PRINCETON UNIVERSITY
LASER SENSING LABORATORY
PULSE

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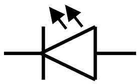
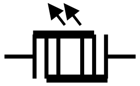
High-Speed Modulation Characteristic of a Quantum Cascade Laser

A. Hangauer[1], G. Spinner[1,2], M. Nikodem[1,3], and G. Wysocki[1]

[1] Electrical Engineering Department, Princeton University
[2] ETH Zurich, Zurich, Switzerland
[3] Wroclaw Research Centre EIT+, Wroclaw, Poland

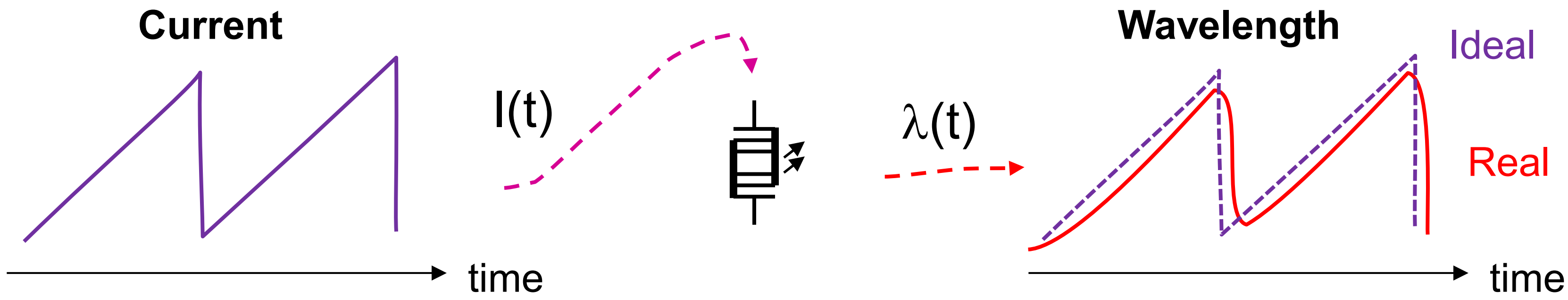
Scope of the work: Quantum Cascade Lasers

	Diode laser	Quantum cascade laser
		
Based on	Interband transitions (fast)	Intersubband transitions (ultra-fast)
Intensity modulation (current mod.)	Many experimental results	Few experimental results
Frequency modulation (current mod.)	Many experimental results	No full characterization so far

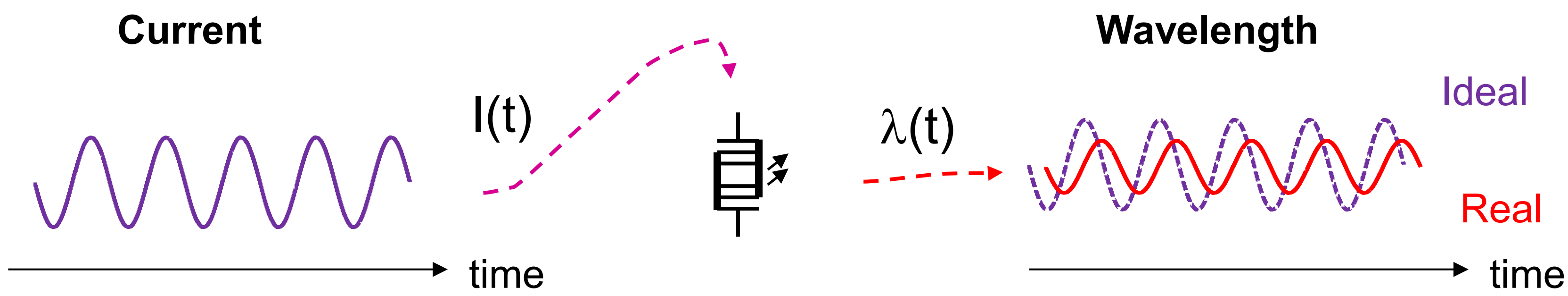
- RF modulation behavior interesting due to ultrafast QCL carrier dynamics
- High speed applications in spectroscopy rely on RF QCL behavior

Modulation behavior: what to expect?

a) Ramp edges appear distorted

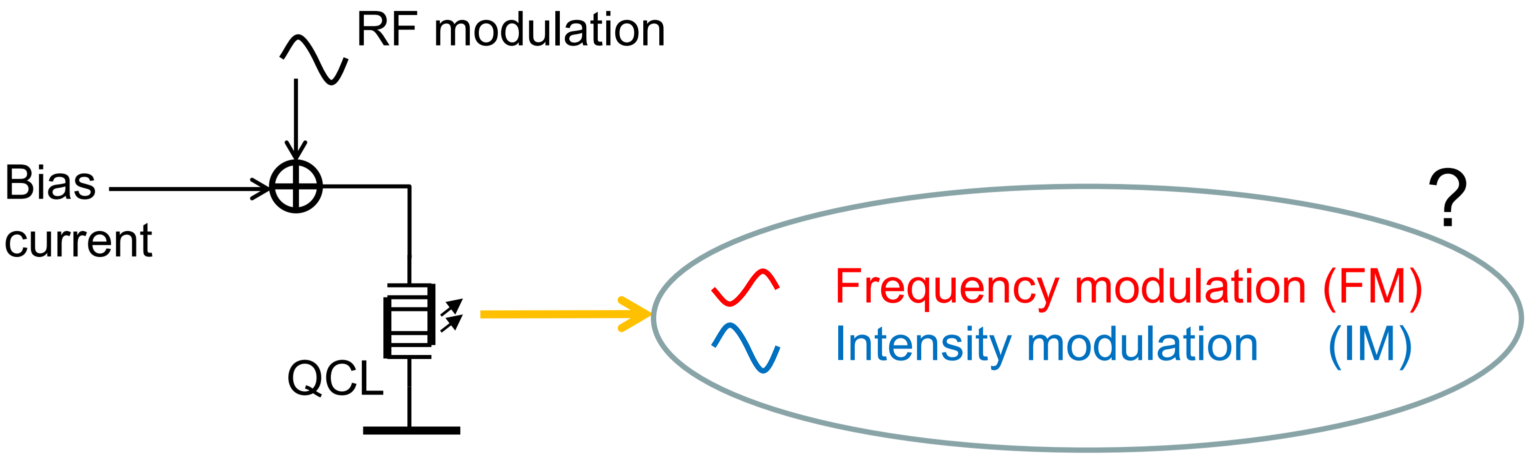


b) Sinusoids appear attenuated and phase-shifted



- Response to sinusoids contains all information on tuning dynamics!

Experiment outline

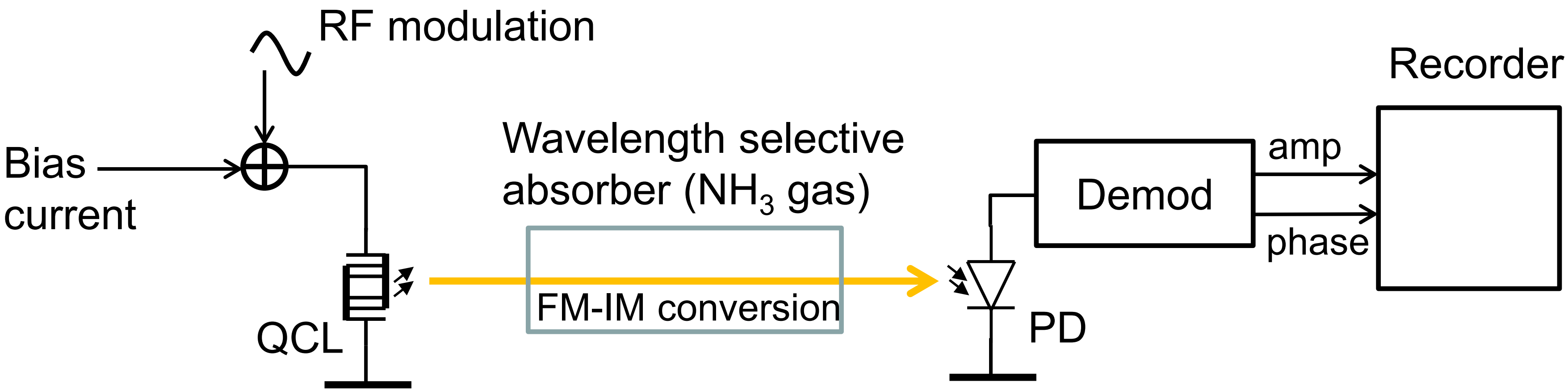


Technical limitations

- No commercial mid-IR detectors for *f* > 1 GHz
- Commercial QCLs not engineered for good RF performance
- (No high speed communication applications in the mid-IR)

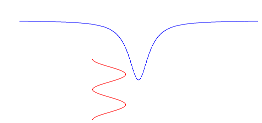
Idea: Quantify FM to IM ratio (independent on laser parasitics!)
up to current detector frequency limits (~1 GHz).

Experimental setup

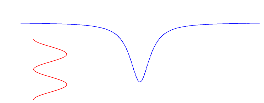


- Gas absorption implements FM to IM conversion
- When slowly scanning laser bias around the NH_3 line, FM and IM are measured:

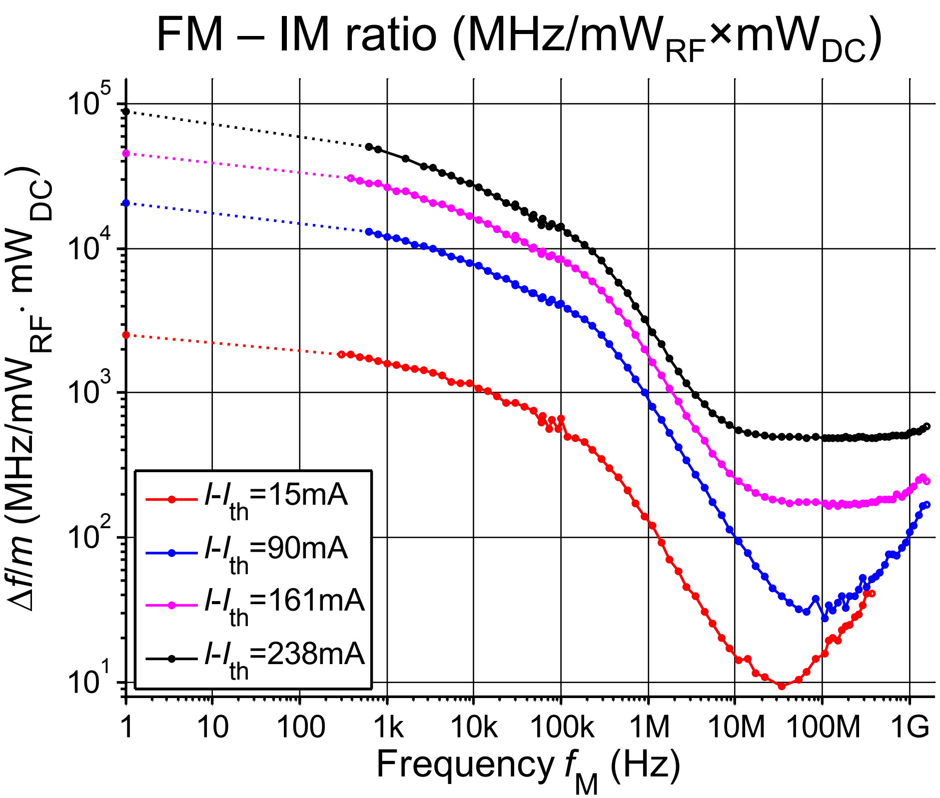
On absorption line: FM and IM

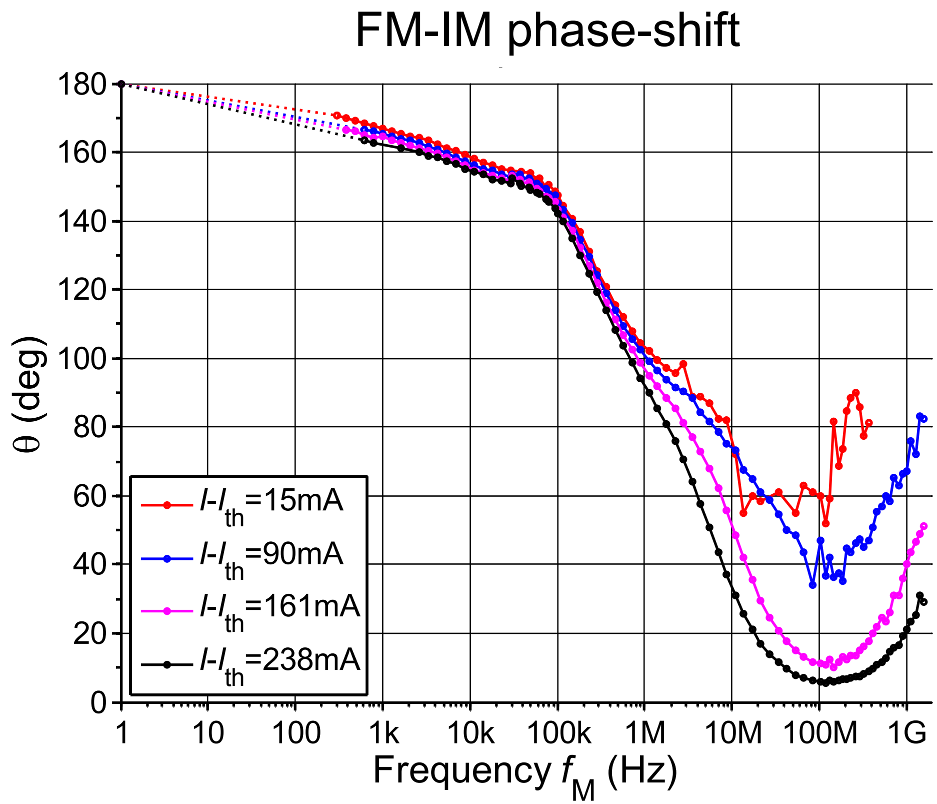


Detuned from line: IM only



Results: FM-IM ratio and phase-shift



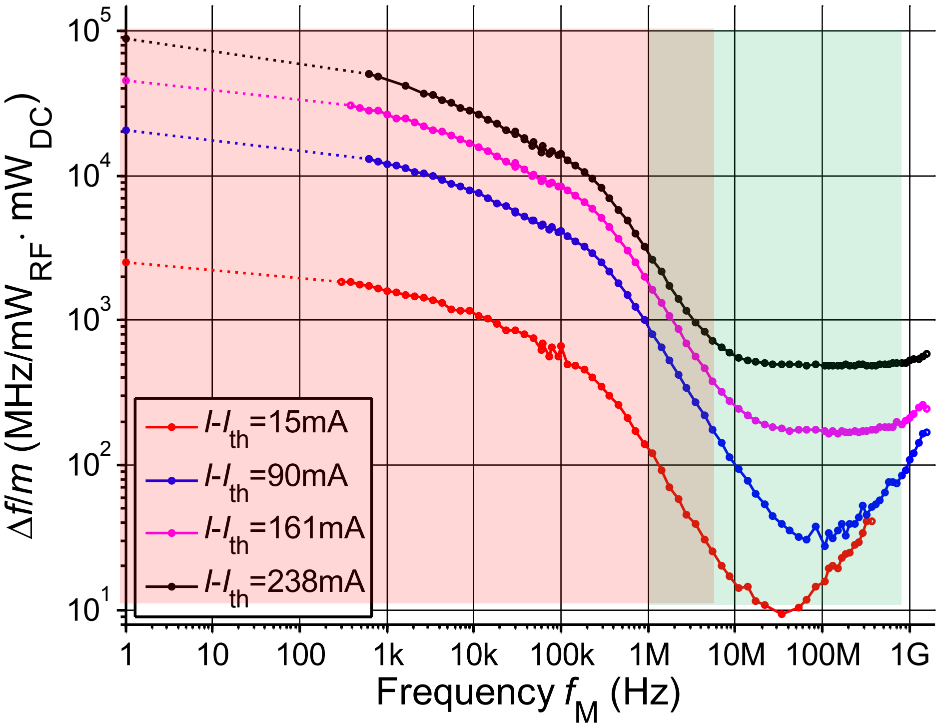


- How to interpret data?

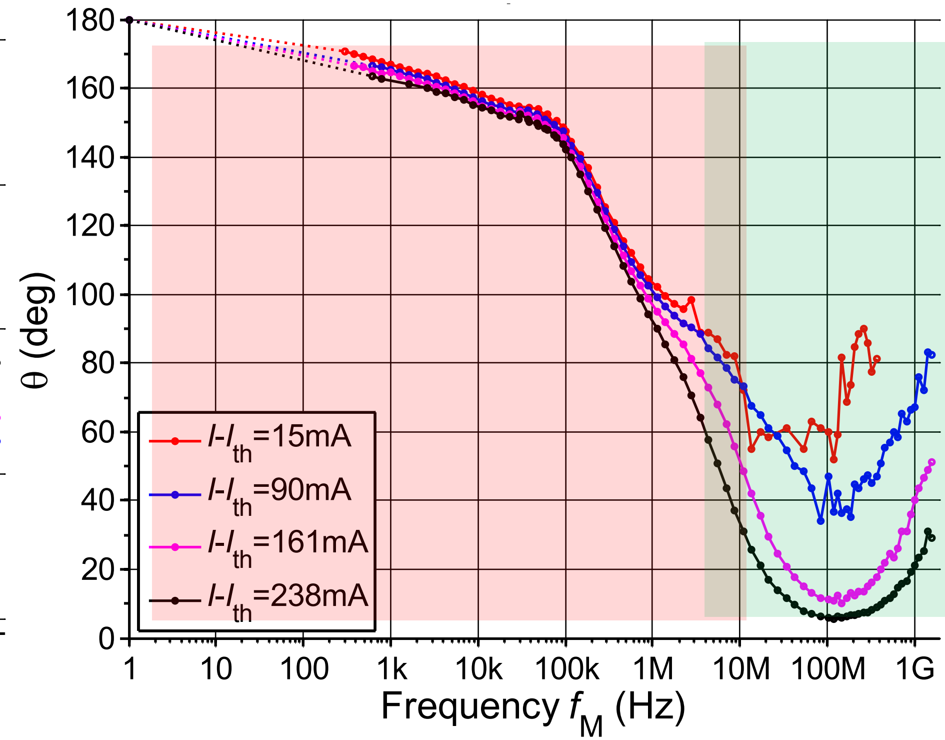
QCL: Hamamatsu λ=9.6μm in HHL (high heat load) package

Results: FM-IM ratio and phase-shift

FM – IM ratio ($MHz/mW_{RF} \times mW_{DC}$)



FM-IM phase-shift

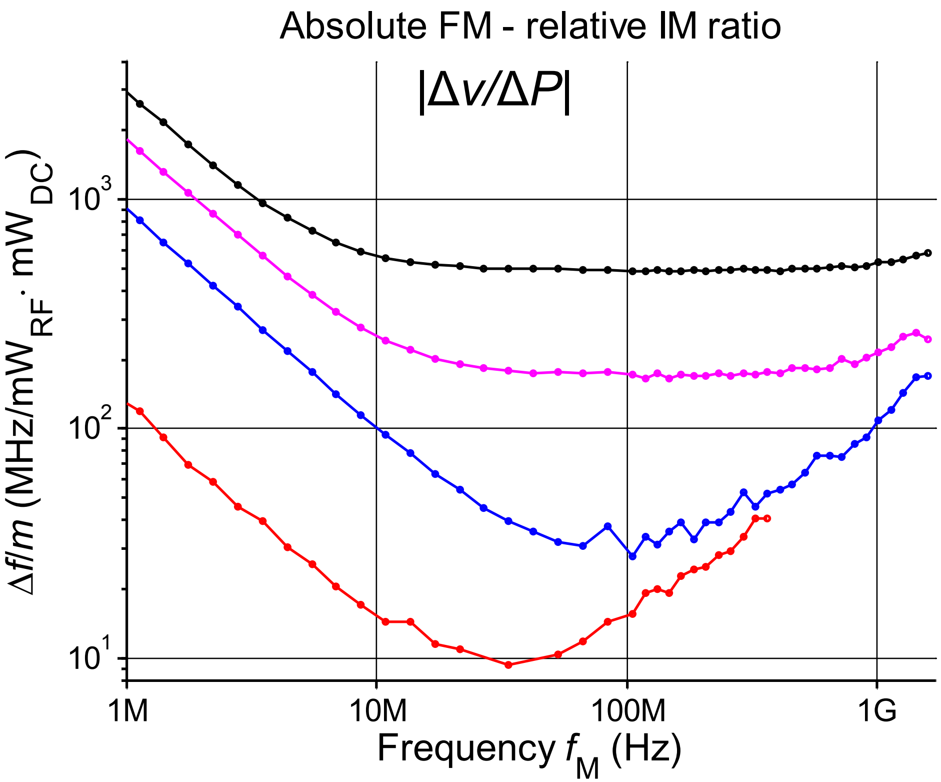


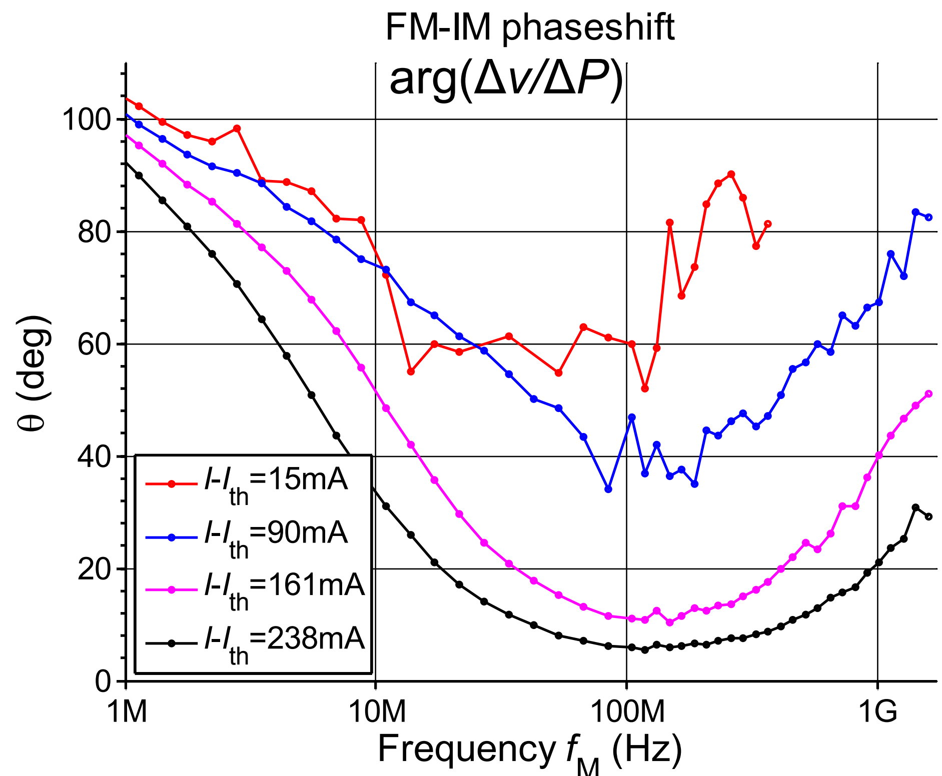
Thermal tuning (due to self heating), slow

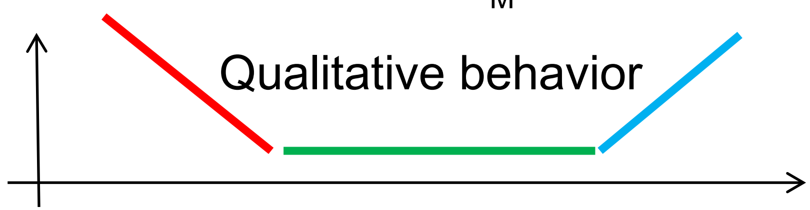
Electronic tuning (carrier density/gain change) (first time observed in QCLs!)

How to interpret results at f > 1 MHz?

Results: Interpretation







$\Delta v(t) \sim -\int \Delta P(t)$ — Thermal tuning

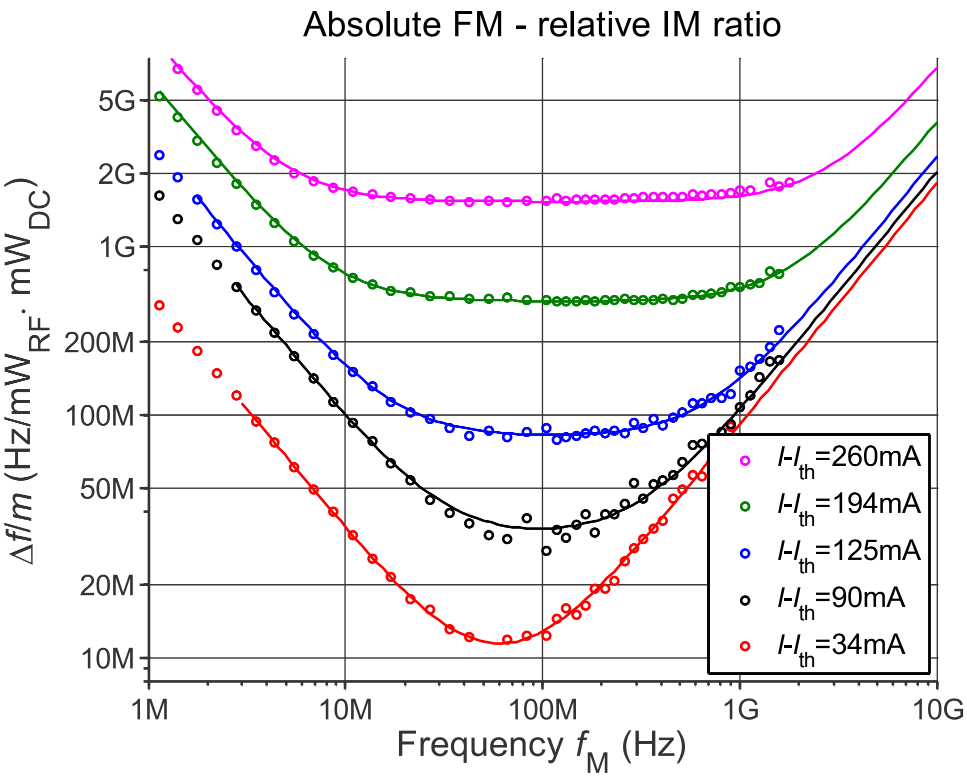
$\Delta v(t) \sim \Delta P(t)$ — Adiabatic chirp

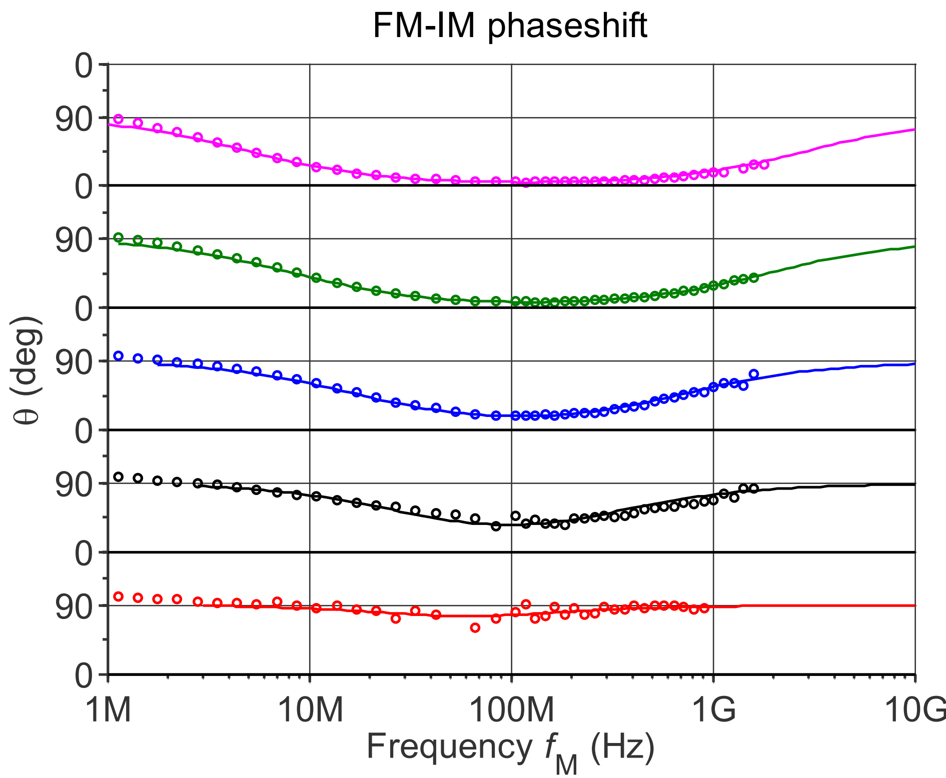
$\Delta v(t) \sim \frac{d}{dt}\Delta P(t)$ — Transient chirp

How accurate is this interpretation (which is inspired from non-QC lasers)?

Fit of experimental data with model

Fit with theoretical model





Excellent agreement between experiment (amplitude *and* phase) and theory

Verified existence of three tuning effects (thermal, adiabatic and transient chirp)

Microphysical interpretation of mechanisms

All tuning effects work by *indirectly* modifying the lasers refractive index

$\Delta\nu(t) \sim -\int \Delta P(t)$

Thermal tuning

Governed by temperature dynamics

At $f > 1/\tau_{therm}$ heat cannot follow injection current: integral behavior

$\Delta\nu(t) \sim \frac{d}{dt}\Delta P(t)$

Transient chirp

General laser behavior

When laser power changes, gain deviates momentarily from steady state value to create or destroy additional photons: derivative behavior

$\Delta\nu(t) \sim \Delta P(t)$

Adiabatic chirp

Gain compression (non-ideal laser behavior)

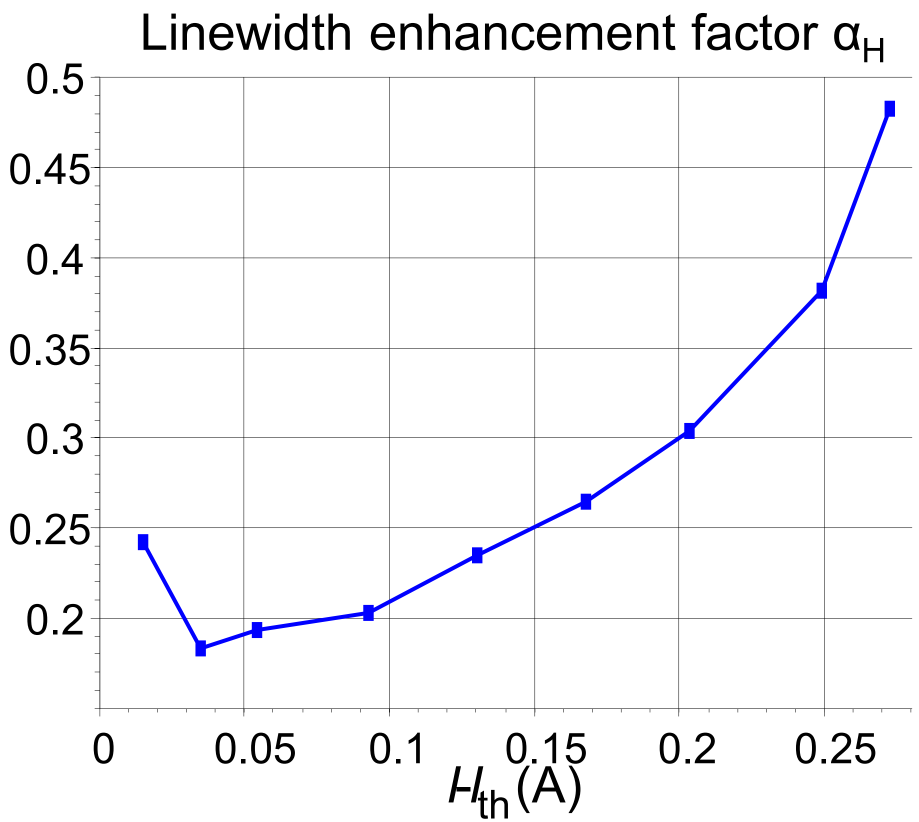
e.g. Gain saturates at high laser power,

gain curve shifts with voltage: proportional behavior

Extraction of linewidth enhancement factor

What else does the experiment tell us?

Transient chirp: $\Delta v(t) = (4\pi P_0)^{-1}\, \alpha_H\, \mathrm{d}P(t)/\mathrm{d}t$ (α_H: linewidth enhancement factor)



- Simple and accurate measurement method for alpha factor
- $\alpha_H < 1$! (diode lasers: $\alpha_H = 3..7$)

Conclusion

- First characterization of FM tuning behavior of QCLs in the RF domain (to 1.7 GHz)
- Many effects observed: $\Delta\nu(t) \sim -K_{th}\int\Delta P(t) + K_{ac}\,\Delta P(t) + K_{tc}\,\frac{d}{dt}\Delta P(t)$
  - Thermal tuning
  - Transient chirp, which allows for measurement of alpha factor
  - Adiabatic chirp (presently not predicted by QCL rate equations)
- Future investigation: Find physical reason for gain compression
  - Include this effect in rate equation modeling
  - Study effects on IM, injection locking, feedback sensitivity, etc…
  - Study relation to four-wave mixing

Acknowledgement

- NSF ERC MIRTHE award EEC-0540832

Origin of chirp

Photon rate equation

$$\dot{S} = v_g g(N,S)S - \frac{S}{\tau_p}$$

S: photon number
N: inversion carrier density (N_u-N_l)
g: gain coefficient

Refractive index of AR and emission frequency

$$2\pi\Delta\nu = \frac{\alpha_H}{2}\Delta N \frac{\partial g}{\partial N}$$

α_H: linewidth enhancement factor

Linearization and solution in frequency domain:

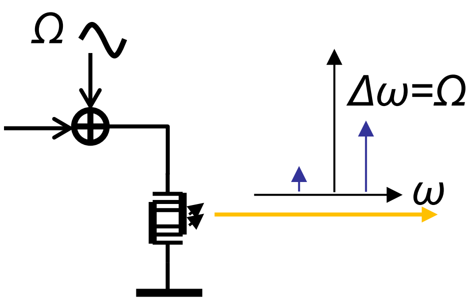
$$\frac{\Delta\nu e^{i\theta}}{\Delta S} S_0 = \frac{\alpha_H}{2}\left(if - \frac{v_g S_0}{2\pi}\frac{\partial g}{\partial S}\right)$$

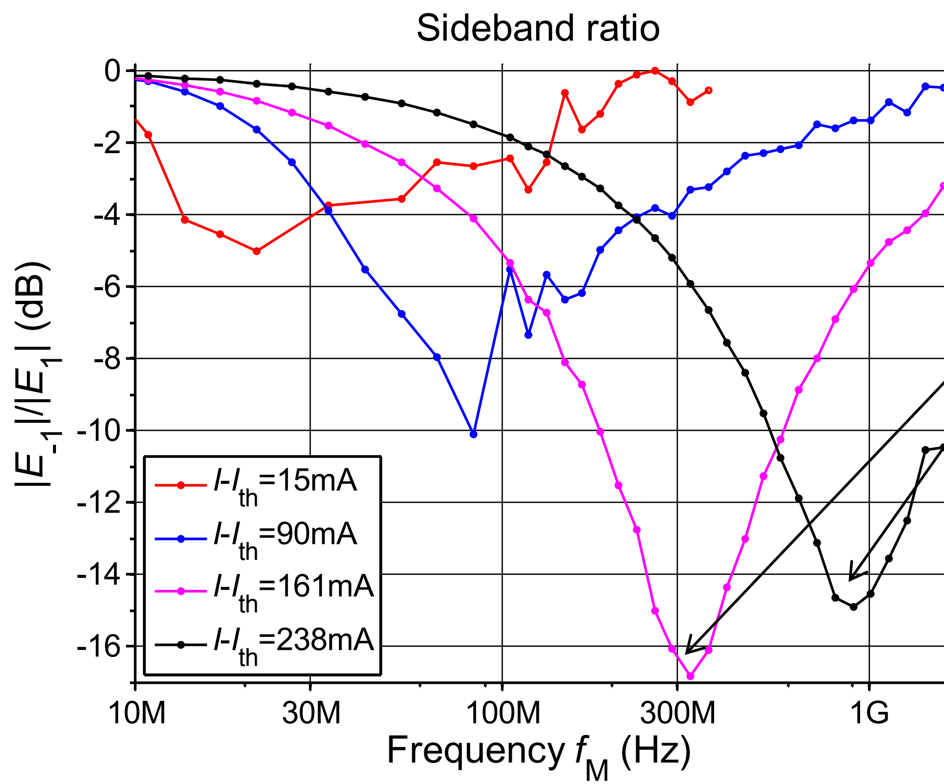
Transient chirp (if) — Adiabatic chirp ($\frac{v_g S_0}{2\pi}\frac{\partial g}{\partial S}$)

No adiabatic chirp, when gain is only dependent on carrier density (*g*=*g*(*N*))
g = g(…, S) dependency is phenomenological assumption
Quantification of gain nonlinearity possible trough adiabatic chirp

Consequence of low linewidth enhancement factor

The low linewidth enhancement factor allows for single sideband modulation (SSB)!

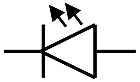
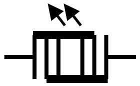
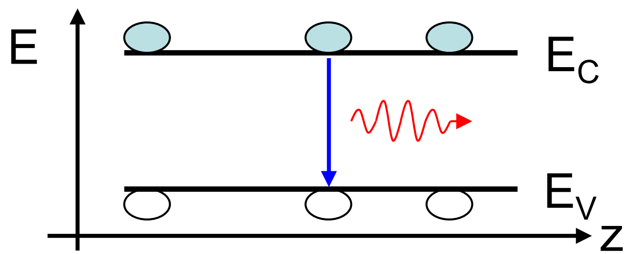
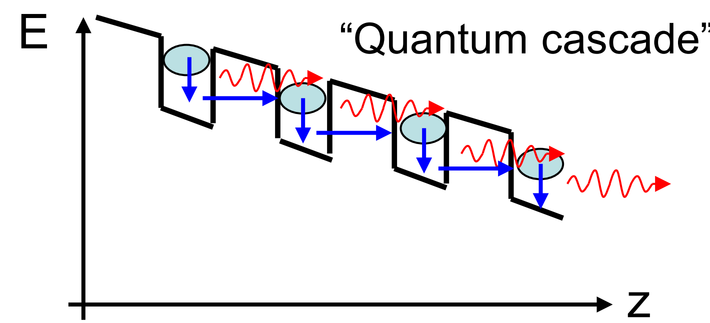




(quasi) single side-band modulation

For SSB α_H < 1 is required (Non QC lasers have α_H=3...10, hence SSB is impossible)

Scope of the work: Quantum Cascade Lasers

	Diode laser 	Quantum cascade laser 
Based on	Interband transitions	Intraband transitions
		
Intensity modulation	Well understood	Few experimental results
Frequency modulation	Well understood	No experimental results

- Experimental results for RF QCL modulation needed (~ 1GHz)