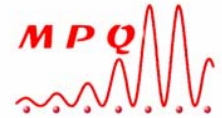


GHz modulation of THz quantum cascade lasers

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W. Mainault, S. Dhillon, C. Sirtori

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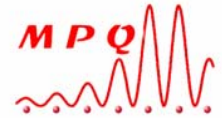
TeraView Ltd., Cambridge CB4 0WS, United Kingdom

N. Breuil

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

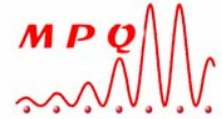
H. Beere, D. Ritchie

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



- 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

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

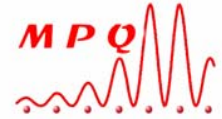
$\delta S \rightarrow$ photon density
 $\delta j \rightarrow$ current density
 $\Omega \rightarrow$ modulation frequency
 $\tau_p \rightarrow$ photon lifetime =
 $\tau_s \rightarrow$ stimulated lifetime
 $\tau_3 \rightarrow$ upper state lifetime

$\tau_s = \frac{1}{\sigma S}$ $\sigma \rightarrow$ cross section
 $S \rightarrow$ photon density

- Relaxation resonance frequency

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

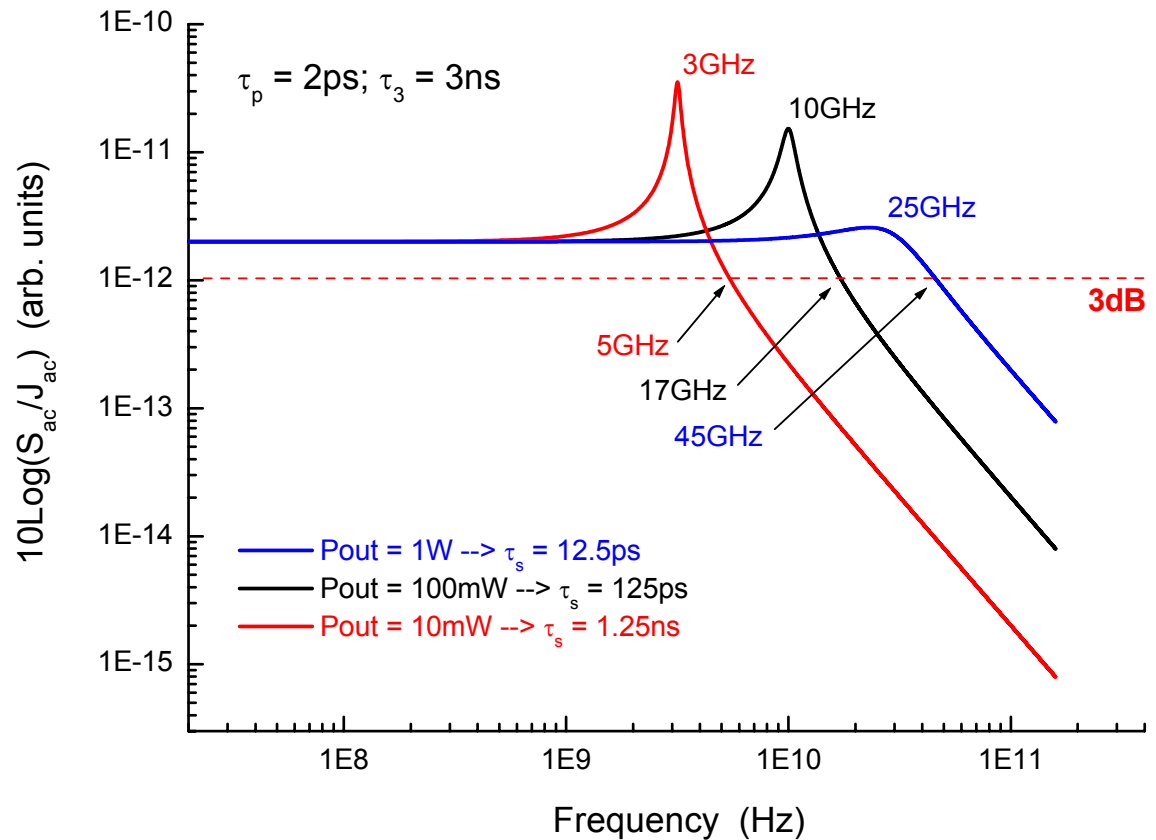
Interband diode lasers: $\tau_3 \sim 1\text{ns}$



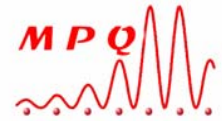
- $\tau_3 \gg \tau_s > \tau_p \Rightarrow \Omega_R = \sqrt{\frac{1}{\tau_s \tau_p} - \frac{1}{2} \left(\frac{1}{\tau_s} + \frac{1}{\tau_3} \right)^2}$ **real**

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

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



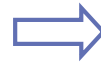
Quantum cascade lasers: $\tau_3 \sim 1$ ps



- “low” power regime
- “high” power regime

- $\tau_s > \tau_3, \tau_p$

- $\tau_3, \tau_p > \tau_s$



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

imaginary

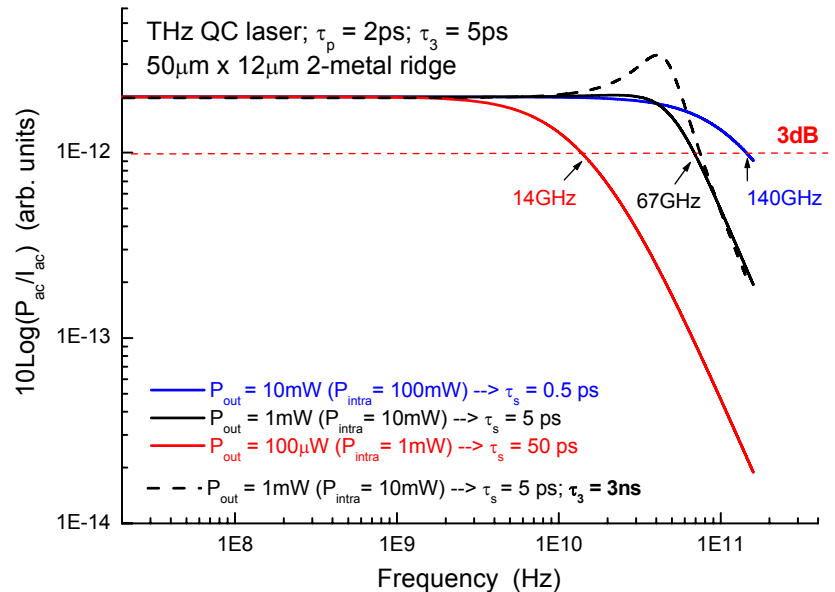
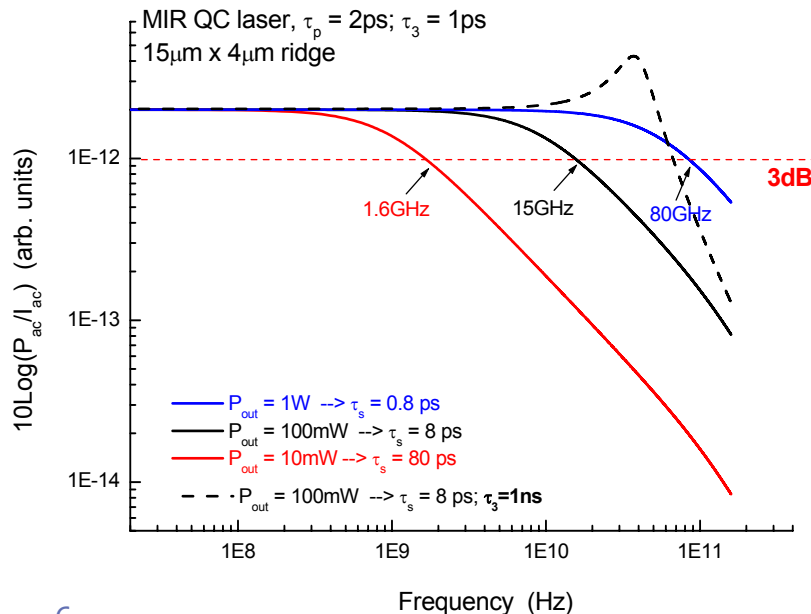
- $f_{3dB} = \frac{1}{2\pi} \left(\frac{\tau_3}{\tau_s \tau_p} \right)^{1/2}$

- $f_{3dB} = \frac{1}{\pi \tau_p}$

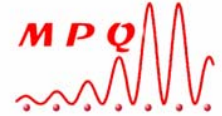
$$\tau_s = \frac{1}{\sigma S N_p}$$

➔ No relaxation oscillations, thanks to small τ_3

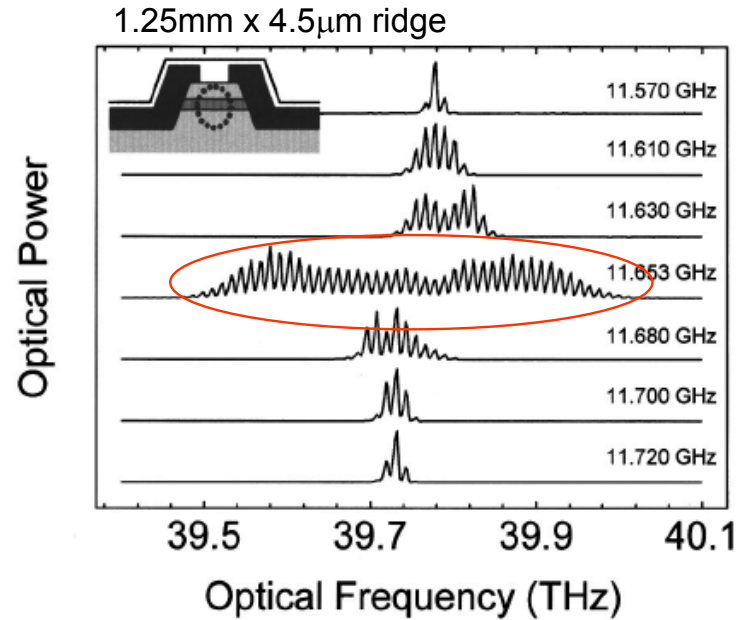
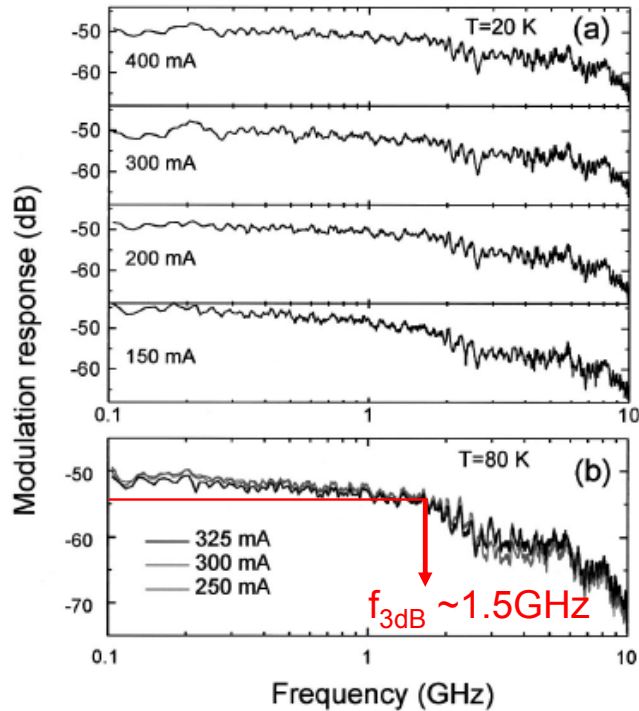
➔ Modulation bandwidth increased, thanks to small τ_s and/or τ_p



GHz modulation of mid-IR QCLs



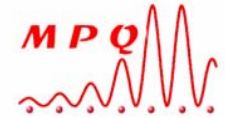
- Modulation up to 3GHz (-3dB)



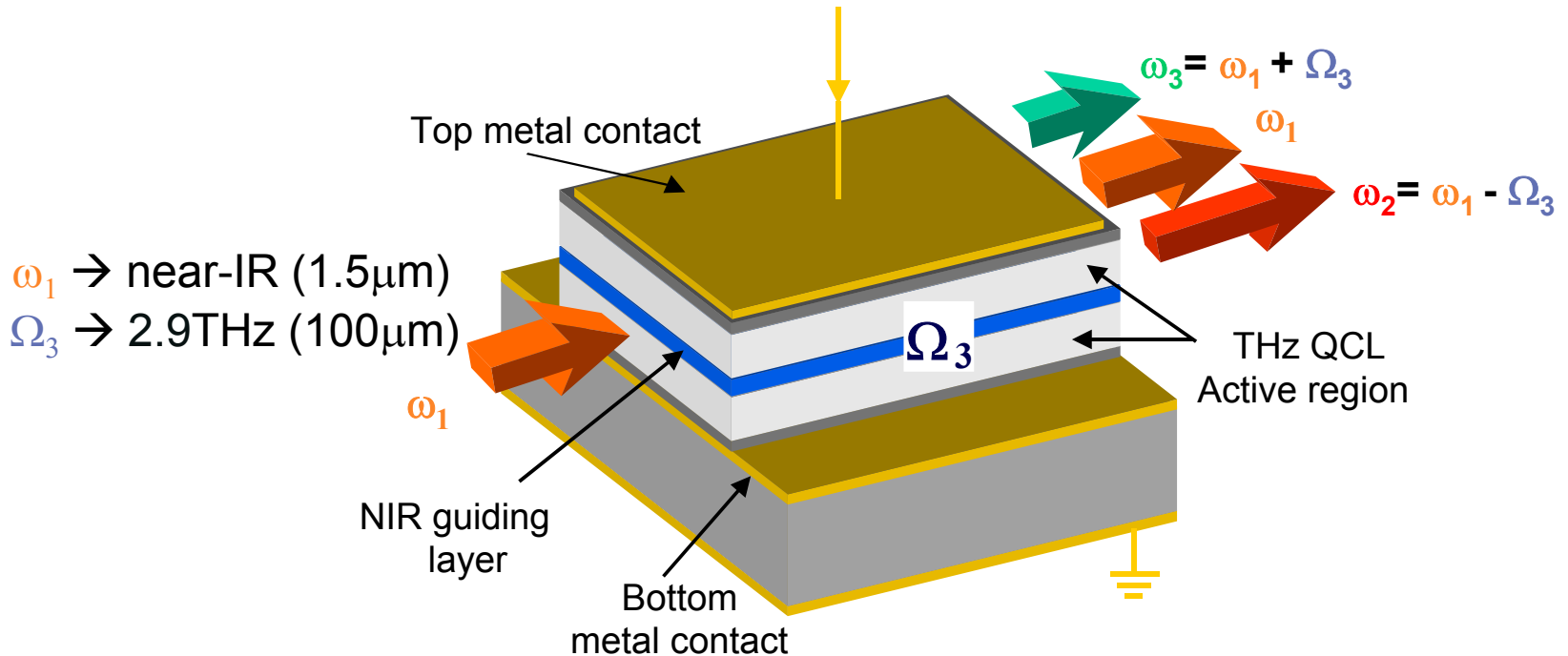
R. Paiella *et al.*, Appl. Phys. Lett. **77**, 169 (2000)
R. Paiella *et al.*, Appl. Phys. Lett. **76**, 2526 (2001)

- Modulation bandwidth limited by RC time constant ($C \sim 10 \text{ pF}$)
- Number of sidebands increases significantly at the roundtrip

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



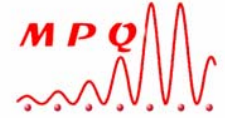
By up-converting the THz field in the near-IR the GHz sidebands can be measured in a few seconds, and resolved spectrally with a high-resolution optical spectrum analyser $\rightarrow \Delta f \sim 1$ MHz. This is much better than the resolution of the FTIR $\rightarrow \Delta f \sim 7$ GHz



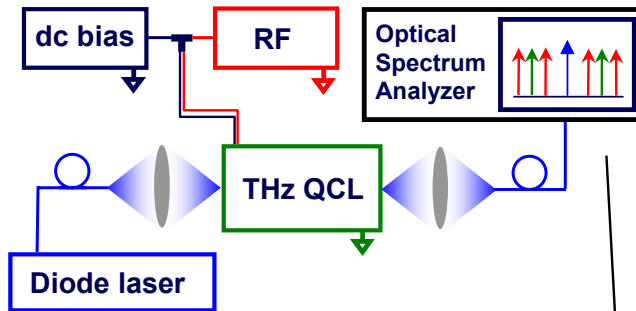
S. Dhillon *et al.*, Appl. Phys. Lett. **87**, 071101 (2005)

S. Dhillon *et al.*, Nature Photonics **1**, 411 (2007)

THz + GHz sidebands on a telecom carrier



- Experimental setup



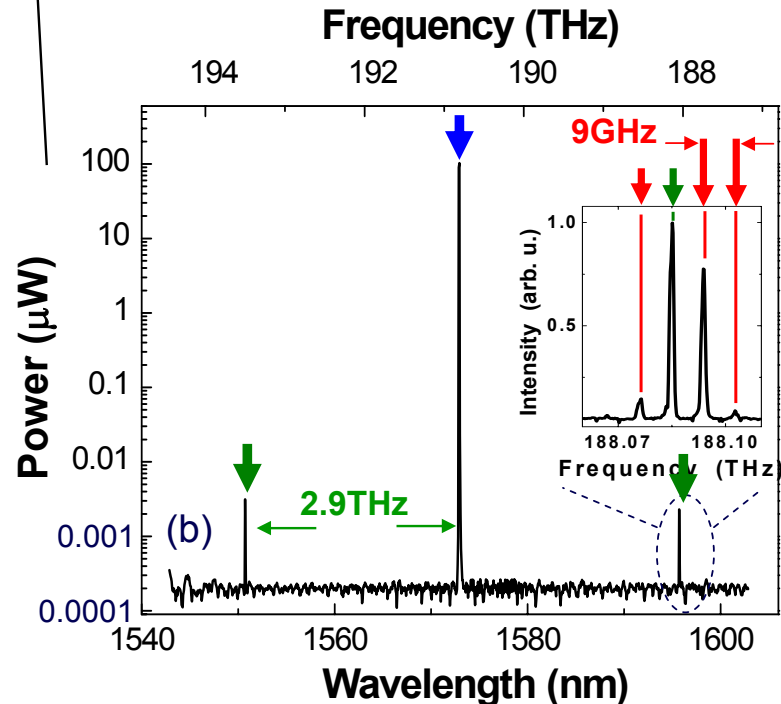
GHz sidebands at 9GHz

- From centimetres to micrometers

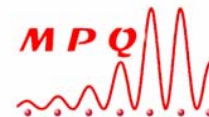
- RF generator
 - $\lambda > 1.5\text{cm}$
 - $0 < f < 20\text{GHz}$

- THz QCL
 - $\lambda = 103\mu\text{m}$
 - $\Omega = 2.9\text{THz}$

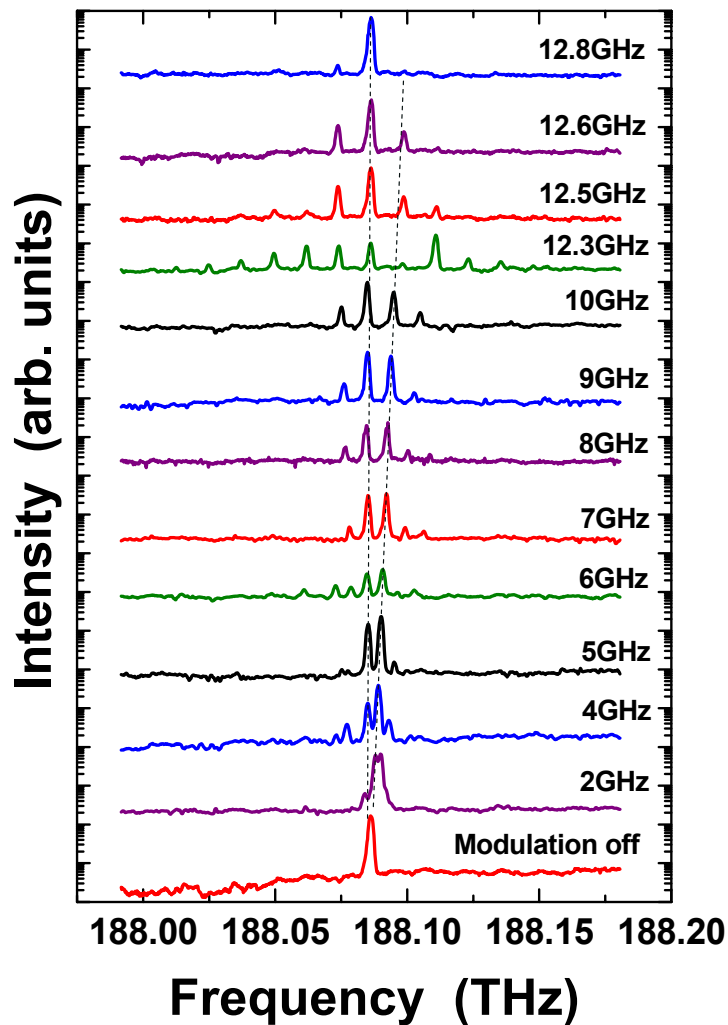
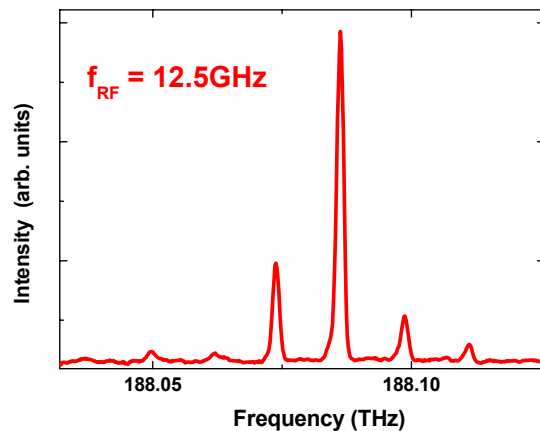
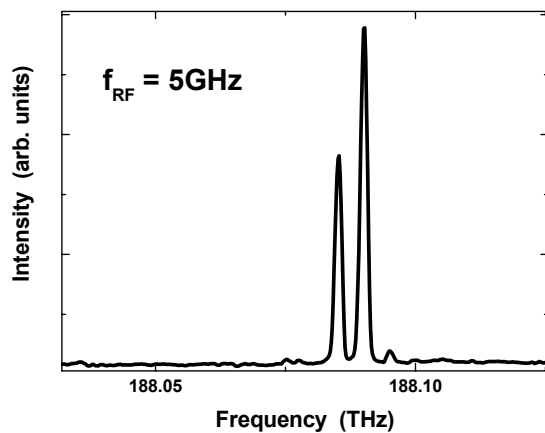
- Diode laser
 - $\lambda = 1571\text{nm}$
 - $f = 190.9\text{THz}$



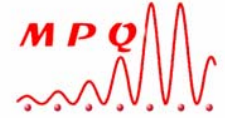
Continuous sideband tuning up to ~13GHz



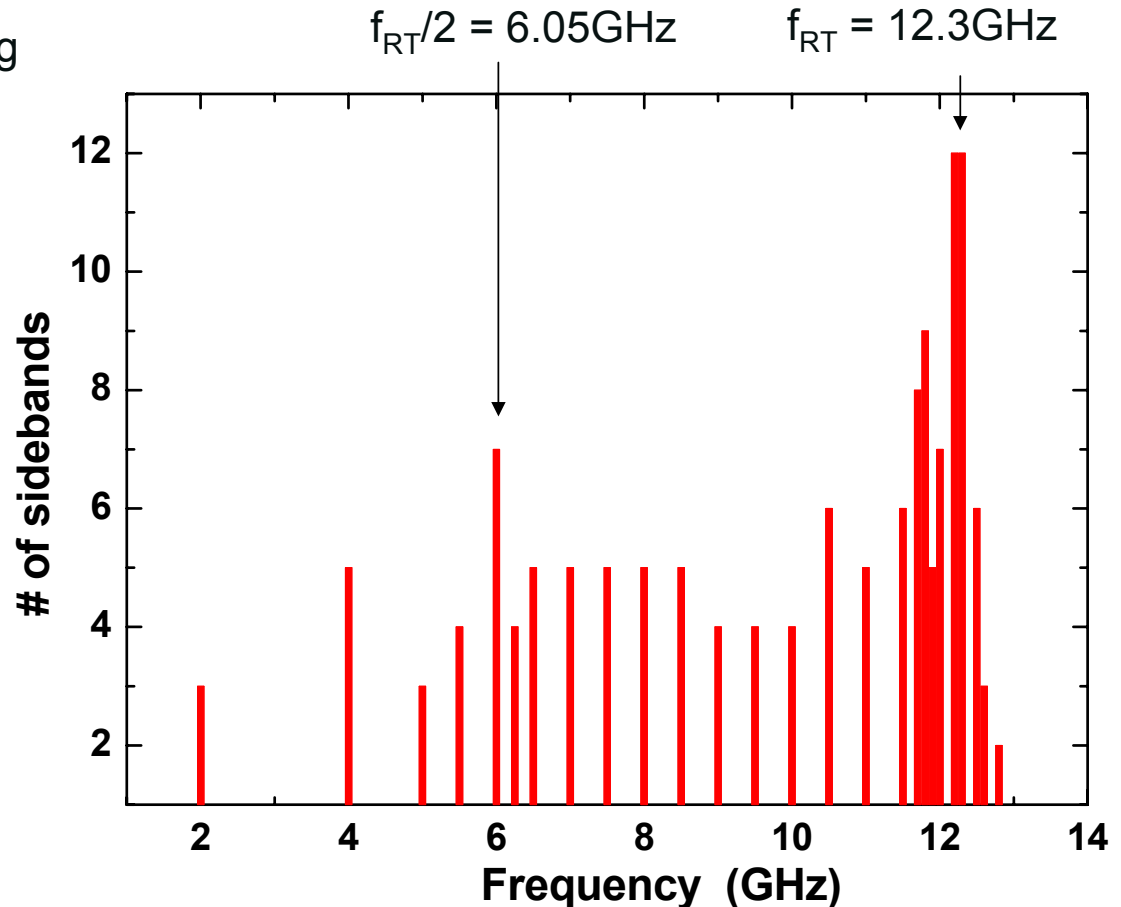
- $P_{RF} = 20\text{dBm}$



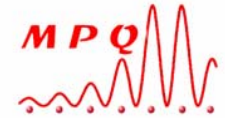
Resonance effect at the round-trip frequency



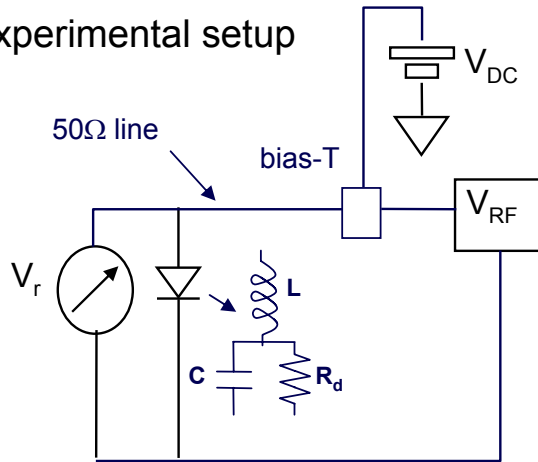
- Number of sidebands increases at $f_{\text{roundtrip}}$ and $f_{\text{roundtrip}}/2$
- Signature of mode-locking
- Round trip measured Independently on 3mm multi mode device.
 $\rightarrow f_{\text{Rtrip}} = 12.287 \text{ GHz}$



Measuring the GHz response by microwave rectification



- Experimental setup



$$V = V_0 + \overbrace{V' \delta I}^{V_{RF \text{ ON}}} + \underbrace{V'' \delta I^2}_{V_{Rect}} + \dots$$

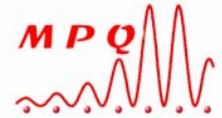
$$V_{Rect} = V'' \delta I (\Omega)^2$$

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

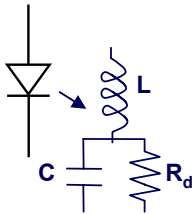
$$V_{Rect}^2 \sim \delta n_3^2 = \left[\frac{A \Omega^2}{\left(\Omega^2 - \frac{1}{\tau_s \tau_p} \right)^2 + \Omega^2 \left(\frac{1}{\tau_s} + \frac{1}{\tau_3} \right)^2} \right] C(f) \delta I^2$$

By measuring the rectified voltage one has in principle access to $H(f) \times C(f)$

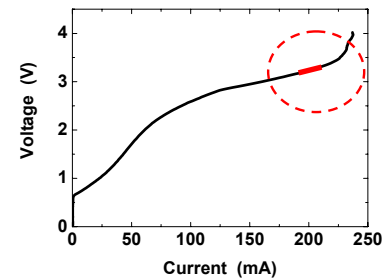
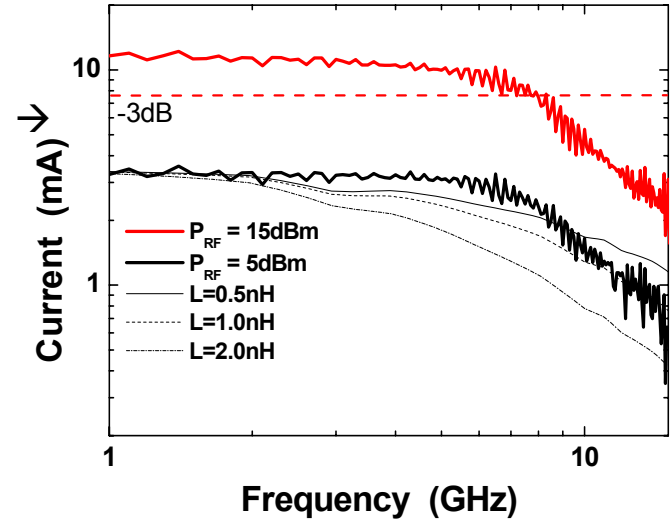
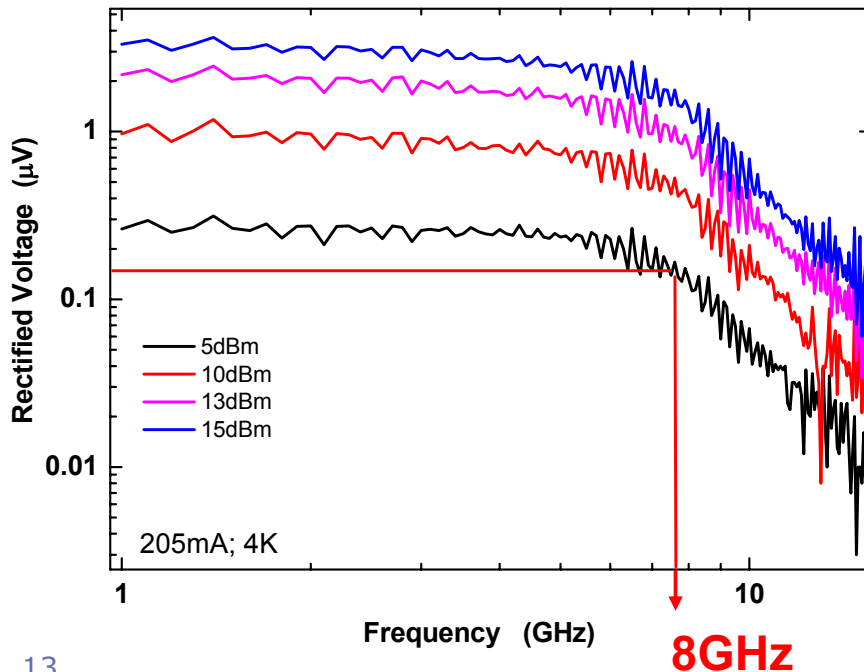
Measuring the GHz response by microwave rectification



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

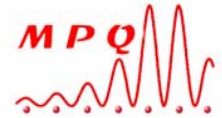


Modulated current \rightarrow
$$\delta I = \sqrt{\frac{V_{\text{Rect}}}{\frac{\delta V^2}{\delta I^2}}}$$



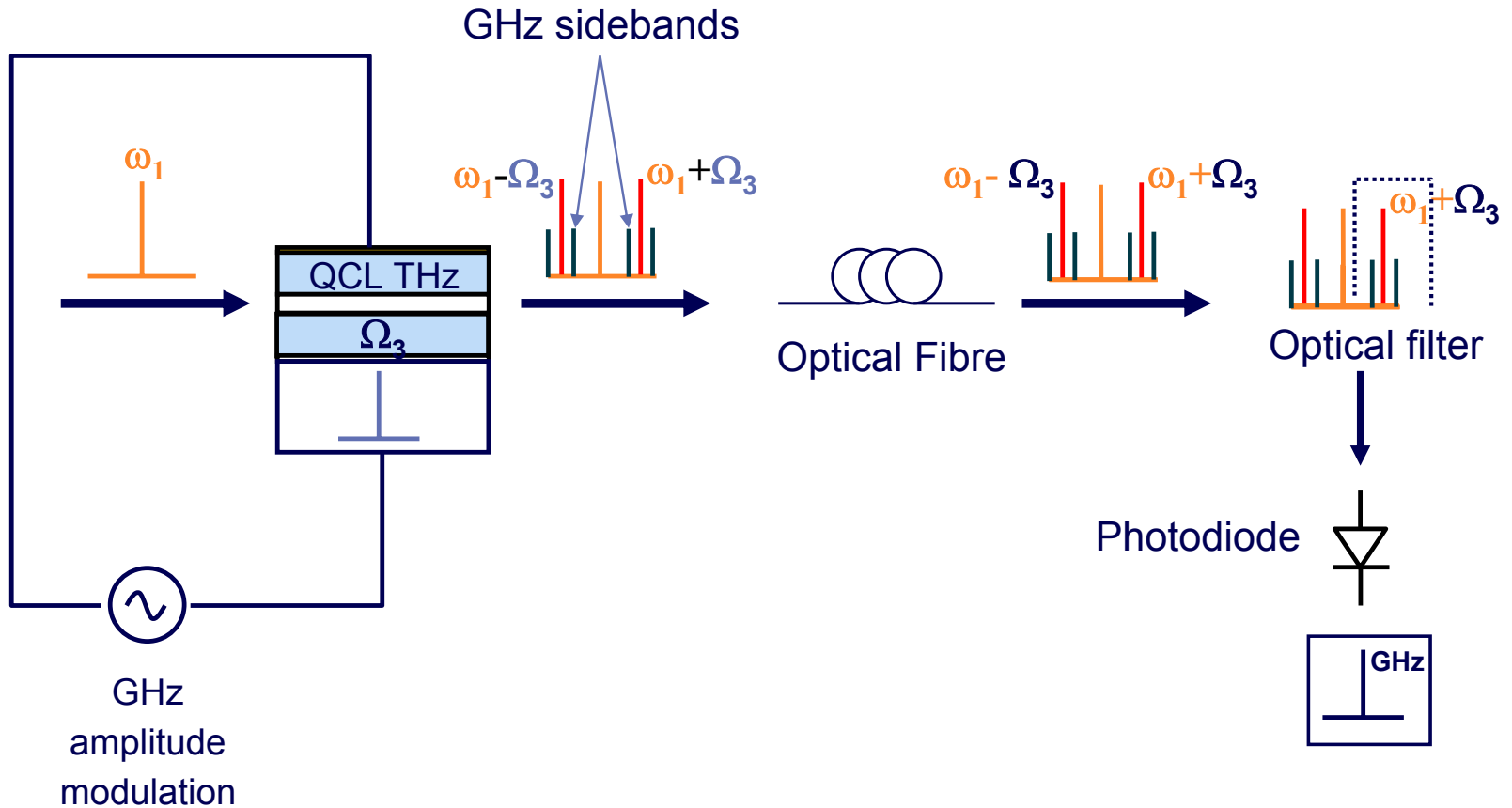
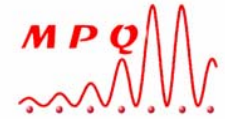
I. Doerr *et al.*, *Proc. El. Components and Techn. Conf.* **51**, 831 (2001)

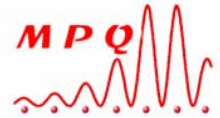
Why high frequency modulation?



- 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

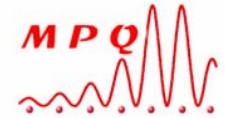




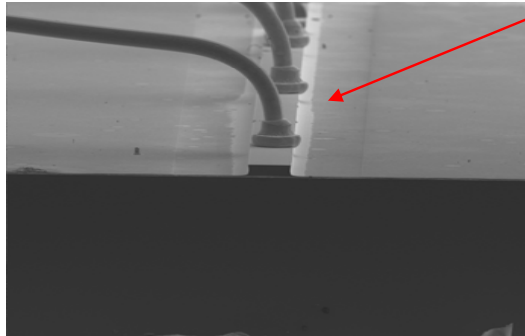
- 13GHz modulation of 2.9 THz QCL demonstrated
- Enhanced modulation amplitude at roundtrip
- Further work aimed at improving device packaging
- Microwave rectification studies at low QCL power
- Modulation on DFB THz QCLs



The device: no need for exotic packaging

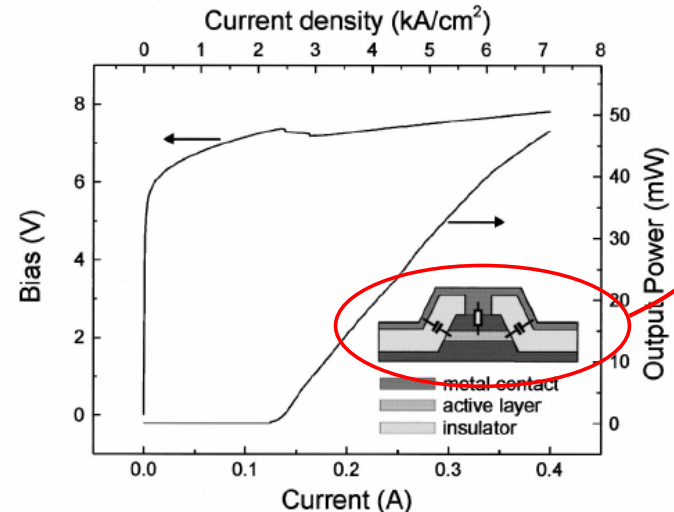
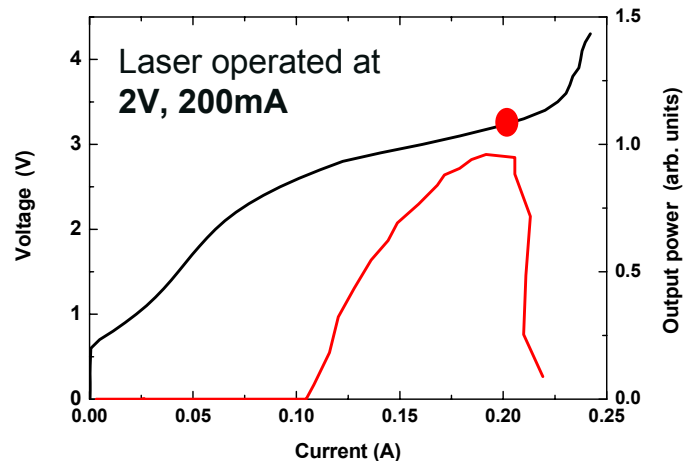


- Double metal QCL; $f=2.9\text{THz}$
3mm x 50 μm x 12 μm ridge
C = 1pF

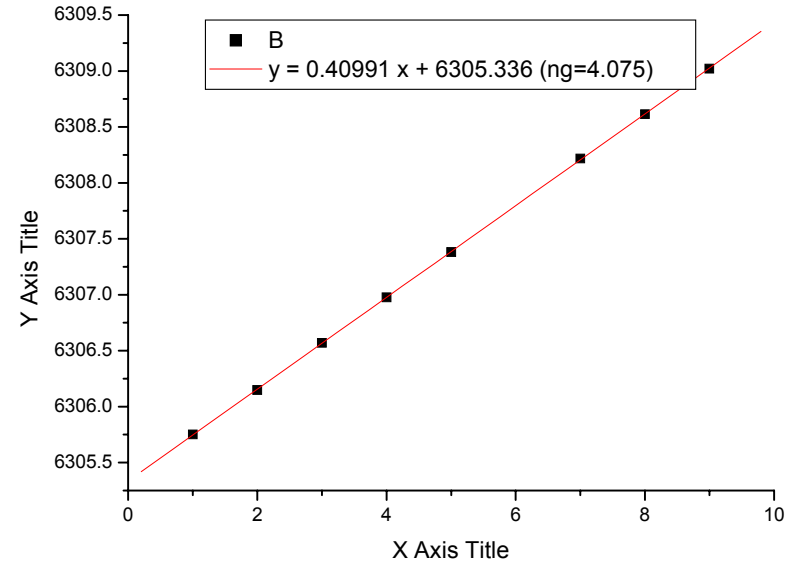
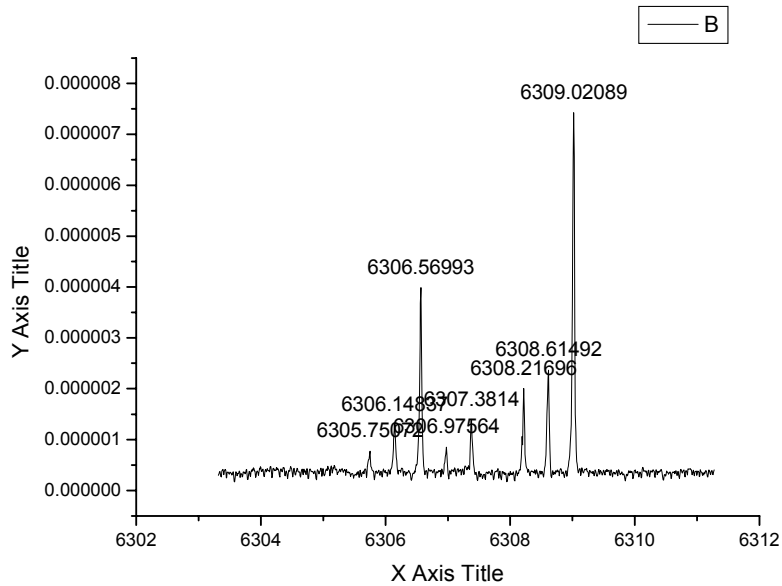
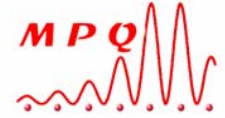


The relatively large width allows bonding directly on top of the ridge, whilst keeping a low capacitance thanks to the thick active region

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



Measurement of the round-trip frequency



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