High-Speed Modulation Characteristic of a Quantum Cascade Laser

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**Scope of the work: Quantum Cascade Lasers**

### Diode laser
- **Based on** Interband transitions (fast)
- **Intensity modulation (current mod.)** Many experimental results
- **Frequency modulation (current mod.)** Many experimental results

### Quantum cascade laser
- **Based on** Intersubband transitions (ultra-fast)
- **Intensity modulation (current mod.)** Few experimental results
- **Frequency modulation (current mod.)** 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

*Princeton University Laser Sensing Group*
Modulation behavior: what to expect?

a) Ramp edges appear distorted

- 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 $\lambda=9.6\mu m$ in HHL (high heat load) package
Results: FM-IM ratio and 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

Absolute FM - relative IM ratio

|Δν/ΔP|

FM-IM phaseshift

arg(Δν/ΔP)

Frequency $f_M$ (Hz)

1M 10M 100M 1G

Absolute FM - relative IM ratio

$\Delta f/m (\text{MHz/mW})$

Qualitative behavior

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

Thermal tuning  
Adiabatic chirp  
Transient chirp

How accurate is this interpretation (which is inspired from non-QC lasers)?
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 \textit{indirectly} modifying the lasers refractive index

\[ \Delta \nu(t) \sim -\int \Delta P(t) \]
\begin{itemize}
  \item **Thermal tuning**
  \item Governed by temperature dynamics
  \item At \( f > 1/\tau_{\text{therm}} \) heat cannot follow injection current: integral behavior
\end{itemize}

\[ \Delta \nu(t) \sim \frac{d}{dt} \Delta P(t) \]
\begin{itemize}
  \item **Transient chirp**
  \item General laser behavior
  \item When laser power changes, gain deviates momentarily from steady state value to create or destroy additional photons: derivative behavior
\end{itemize}

\[ \Delta \nu(t) \sim \Delta P(t) \]
\begin{itemize}
  \item **Adiabatic chirp**
  \item Gain compression (non-ideal laser behavior)
  \item e.g. Gain saturates at high laser power, gain curve shifts with voltage: proportional behavior
\end{itemize}
What else does the experiment tell us?

Transient chirp: \( \Delta \nu(t) = (4\pi P_0)^{-1} \alpha_H \frac{dP(t)}{dt} \)  
\( (\alpha_H: \text{linewidth enhancement factor}) \)

- 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
• 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

\[
2\pi\Delta v = \frac{\alpha_H}{2} \Delta N \frac{\partial g}{\partial N}
\]

$\alpha_h$: linewidth enhancement factor

Linearization and solution in frequency domain:

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

No adiabatic chirp, when gain is only dependent on carrier density $(g = g(N))$

$g = g(\ldots, S)$ dependency is phenomenological assumption

Quantification of gain nonlinearity possible through adiabatic chirp
Consequence of low linewidth enhancement factor

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

For SSB $\alpha_H < 1$ is required (Non QC lasers have $\alpha_H=3...10$, hence SSB is impossible)
Scope of the work: Quantum Cascade Lasers

Based on

**Diode laser**
- Interband transitions

**Quantum cascade laser**
- Intraband transitions

**Intensity modulation**
- Well understood

**Frequency modulation**
- Well understood

- Few experimental results
- No experimental results

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