# GHz modulation of THz quantum cascade lasers

Stefano Barbieri
**Matériaux et Phénomènes Quantiques, University of Paris VII - Denis Diderot**

université PARIS DIDEROT PARIS 7

CNRS MPQ TeraView UNIVERSITY OF CAMBRIDGE

ITQW 2007

# Contributors

W. Maineult, S. Dhillon, C. Sirtori

Laboratoire MPQ, University of Paris 7, 75205 Paris, France

J. Alton

TeraView Ltd., Cambridge CB4 0WS, United Kingdom

N. Breuil

Thales Airborne Systems, 2 Ave. Gay Lussac, 78851 Enancourt, France

H. Beere, D. Ritchie

Cavendish Laboratory, University of Cambridge, Cambridge CB3 0HE, United Kingdom

# Outline

- Relaxation oscillations and Modulation bandwidth in QCLs
- Intracavity non-linear up conversion
- GHz sideband generation
- Microwave rectification
- Possible applications
- Conclusions and perspectives

# Rate equations and relaxation oscillations

- Frequency response

$$\left|\frac{\delta s}{\delta j}\right|^2 = \frac{1}{\tau_s^2}\,\frac{1}{\left(\Omega^2 - \frac{1}{\tau_s \tau_p}\right)^2 + \Omega^2\left(\frac{1}{\tau_s} + \frac{1}{\tau_3}\right)^2}$$

$\delta s \rightarrow$ photon density
$\delta j \rightarrow$ current density
$\Omega \rightarrow$ modulation frequency
$\tau_p \rightarrow$ photon lifetime =
$\tau_s \rightarrow$ stimulated lifetime
$\tau_3 \rightarrow$ upper state lifetime

$$\tau_s = \frac{1}{\sigma S}$$

$\sigma \rightarrow$ cross section
$S \rightarrow$ photon density

- Relaxation resonance frequency

$$\Omega_R = \sqrt{\frac{1}{\tau_s \tau_p} - \frac{1}{2}\left(\frac{1}{\tau_s} + \frac{1}{\tau_3}\right)^2} \longrightarrow$$

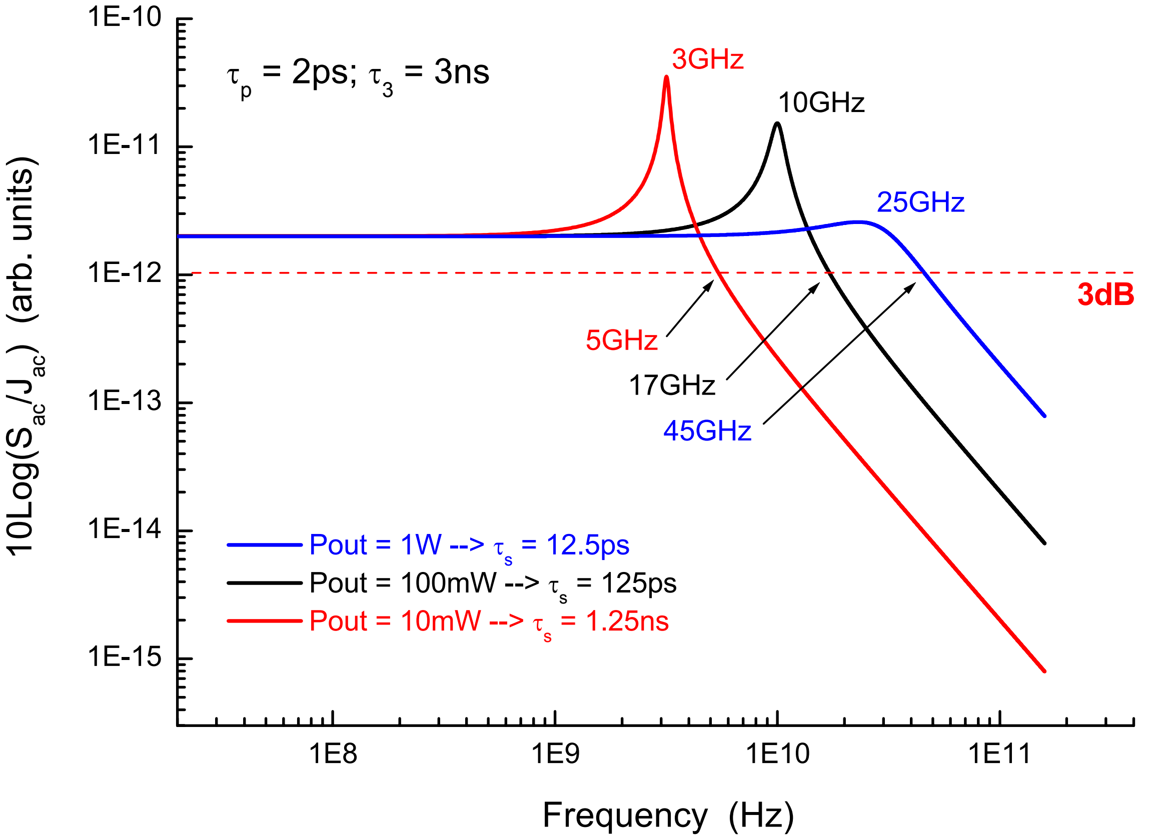
real → **Relaxation oscillations**

# Interband diode lasers: $\tau_3 \sim 1$ns

- $\tau_3 >> \tau_s > \tau_p \Rightarrow \Omega_R = \sqrt{\frac{1}{\tau_s \tau_p} - \frac{1}{2}\left(\frac{1}{\tau_s} + \frac{1}{\tau_3}\right)^2}$ **real**

- $f_{relax} = \frac{1}{2\pi} \frac{1}{\tau_s \tau_p}$

- $f_{3dB} = \sqrt{1 + \sqrt{2}}\, f_{relax}$



# Quantum cascade lasers: $\tau_3$ ~ 1ps

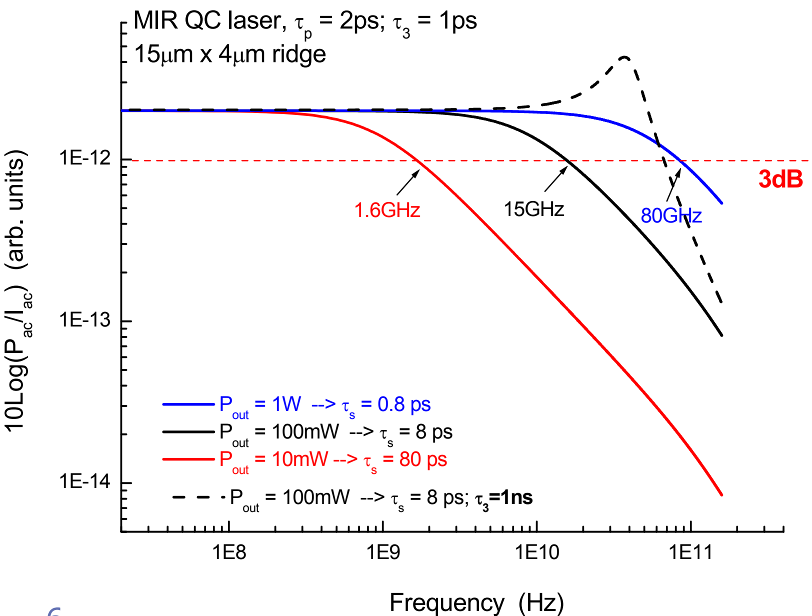
- "low" power regime
  - $\tau_s > \tau_3, \tau_p$
  - $f_{3dB} = \frac{1}{2\pi}\left(\frac{\tau_3}{\tau_s \tau_p}\right)^{1/2}$
- "high" power regime
  - $\tau_3, \tau_p > \tau_s$
  - $f_{3dB} = \frac{1}{\pi \tau_p}$

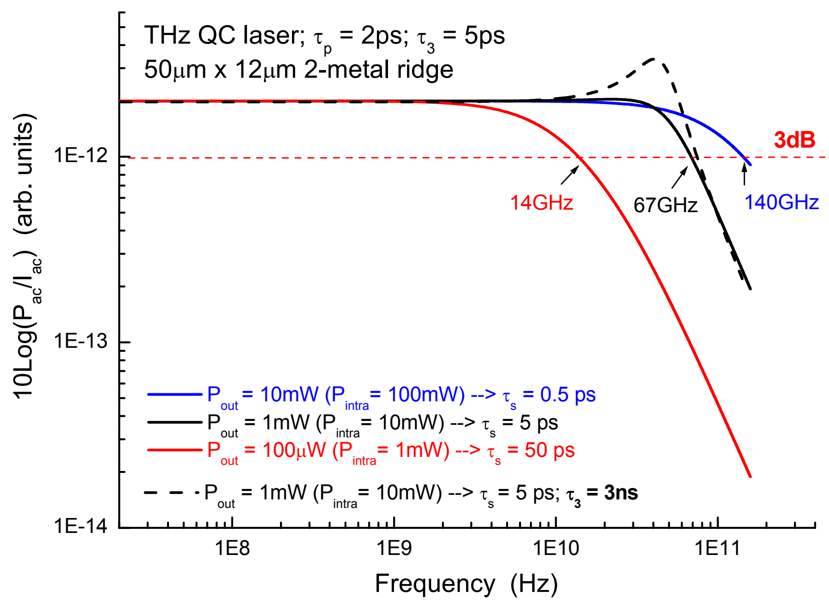
$$\Omega_R = \sqrt{\frac{1}{\tau_s \tau_p} - \frac{1}{2}\left(\frac{1}{\tau_s} + \frac{1}{\tau_3}\right)^2}$$ imaginary

$$\tau_s = \frac{1}{\sigma S N_P}$$

➡ **No relaxation oscillations, thanks to small $\tau_3$**

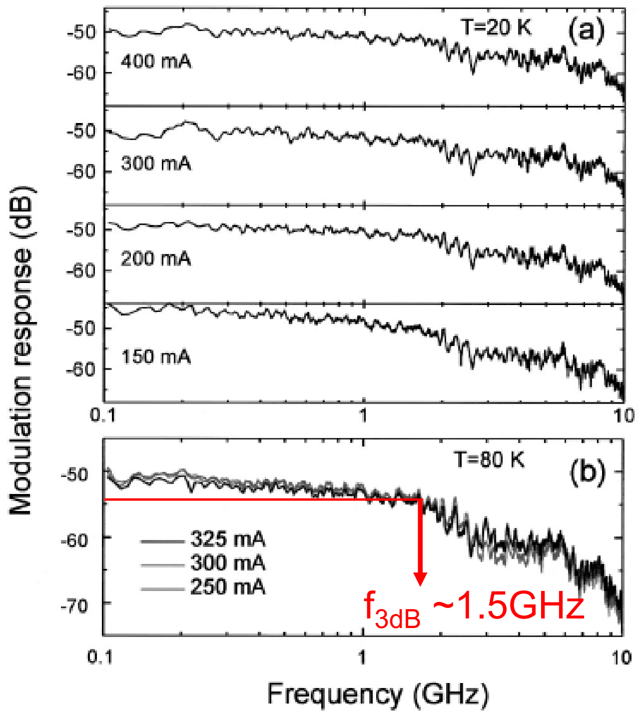
➡ **Modulation bandwidth increased, thanks to small $\tau_s$ and/or $\tau_p$**



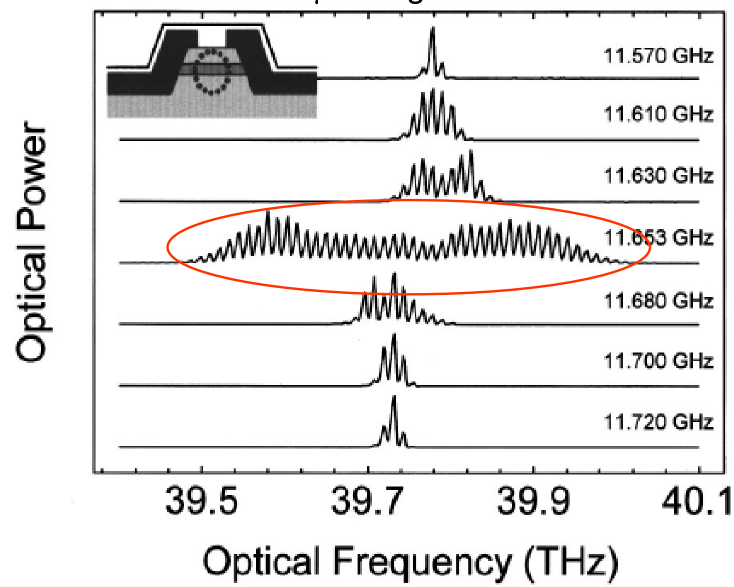



# GHz modulation of mid-IR QCLs

- Modulation up to 3GHz (-3dB)




1.25mm x 4.5µm ridge



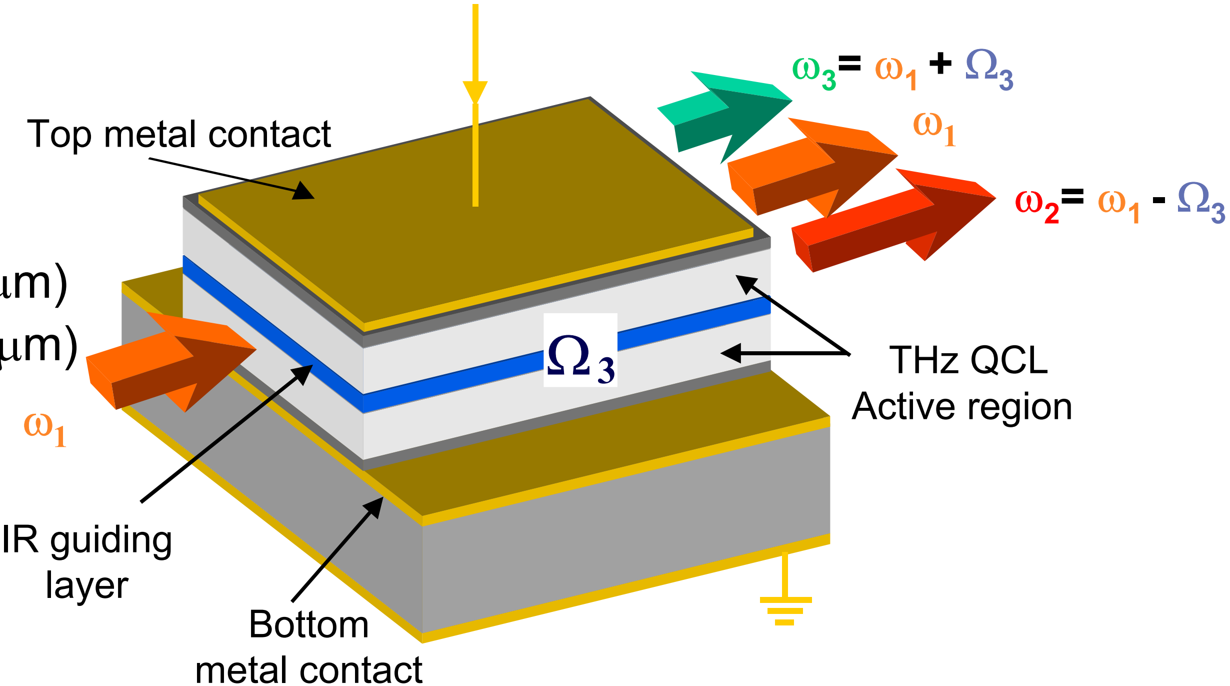

R. Paiella *et al.*, Appl. Phys. Lett. **77**, 169 (2000)
R. Paiella *et al.*, Appl. Phys. Lett. **76**, 2526 (2001)

- Modulation bandwidth limited by RC time constant (C~10pF)
- Number of sidebands increases significantly at the roundtrip

# Probing high f. modulation by THz up-conversion in the near-IR

By up-converting the THz field in the near-IR the GHz sidebands can be measured in a few seconds, and resolved spectrally with a high-resolution optical spectrum analyser → $\Delta f \sim 1$ MHz. This is much better than the resolution of the FTIR → $\Delta f \sim 7$ GHz

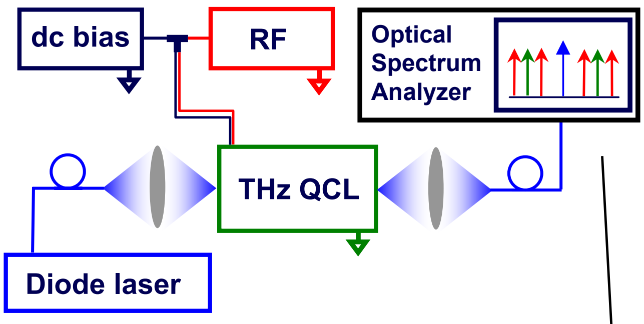
$\omega_1$ → near-IR (1.5µm)
$\Omega_3$ → 2.9THz (100µm)



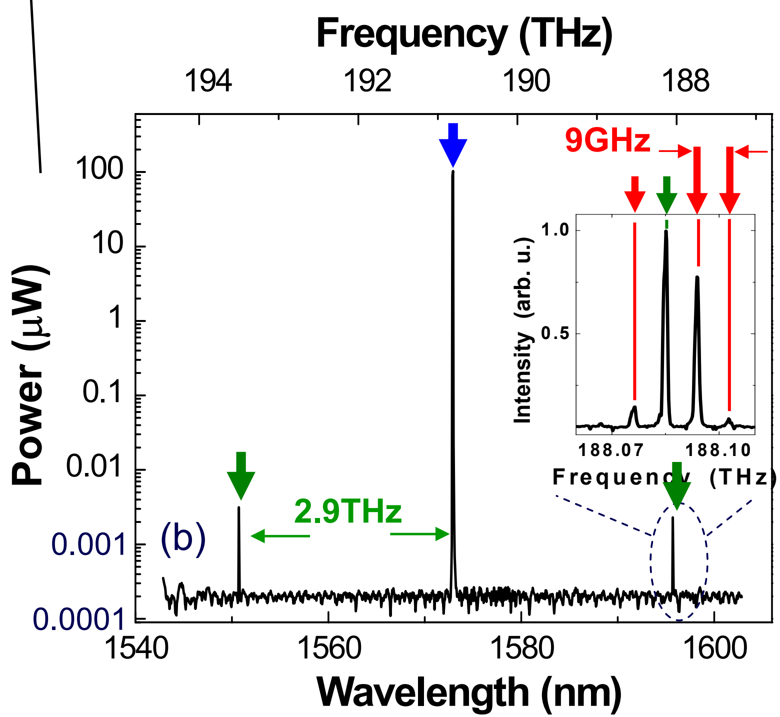

S. Dhillon *et al.*, Appl. Phys. Lett. **87**, 071101 (2005)
S. Dhillon *et al.*, Nature Photonics **1**, 411 (2007)

# THz + GHz sidebands on a telecom carrier

- Experimental setup



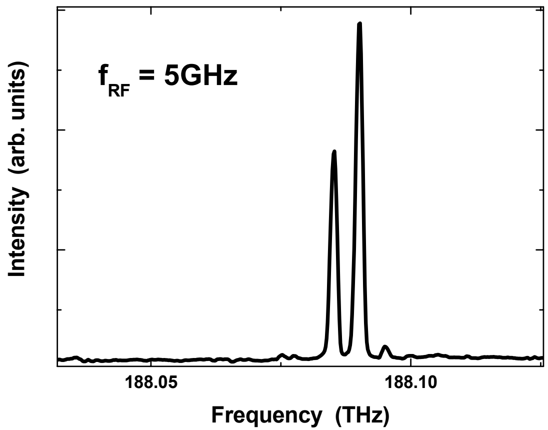

GHz sidebands at 9GHz

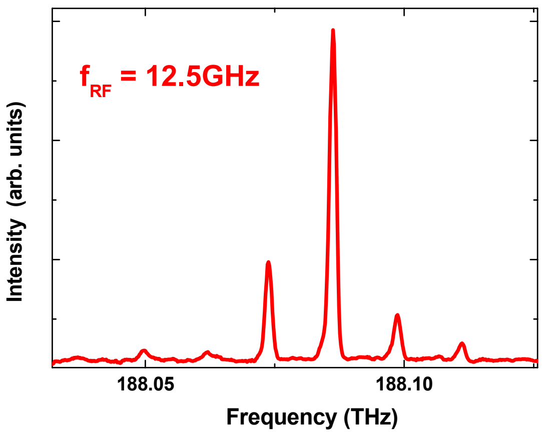


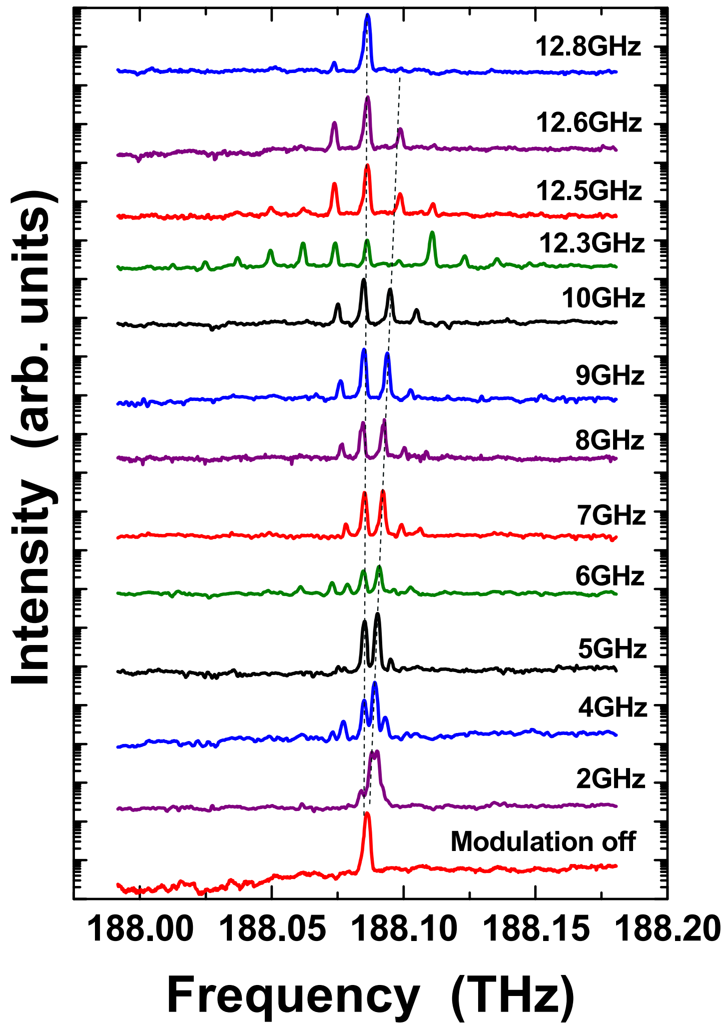

- From centimetres to micrometers
  - **RF generator**
    $\lambda > 1.5$cm
    $0 < f < 20$GHz
  - **THz QCL**
    $\lambda = 103\mu$m
    $\Omega = 2.9$THz
  - **Diode laser**
    $\lambda = 1571$nm
    f = 190.9 THz

# Continuous sideband tuning up to ~13GHz

- $P_{RF}$ = 20dBm

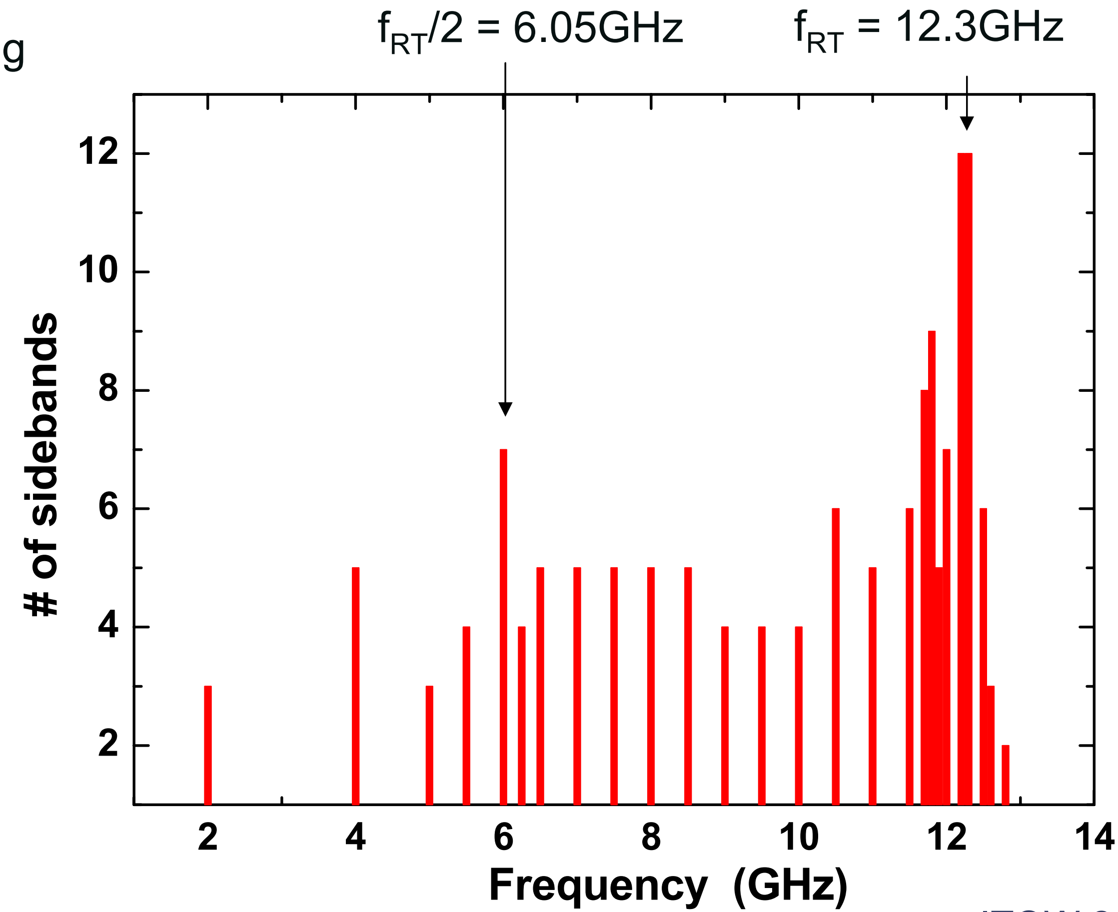


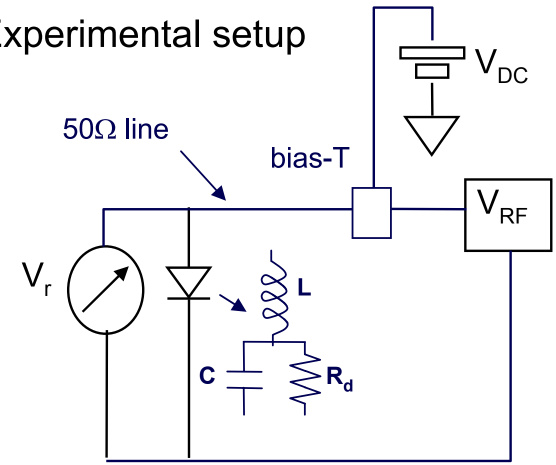
# Resonance effect at the round-trip frequency

- Number of sidebands increases at $f_{roudtrip}$ and $f_{roudtrip}/2$
- Signature of mode-locking
- Round trip measured Independently on 3mm multi mode device.
  → $f_{Rtrip}$ = **12.287 GHz**



# Measuring the GHz response by microwave rectification

- Experimental setup




$$\overbrace{V = V_o + V'\,\delta I + \underbrace{V''\,\delta I^2}_{V_{Rect}} + \ldots}^{V_{RF}\ \mathrm{ON}}$$

$$V_{Rect} = V''\,\delta I(\Omega)^2$$

| |
|---|
| $\delta I$ → RF modulated current |
| $H(f)$ → intrinsic device response |
| $C(f)$ → circuit response |
| $\delta n_3$ → upper state population |

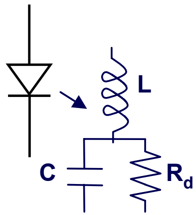
$$V_{Rect}^2 \sim \delta n_3^2 = \overbrace{\left\{ \frac{A\,\Omega^2}{\left(\Omega^2 - \frac{1}{\tau_s \tau_p}\right)^2 + \Omega^2\left(\frac{1}{\tau_s} + \frac{1}{\tau_3}\right)^2} \right\}}^{H(f)} C(f)\ \delta I^2$$

**By measuring the rectified voltage one has in principle access to H(f) x C(f)**

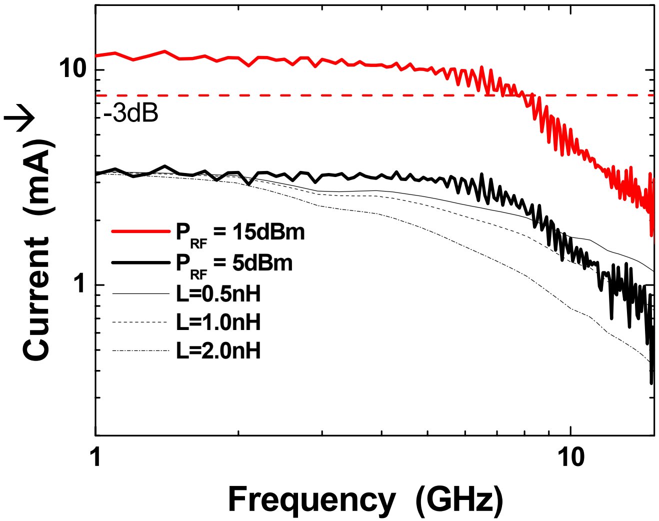
H. C. Liu *et al.*, *IEEE* J. Quantum Electron **32**, 1024 (1996)

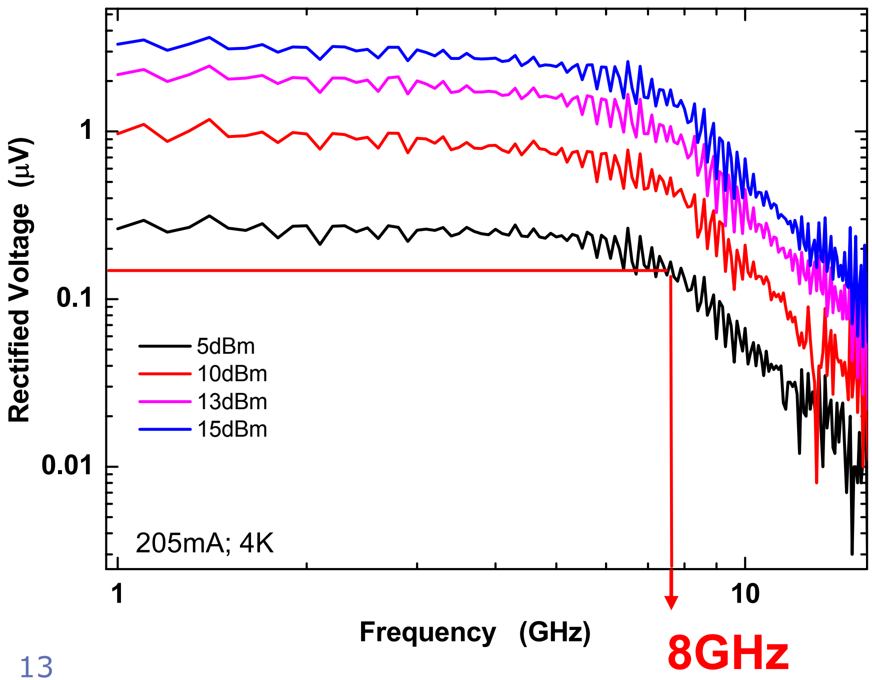
# Measuring the GHz response by microwave rectification

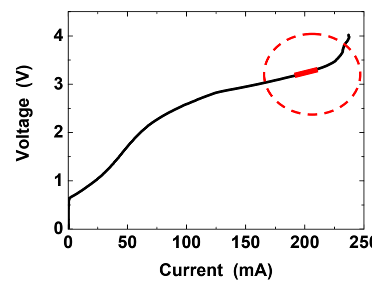
- Modulation up to **11GHz** (-10dB) limited by wire-bond inductance




Modulated current → $\delta I = \sqrt{\dfrac{V_{Rect}}{\left(\dfrac{\delta V^2}{\delta I^2}\right)}}$ →

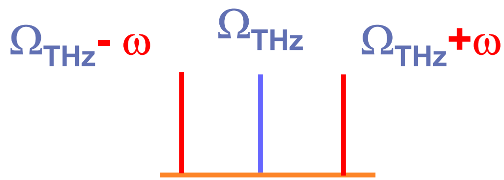


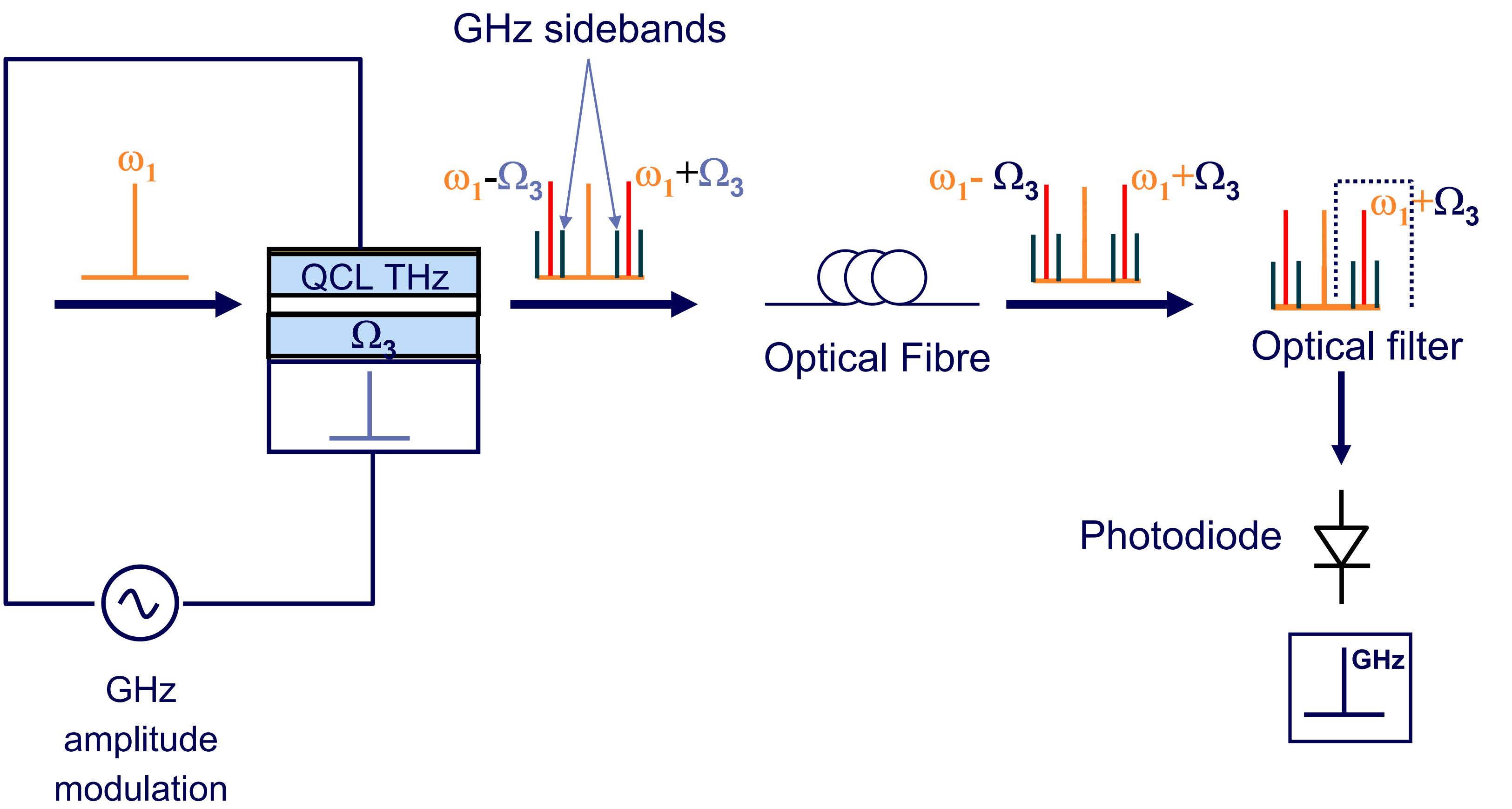

I. Doerr *et al.*, *Proc.* El. Components and Techn. Conf. **51**, 831 (2001)

# Why high frequency modulation?




- mid-IR QCLs
  - Free space communications
  - Spectroscopy
- THz QCLs
  - Spectroscopy
  - Imaging
  - Telecom applications

# Integrated amplitude modulator and tunable THz frequency shifter at 1.55 mm



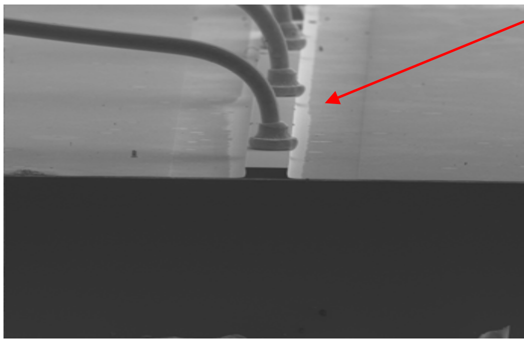
# Conclusions & Perspectives

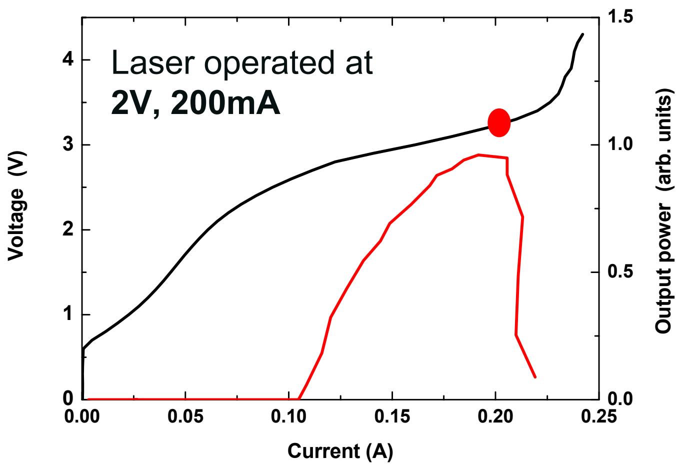
- 13GHz modulation of 2.9 THz QCL demonstrated
- Enhanced modulation amplitude at roundtrip
- Further work aimed at improving device packaging
- Microwave rectification studies at low QCL power
- Modulation on DFB THz QCLs

# The device: no need for exotic packaging

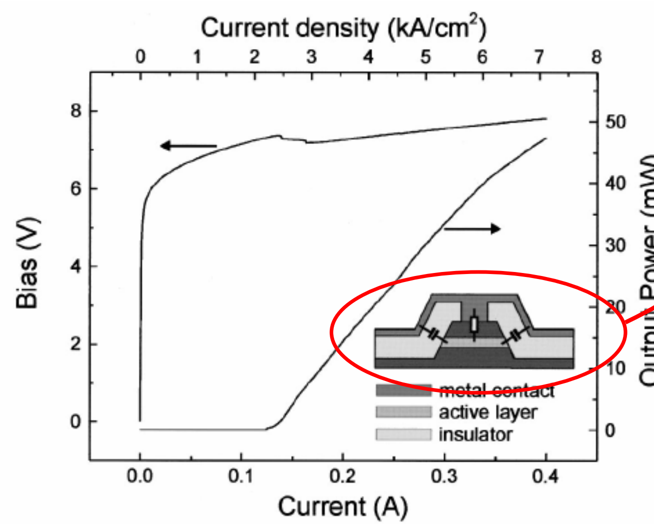
- Double metal QCL; f=2.9THz
  3mm x 50$\mu$m x 12 $\mu$m ridge
  **C = 1pF**

The relatively large width allows bonding directly on top of the ridge, whilst keeping a low capacitance thanks to the thick active region

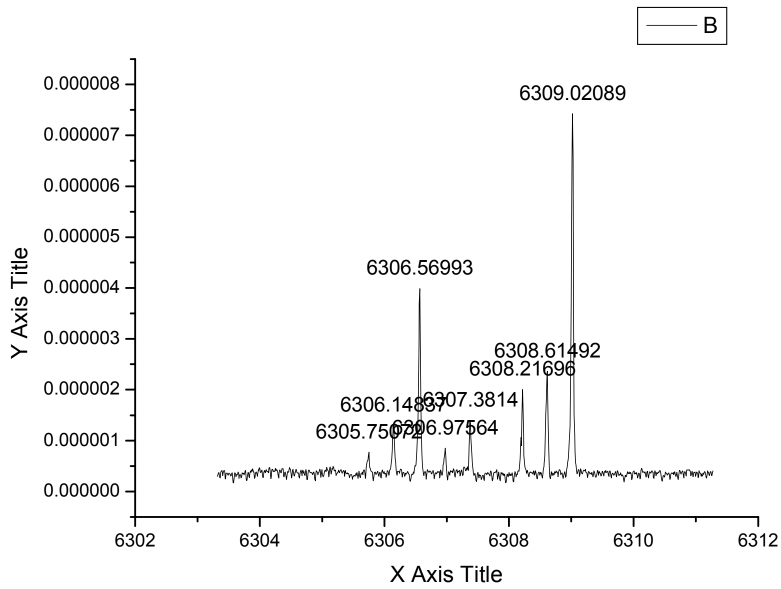


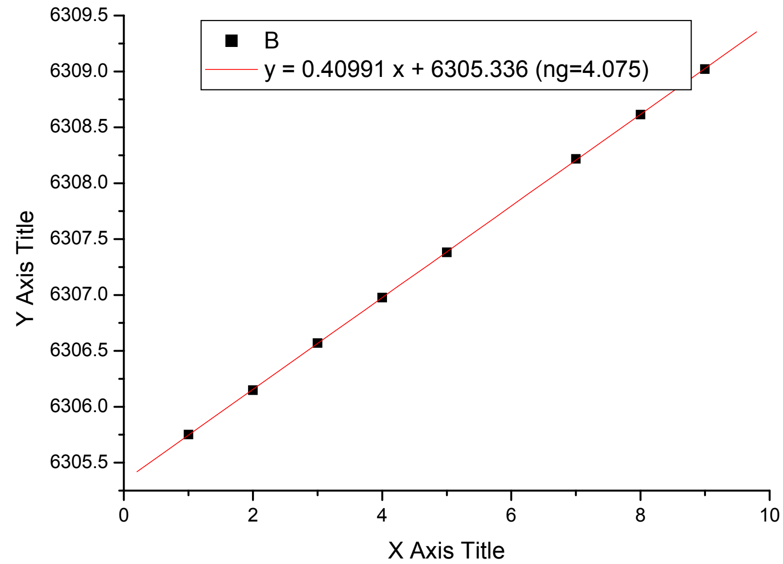



- 1.25 mm long ridge with Chalcogenide glass insulation layer to reduce device capacitance to **C = 10pF**



# Measurement of the round-trip frequency




$\Delta\nu = 0.40991\ cm^{-1}$, round trip = 12.287 GHz