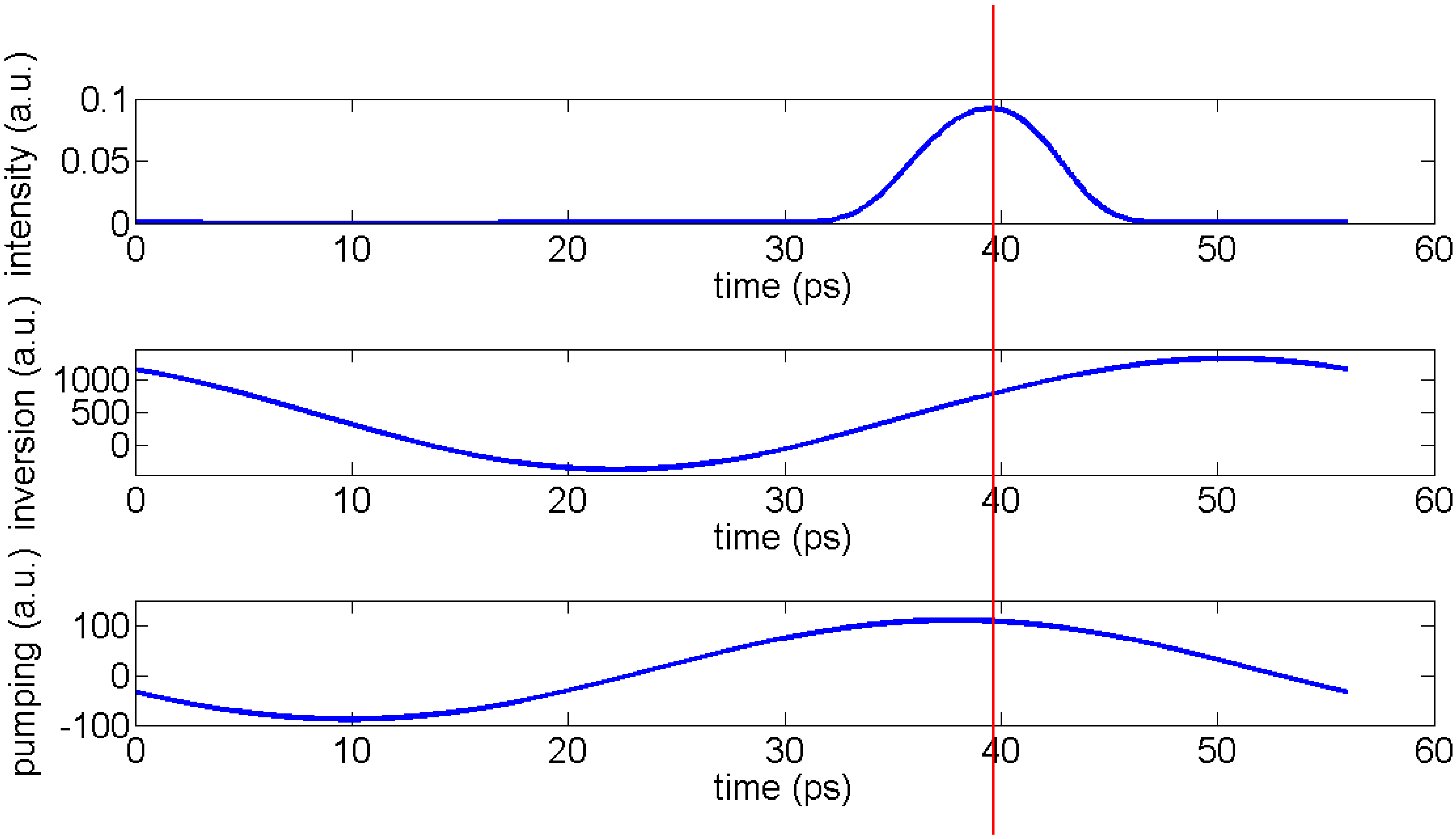
Laser Dynamics

Inside the modulation region:



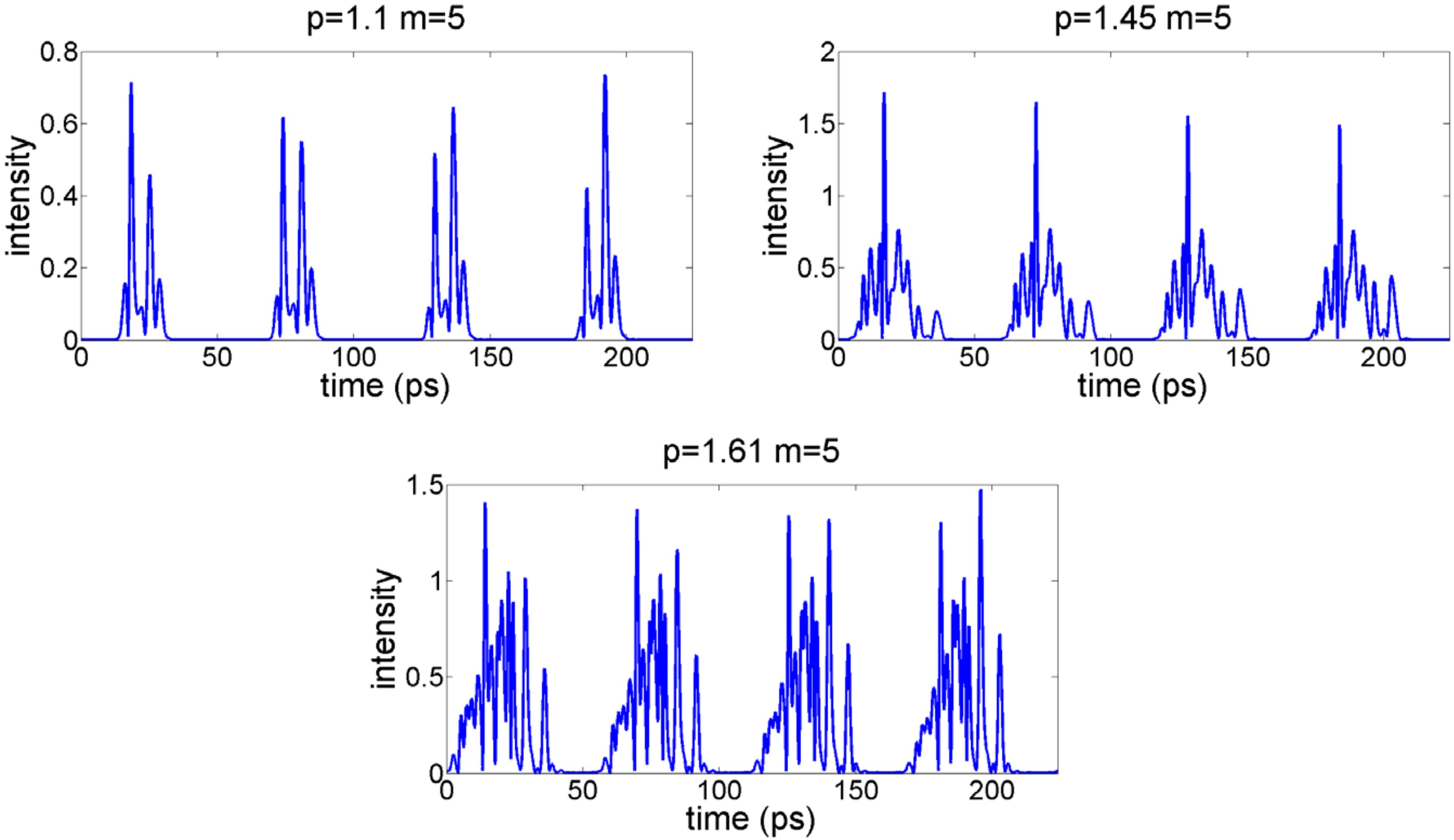
Laser Dynamics

Inside the modulation region without SHB:



PRL 82, 4428, (1999)

Pulse Trains at Output with SHB



Summary

1. Short gain recovery time

   • Enhances spectral holeburning – wideband multimode operation
   • No stable modelocking

2. Including saturable absorber effects

   • RNGH like coherent instability
   • Explains double-humped spectral shape
   • A ring laser suppresing SBH could confirm this picture

3. Routes to stable short pulses:

   a. Long gain recovery – superdiagonal structure
      Active modelocking leads to isolated "modelocked" pulses.

   b. Next: Passive mode locking with reverse biased section