Microwave modulation of quantum cascade lasers

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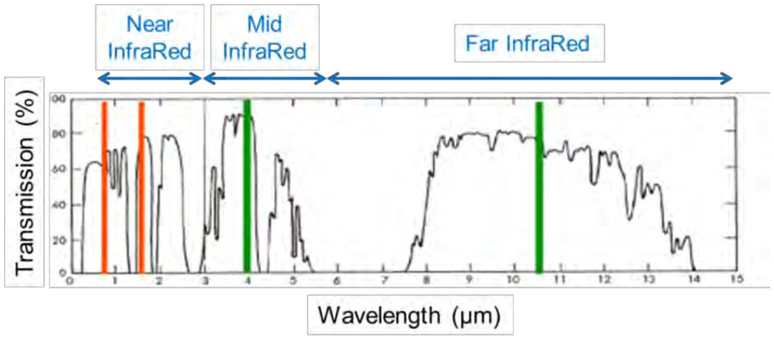
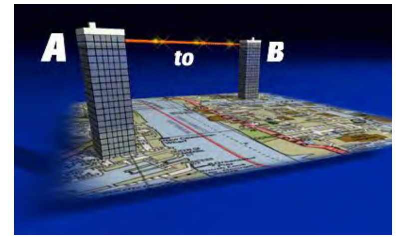
LPN

ADEQUATE

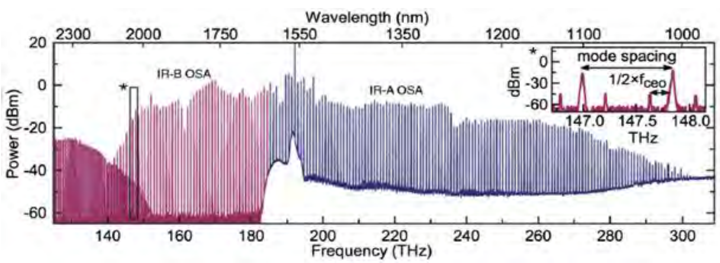
Motivations for high frequency modulation

- **Free space communications**



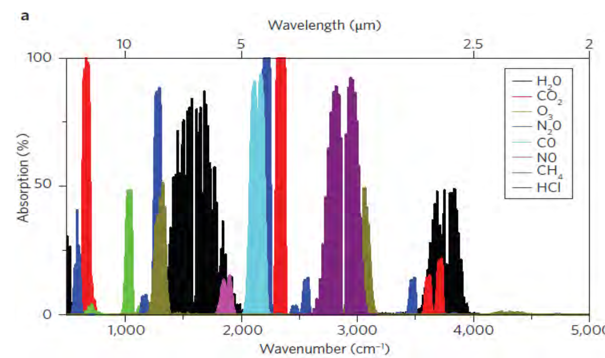


- **Frequency combs**



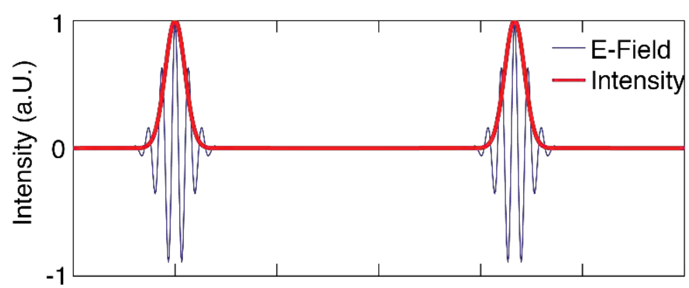
P. Del'Haye, et al., *Physical Review Letters* **107** 063901 (2011)

High resolution and high sensitivity spectroscopy



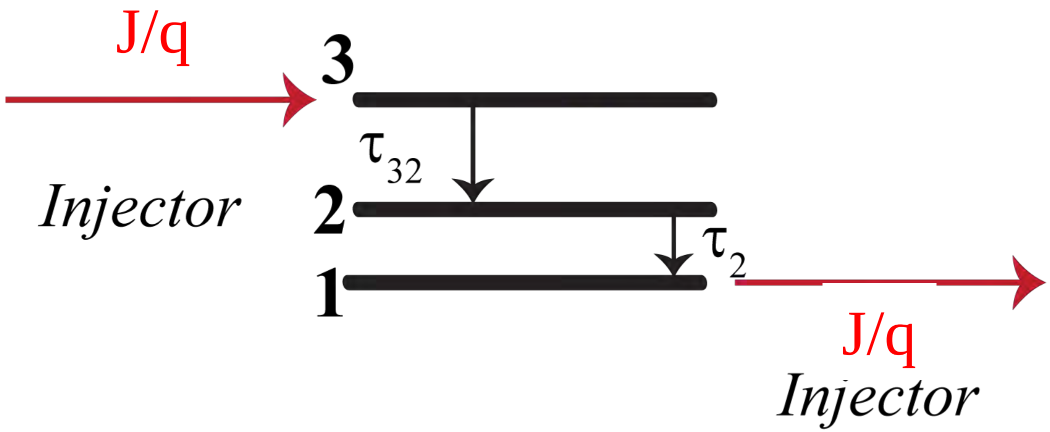
A. Schliesser, et al., *Nature Photonics* **6** 440-449 (2012)

- **Mode locking**



Ultrafast unipolar optoelectronics

Rate equation analysis



$$\frac{1}{\tau_3} = \frac{1}{\tau_{31}} + \frac{1}{\tau_{32}}$$

$$\frac{dn_3}{dt} = \frac{J}{q} - \frac{n_3}{\tau_3} - Sg_c(n_3 - \cancel{n_2})$$

$$\xcancel{\frac{dn_2}{dt} = \frac{n_3}{\tau_{32}} - \frac{n_2}{\tau_2} + Sg_c(n_3 - n_2)}$$

$\tau_2 = 0$!

$$\frac{dS}{dt} = \left(g_c(n_3 - \cancel{n_2}) - \frac{c\alpha_{tot}}{n_o} \right) S + \cancel{\beta} \frac{n_3}{\tau_{sp}}$$

Small amplitude analysis

Small signal approximation

$$S(t) = S^{(0)} + \mathbf{S}e^{i\omega t}$$
$$J(t) = J^{(0)} + \mathbf{J}e^{i\omega t}$$
$$n_i(t) = n_i^{(0)} + \mathbf{n_i}e^{i\omega t} (i = 3, 2)$$

Transfer function

photon population → $$\mathbf{S} = h(\omega)\frac{S^{(0)}}{J^{(0)}}\mathbf{J}$$ ← **Current modulation**

$$|h(\omega)|^2 = \frac{1}{1 + \omega^4\tau_p^2\tau_{stim}^2 + \omega^2\tau_{stim}\tau_p(\frac{\tau_p}{\tau_{stim}} + 2\frac{\tau_p}{\tau_{up}} + \frac{\tau_p\tau_{stim}}{\tau_{up}^2} - 2)}.$$

with:

$\tau_p \approx 10ps$ ($\alpha = 10cm^{-1}$)

$0.5ps < \tau_{up} < 1ps$

$0.1ps < \tau_{stim} < 100ps$

J. Faist, *Quantum Cascade Lasers* (2013)

A. Yariv, *Photonics* (2007)

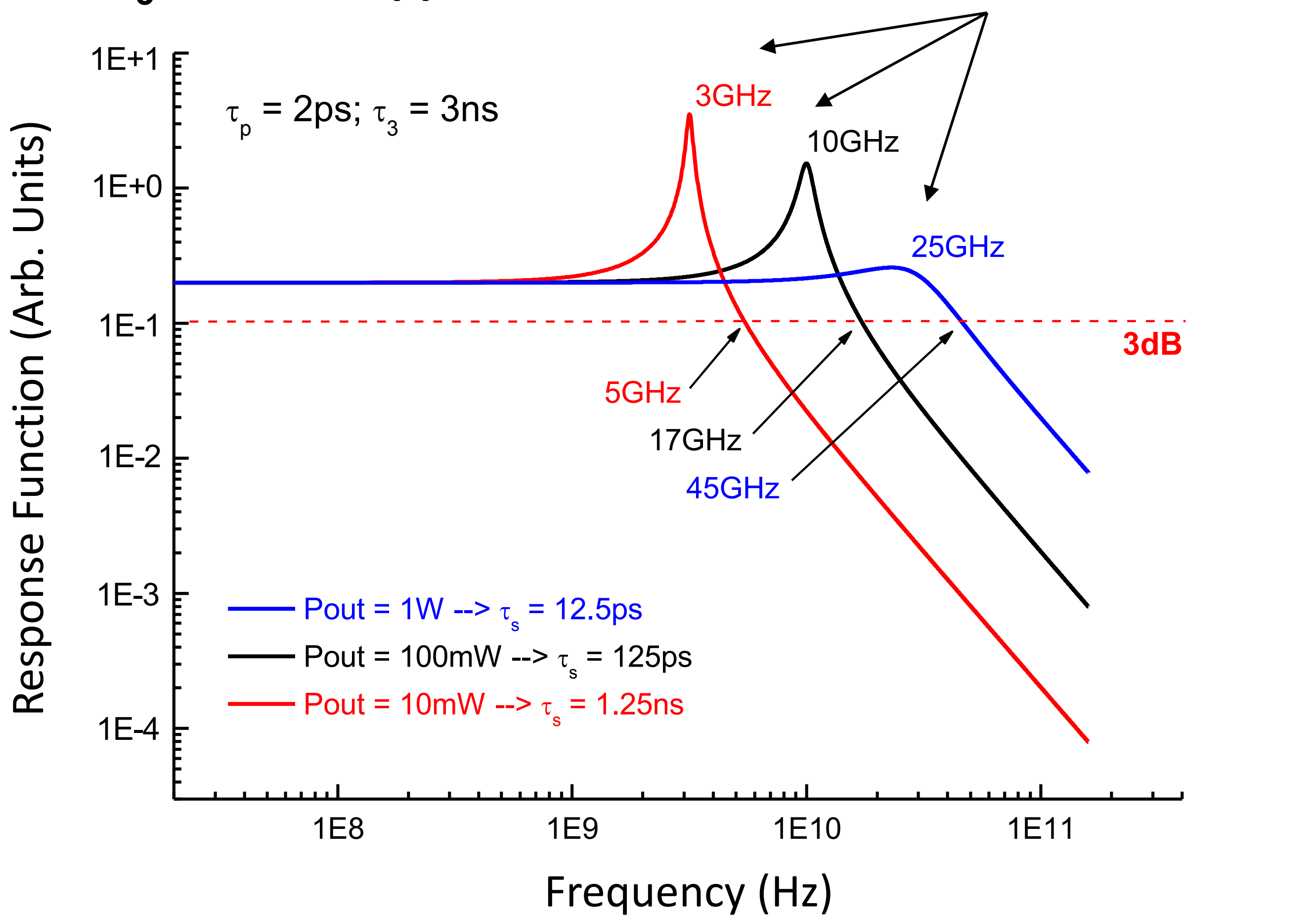
Frequency response function of a diode laser : H(ω)

$\delta P_{Opt} = H(\omega)\ \delta I$

H(ω) describe the efficiency of transferring a current modulation into an optical modulation

$\tau_3 >> \tau_s > \tau_p$

τ_3 ~ 1ns = upper state lifetime



Frequency response function of QC lasers

τ_3 ~ 1ps = upper state lifetime

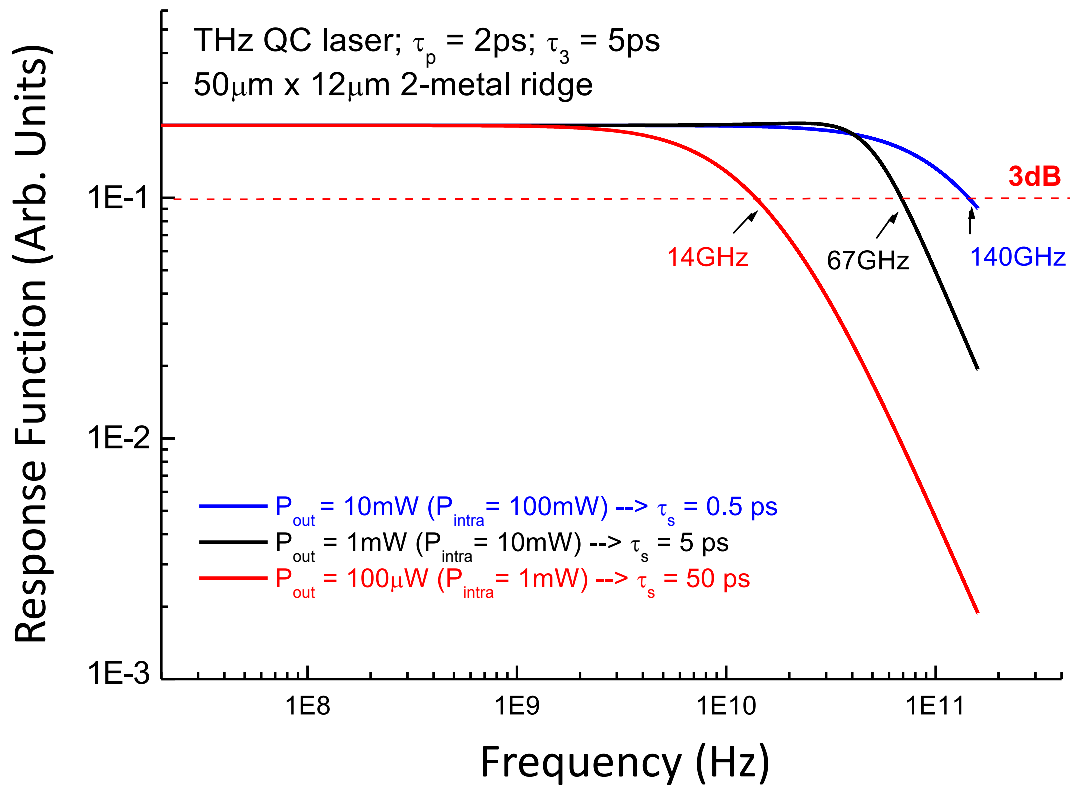
$\tau_3 \sim \tau_s \sim \tau_p$

➡ **Short non-radiative lifetime ~ 1ps → <u>no relaxation oscillations!</u>**

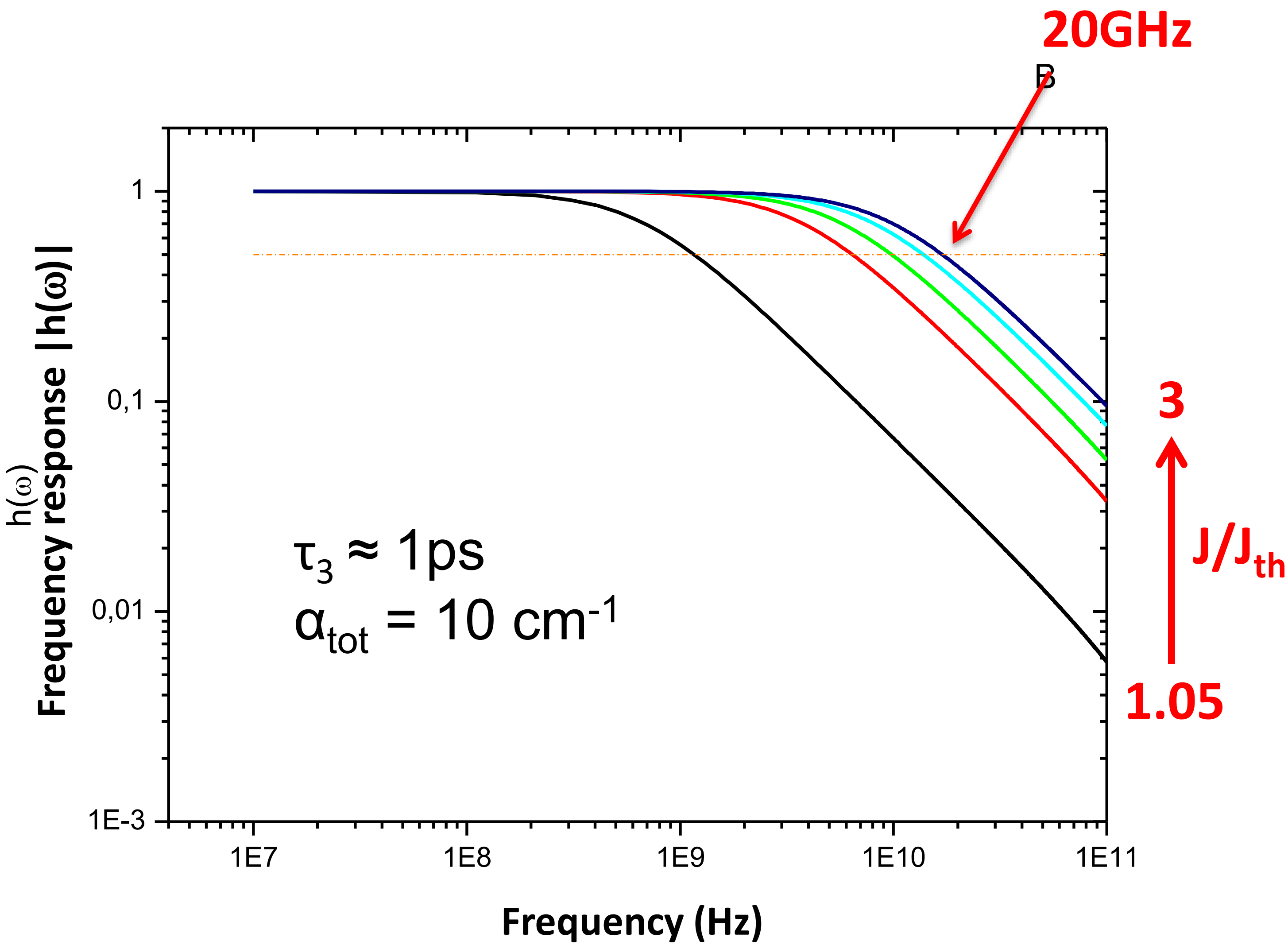
The system acts as an over-dumped oscillator

➡ **Short stimulated lifetime ~ 1ps → <u>very wide band of modulation</u>**

The cascade enhance the number of photon in the cavity

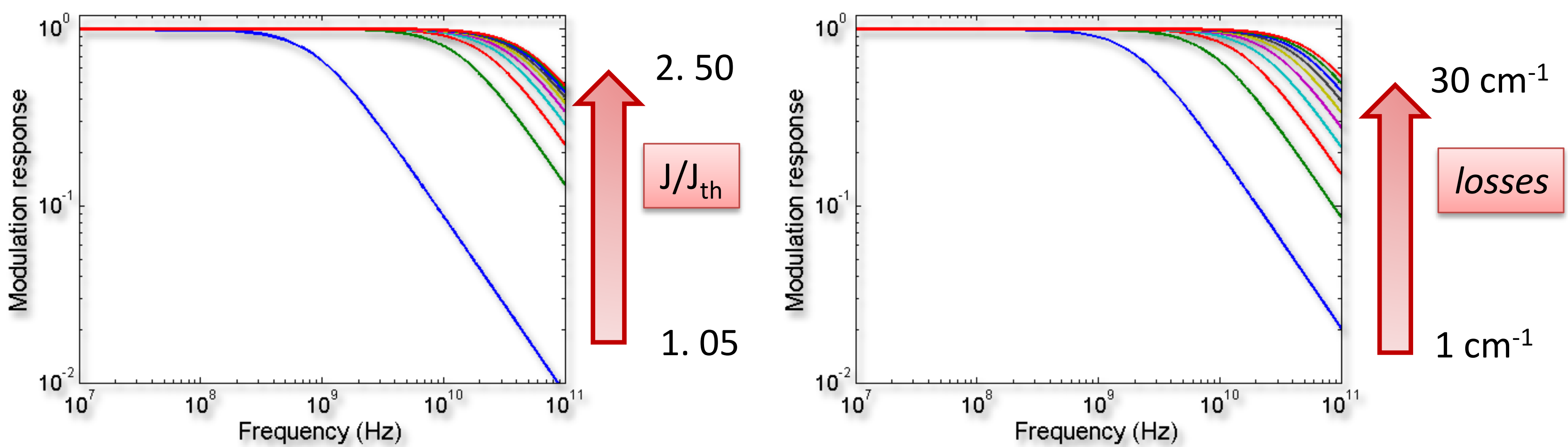


Calculated frequency response for a *"real"* QC laser



A. Calvar et al., *Applied Physics Letters* **102,** 181114 (2013)

High frequency modulation band-width



For laser driven well above threshold the modualtion band is

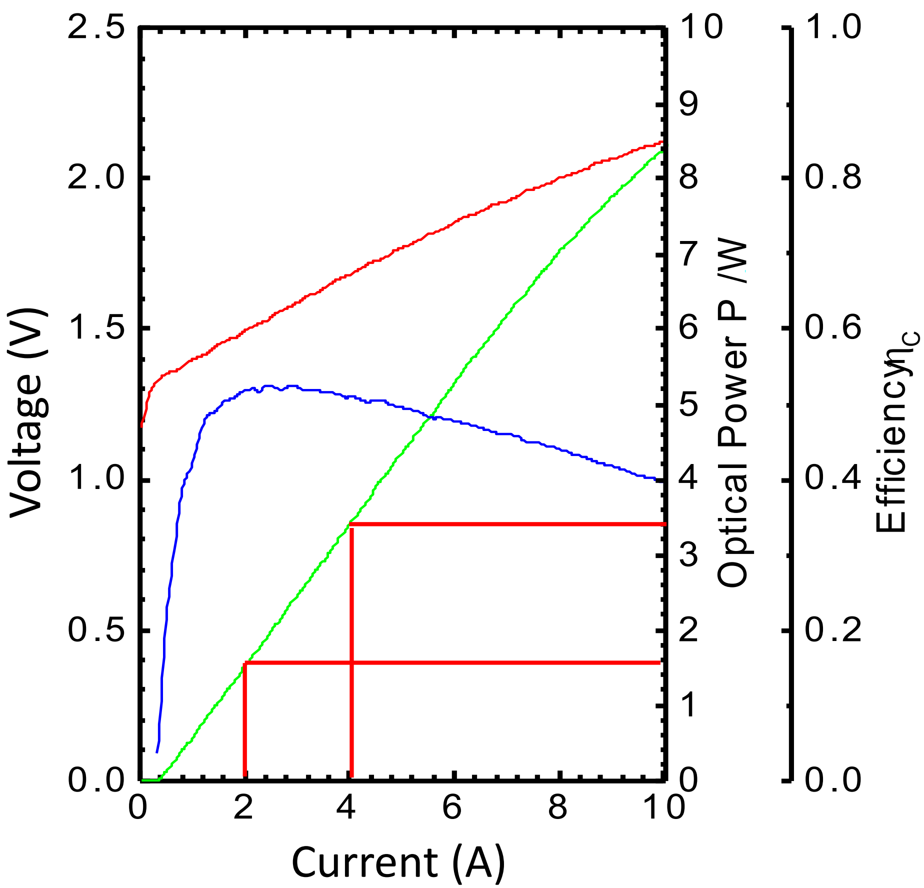
$$\Delta\omega_{Mod} \approx \frac{1}{\sqrt{\tau_{stim}\tau_p}} \qquad \tau_{up}\,?$$

Performance comparison between DLs and QCLs

(State-of-the-art)

λ = 0.8μm => 1500 meV

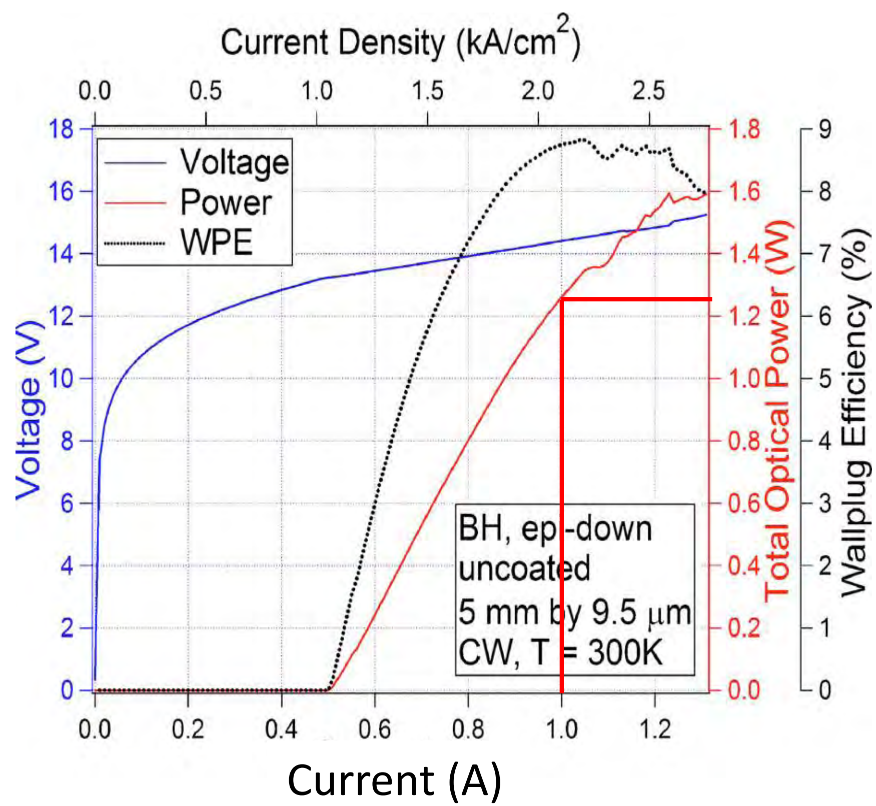
Facet surface = 100 μm²



Diode Laser

λ = 5μm => 240 meV

Facet surface = 25 μm²



QC Laser

Y. Bai, et al., APL **93,** 21103 (2008)

L'effet cascade

Cascade injection

***Electron recycling* due to a sequence of active region in series**

Threshold and slope efficiency are functions of the number (N_p) of repeated active regions

$$J_{th} = \frac{\alpha_w + \alpha_m}{g \boxed{N_p} \Gamma_p}$$

$$\frac{dP}{dI} = \frac{1}{2} \boxed{N_p} \frac{e}{h\nu} \frac{\alpha_m}{\alpha_w + \alpha_m} \left[1 - \frac{\tau_2}{\tau_{32}} \right]$$

Quantum efficiency = $N_p/N_e > 1$

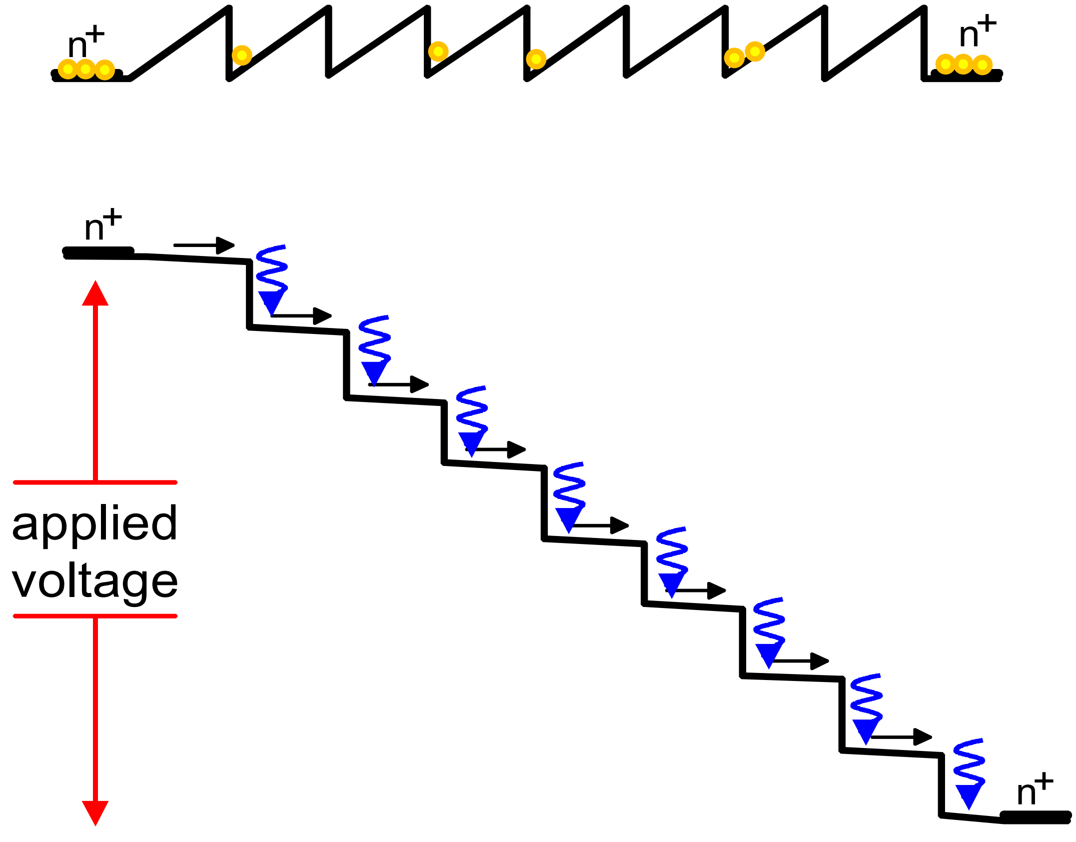
$$\eta_d = \frac{2e}{h\nu} \frac{dP}{dI}$$ **~ 10 at room temperature**

Sawtooth to staircase transition

Electron recycling and
Trading current for voltage

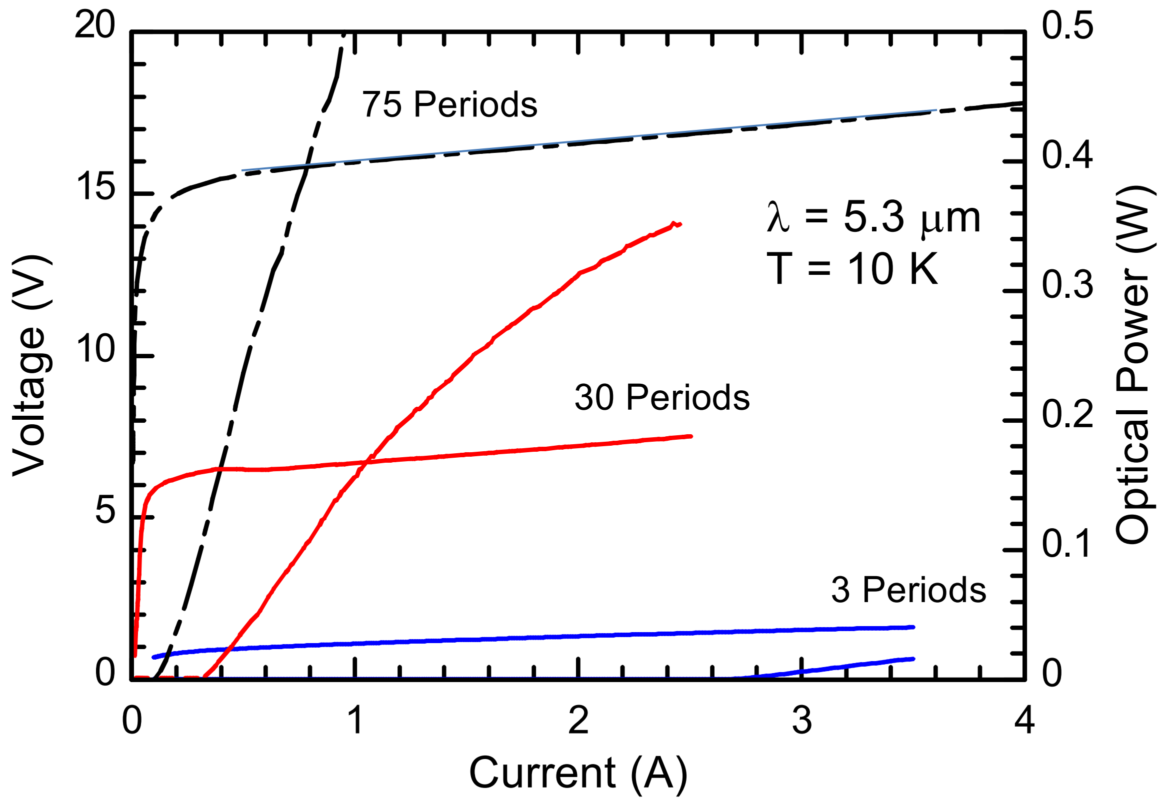
Unbiased: V = 0

Biased: $V > V_{th}$

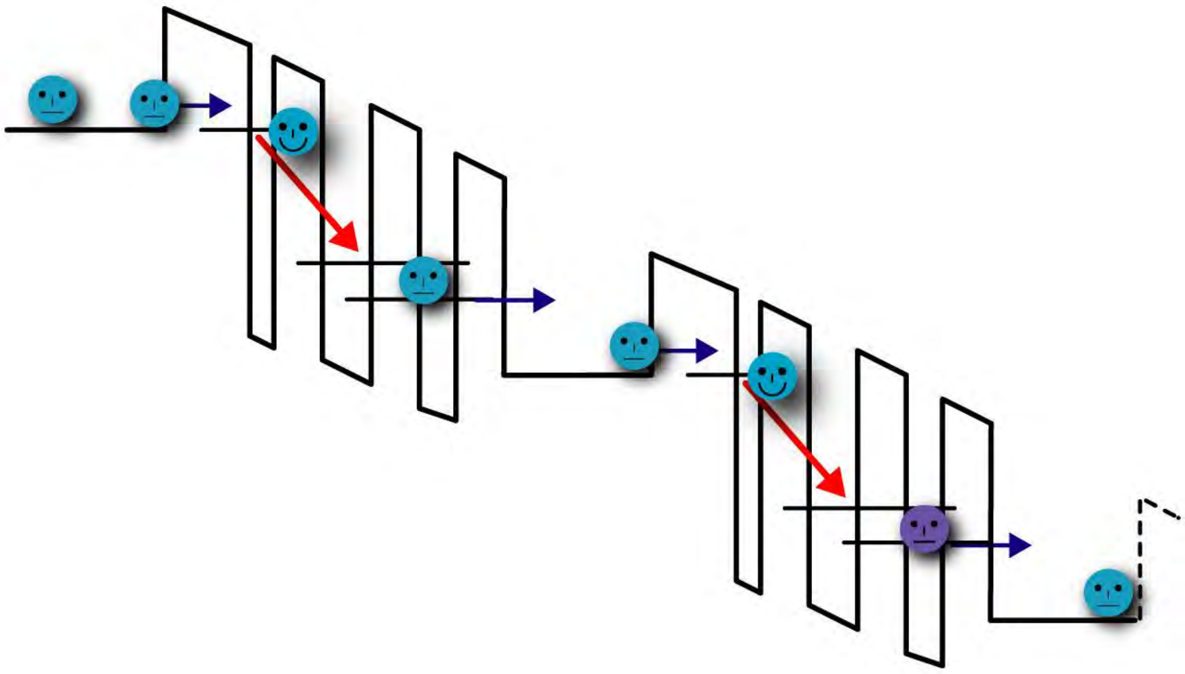


QC lasers as a function of the number of period

Experimental evidence of V-I trade

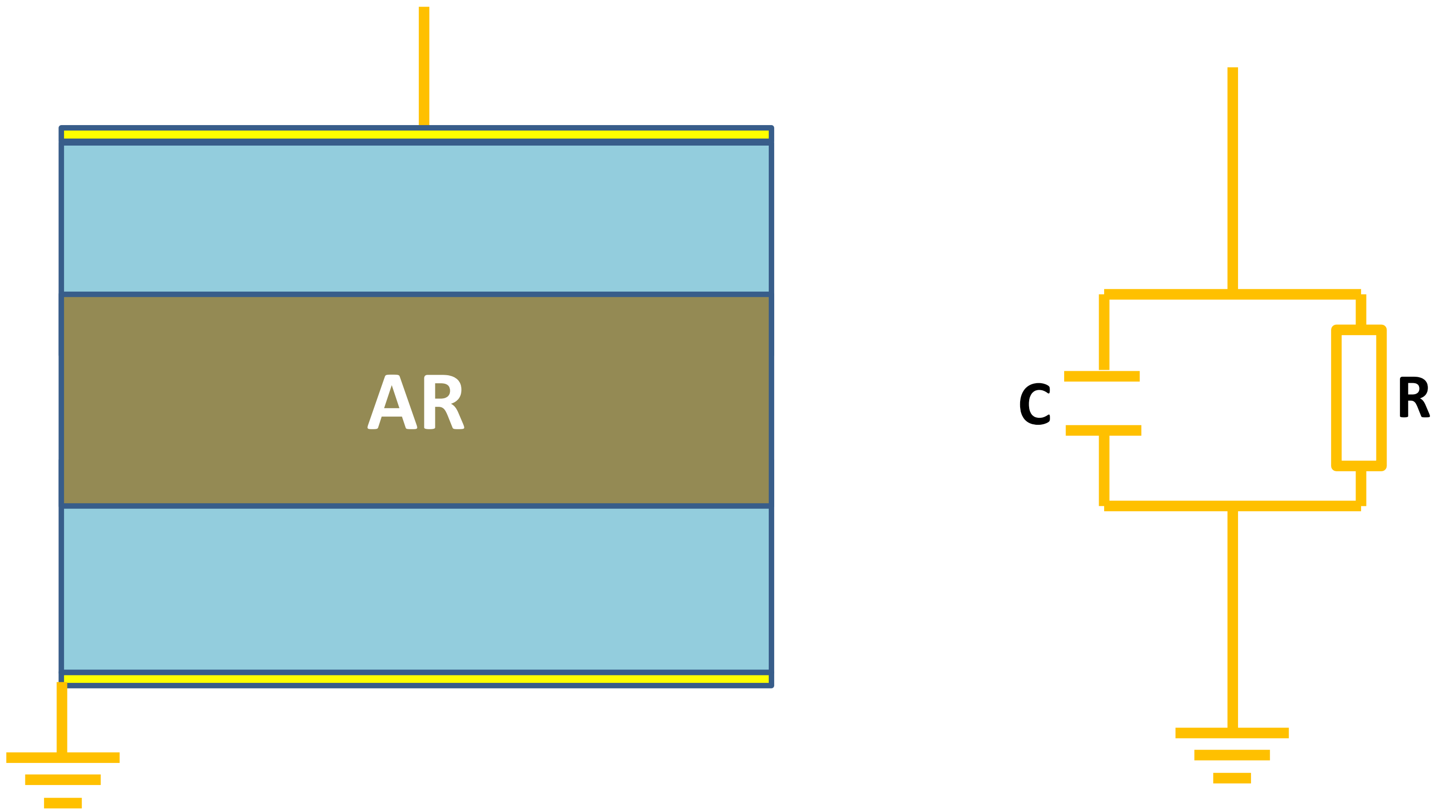


Cascade



Cascade: répétition d'une période
-> 1 électron peut générer plusieurs photons

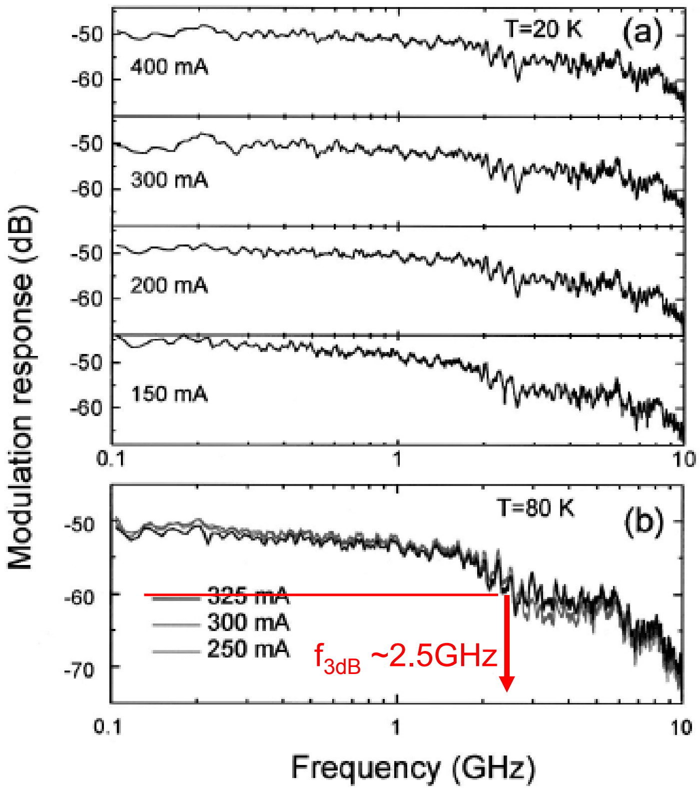
100GHz band width?



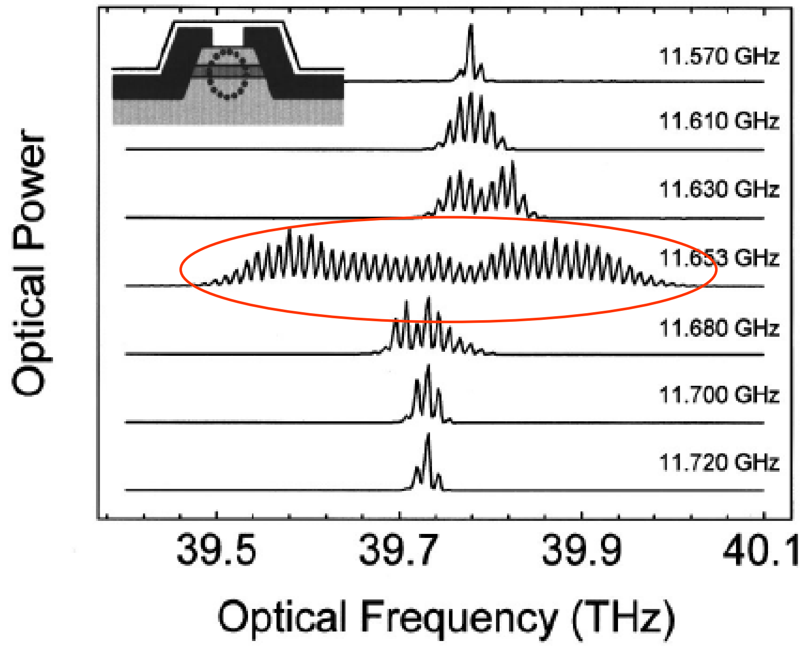
$$\omega_{cut-off} \approx \frac{1}{2\pi RC} = \frac{1}{2\pi(\frac{dV}{dI})C} \approx 20 - 30\ GHz$$

Absence of relaxation oscillations

- Modulation up to 3GHz (-3dB)



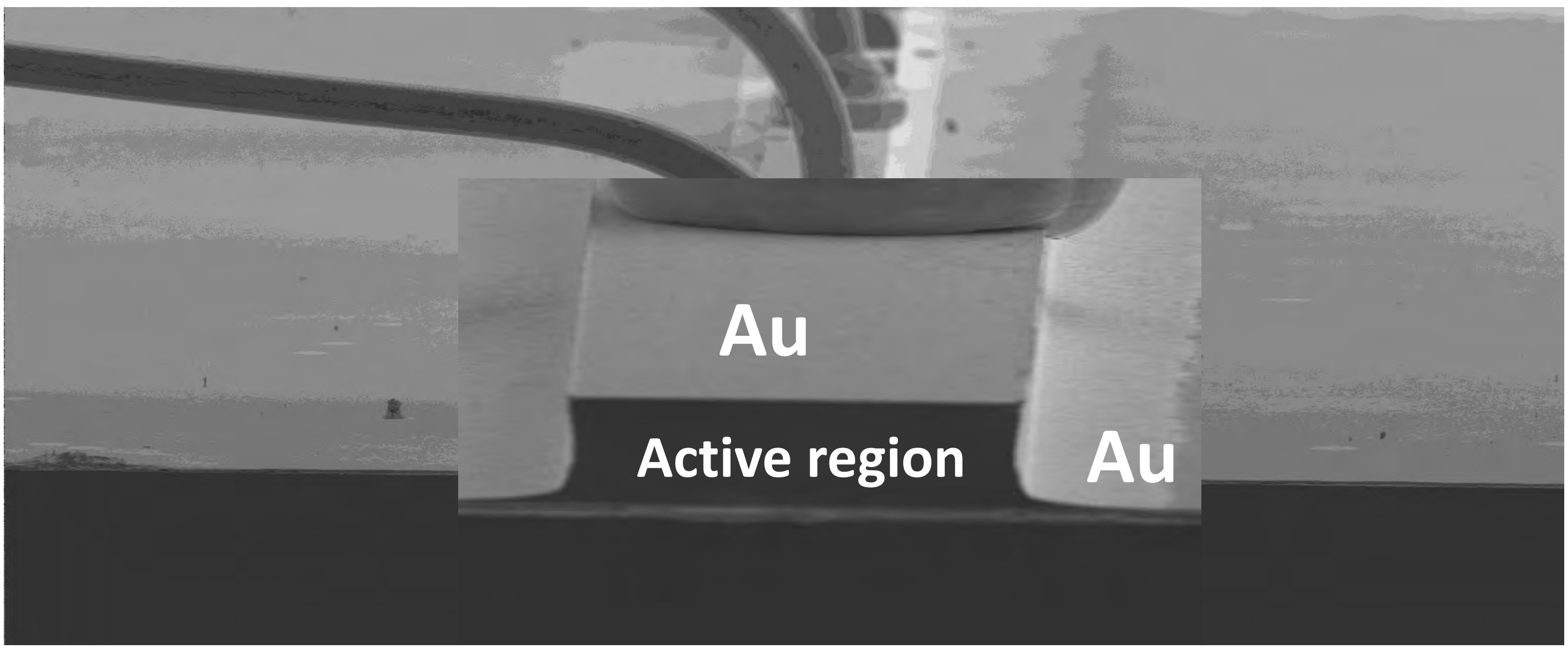
1.25mm x 4.5mm ridge



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

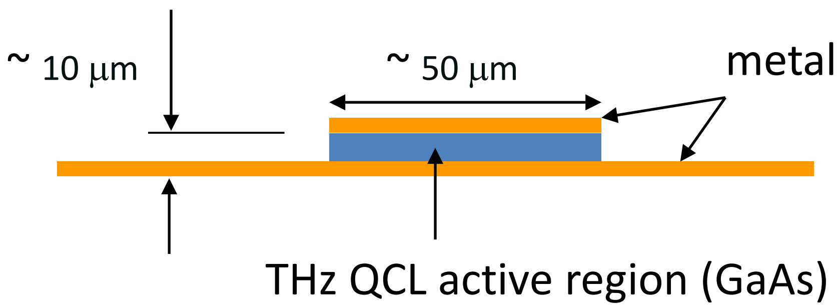
THz quantum cascade laser



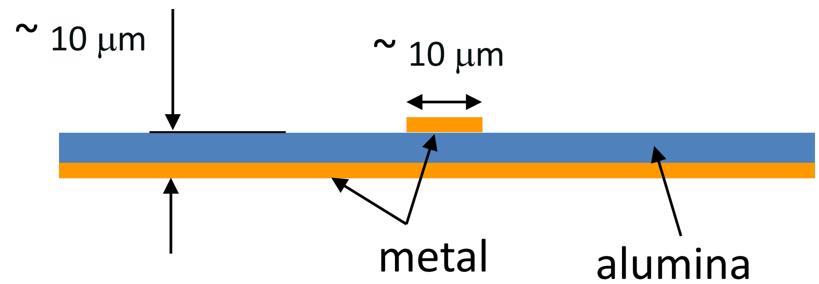
S. Barbieri, M. Ravaro, G. Santarelli

THz Waveguide and μ-wave transmission line

➔ MM THz QCL waveguide



➔ Thin-film μ-wave micro-strip line



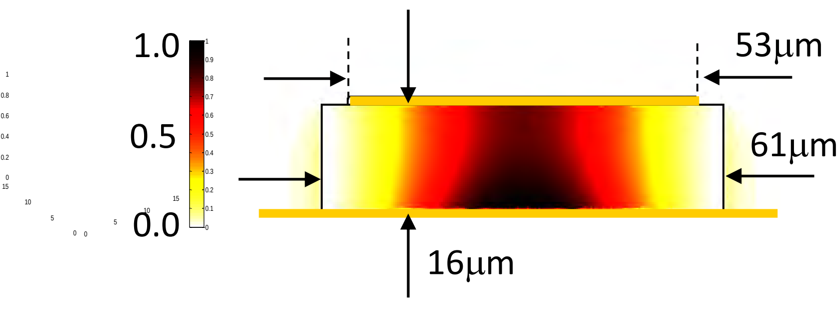
Main differences

- Dielectric: doped heterostructure
- Dielectric etched on both sides

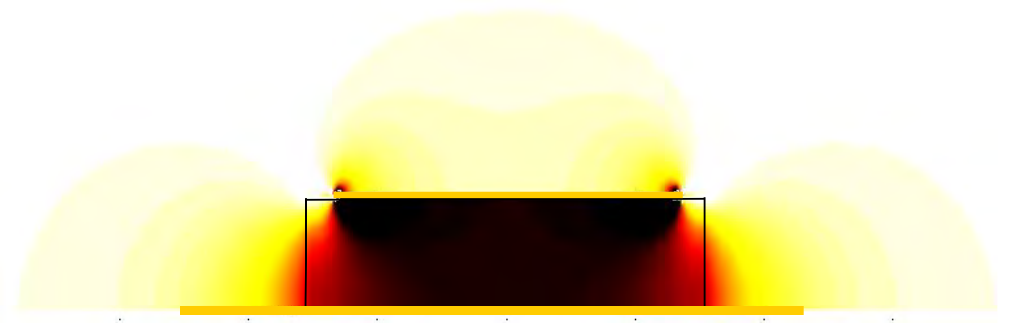
- Insulating dielectric
- Semi-infinite dielectric plane

Computed 2-D mode profiles

- 2.3THz

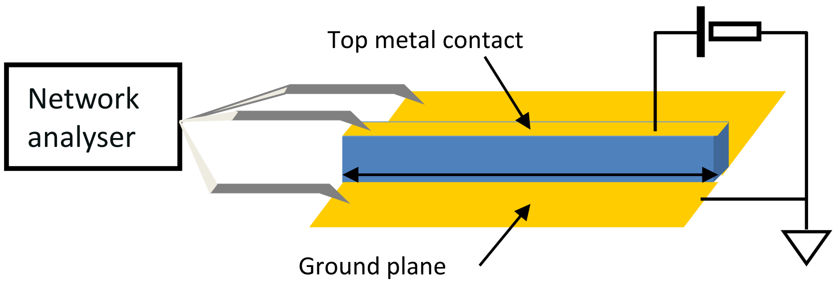


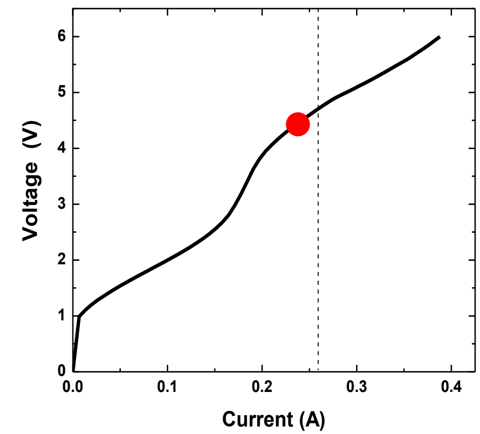
- 20GHz



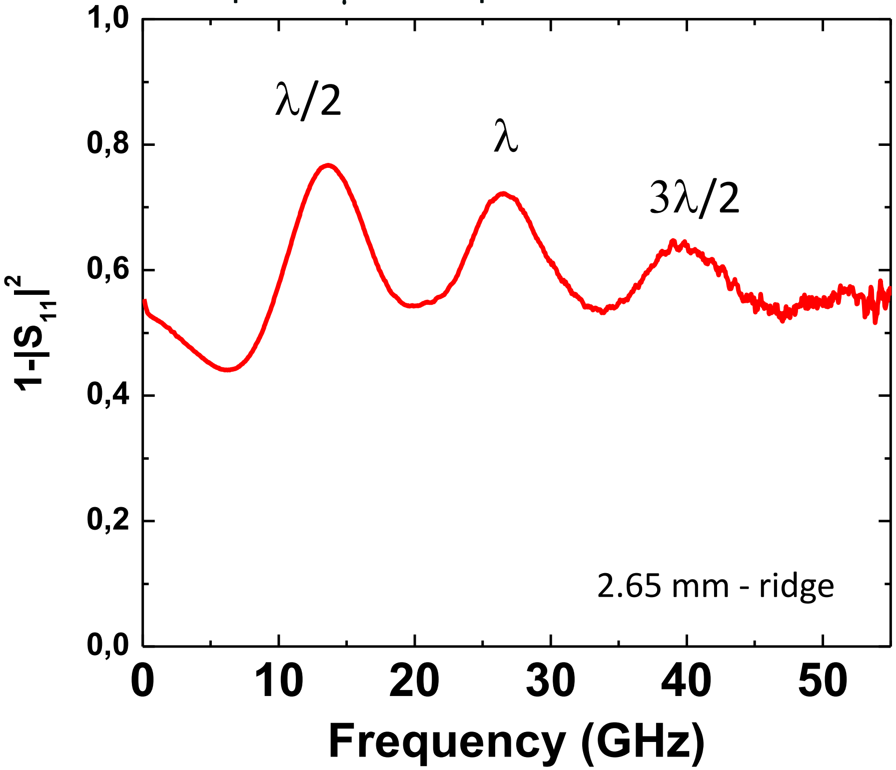
What is the impedance of Metal-Metal THz QCL waveguides at microwave frequencies?

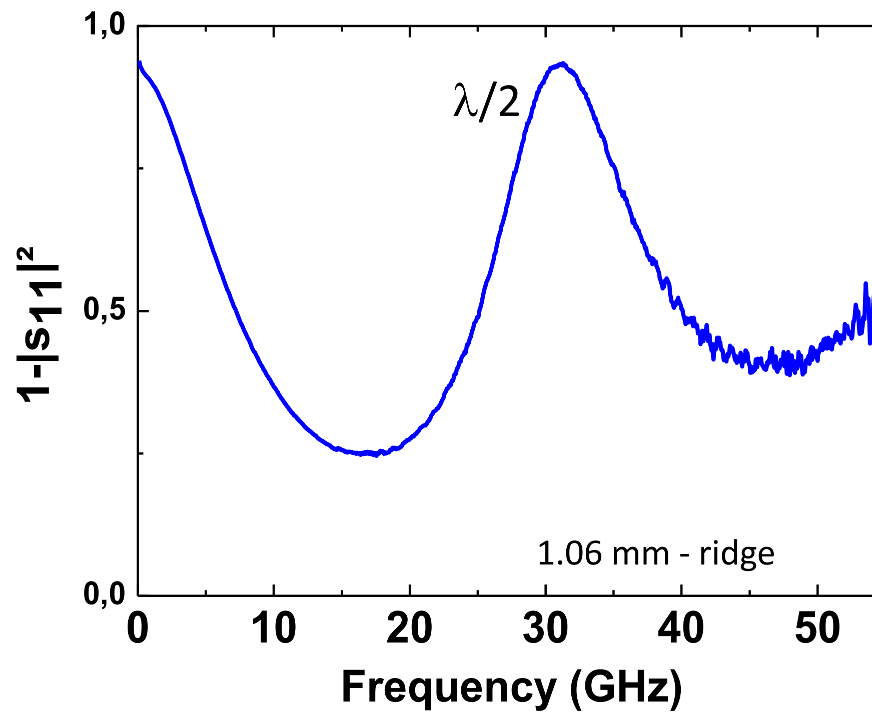
Impedance measurements





Dissipated μ-wave power in the device



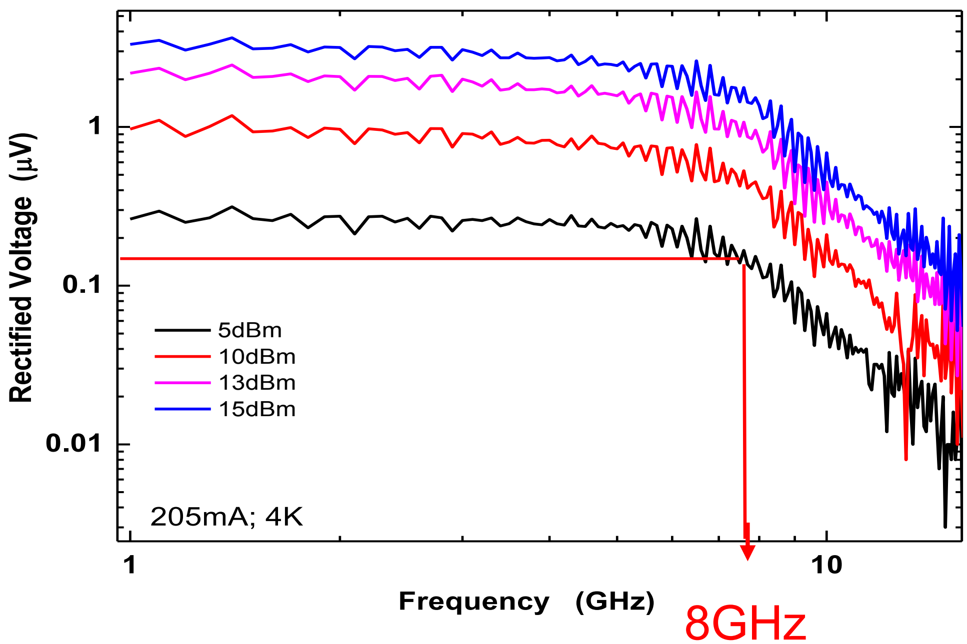


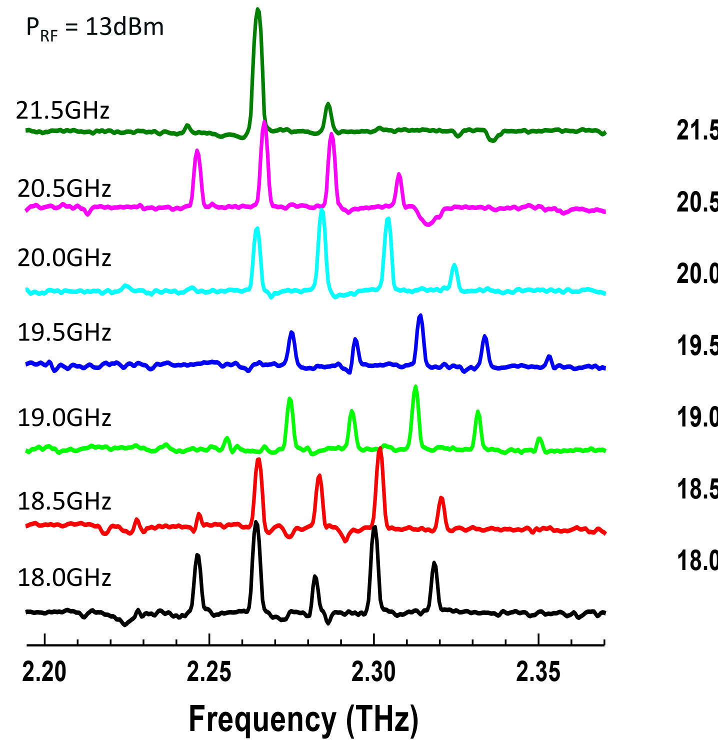
Modualtion of THz- QC lasers

S. Barbieri *et al.*, Appl. Phys. Lett. (2007)

W.Maineault *et al.*, Appl. Phys. Lett. (2010)

Modulation up to > 20 GHz using a shunt-stub matching



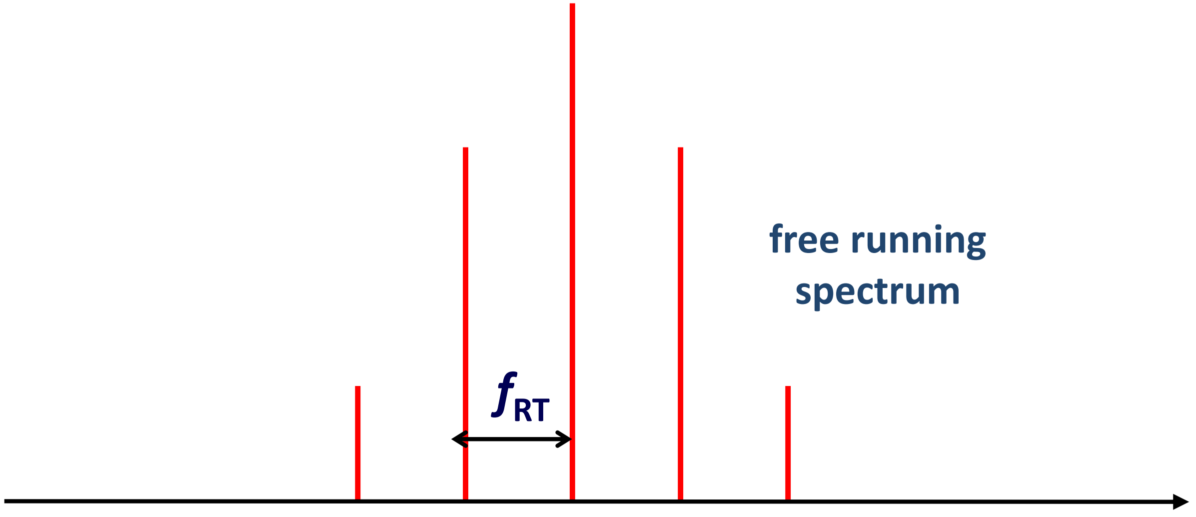


Band pass limited by our microwave circuits

Intermodal (*round-trip*) injection locking @ THz

Phase locking on a mode only…

f_{RT}= 10 – 50 GHz



How to stabilize f_{RT} the round trip frequency

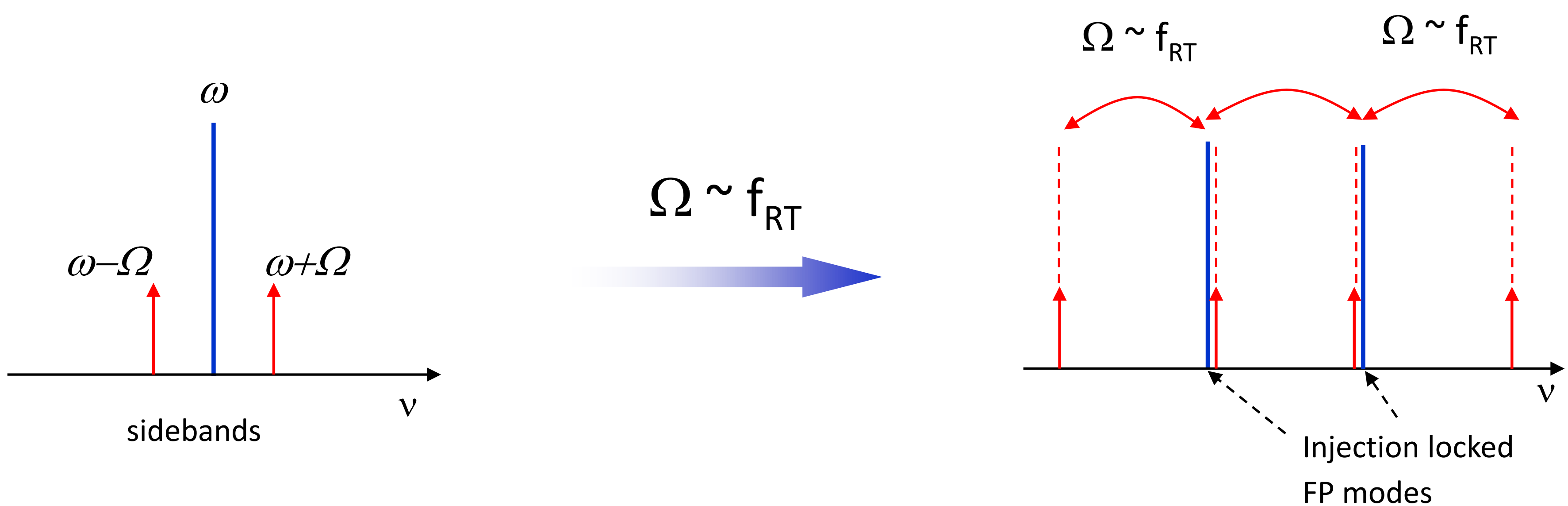
Amplitude modualtion

Amplitude modulation at frequency Ω :

Monochromatic lasers $\boldsymbol{E}\cos(\omega t+\phi)$

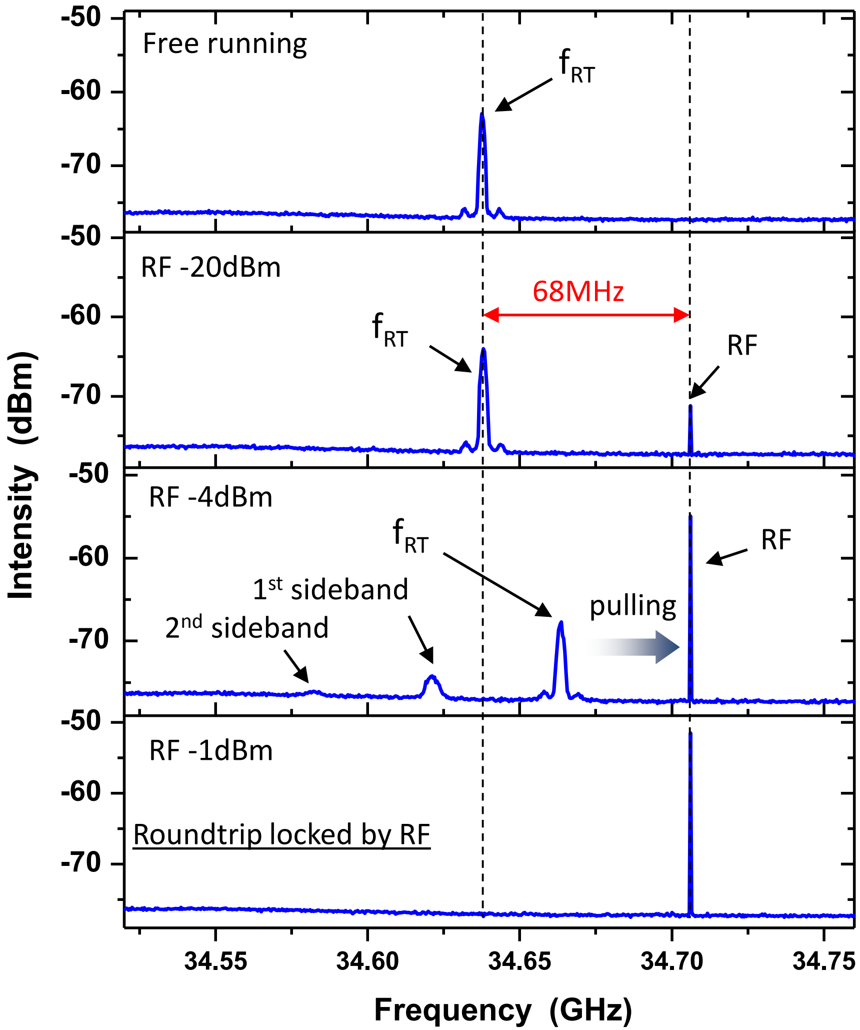
Modulation at Ω of the laser $(\boldsymbol{E}\sin(\omega t+\phi))\,(A+B\cos(\Omega t))=$

$$= \frac{B\boldsymbol{E}}{2}\sin((\omega+\Omega)t+\phi)) + \sin(\omega-\Omega)t+\phi) + A\boldsymbol{E}\sin(\omega t+\phi))$$

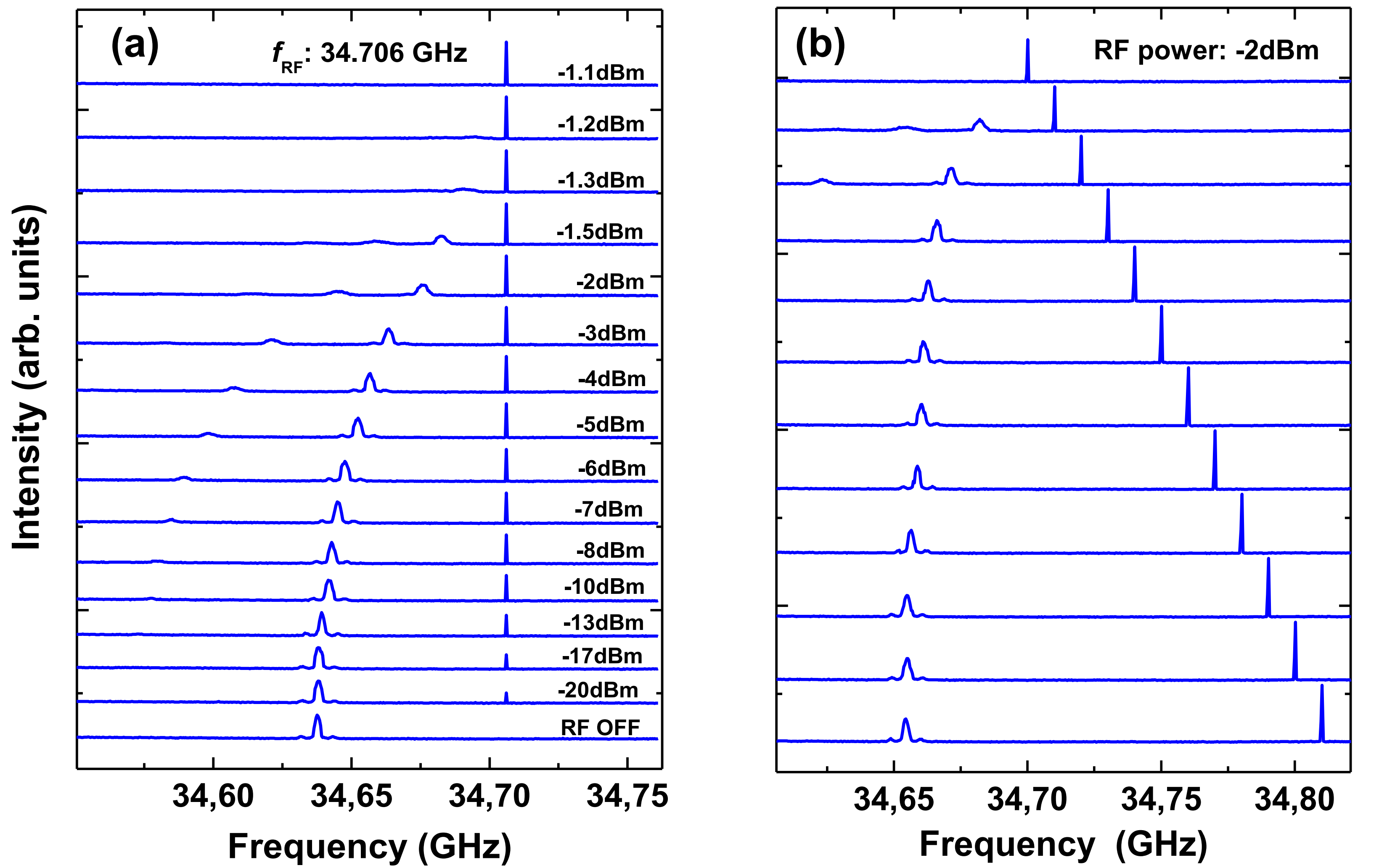


Intermodal injection locking at 34.7GHz

1.3mm long laser → Injection at ~ 35GHz !



Gellie *et al. Opt. Express* 18, 20799 (2010)

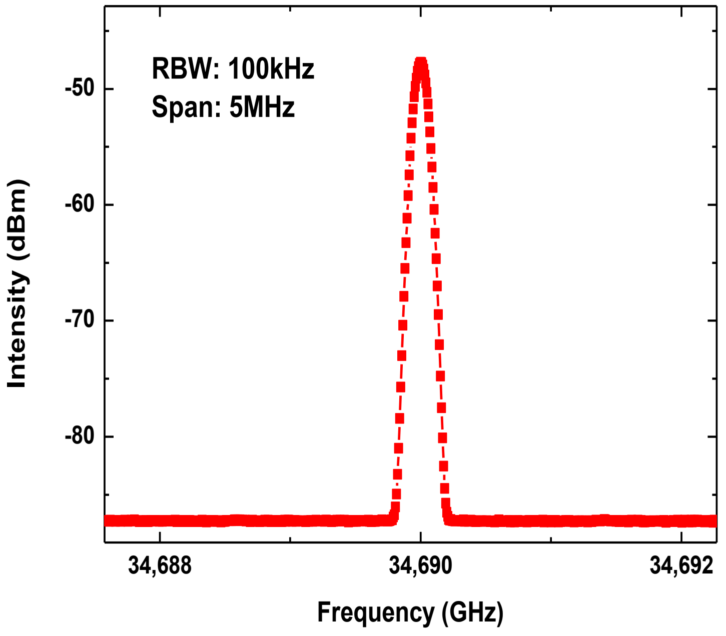


Measurements @ IEMN JFL

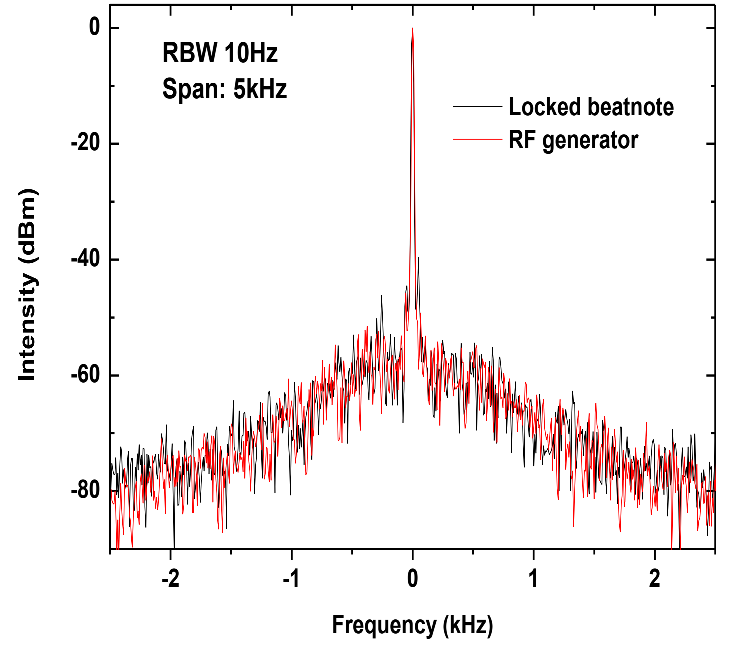
Gellie *et al. Opt. Express* 18, 20799 (2010)

Fig.5

Locked beat-note linewidth



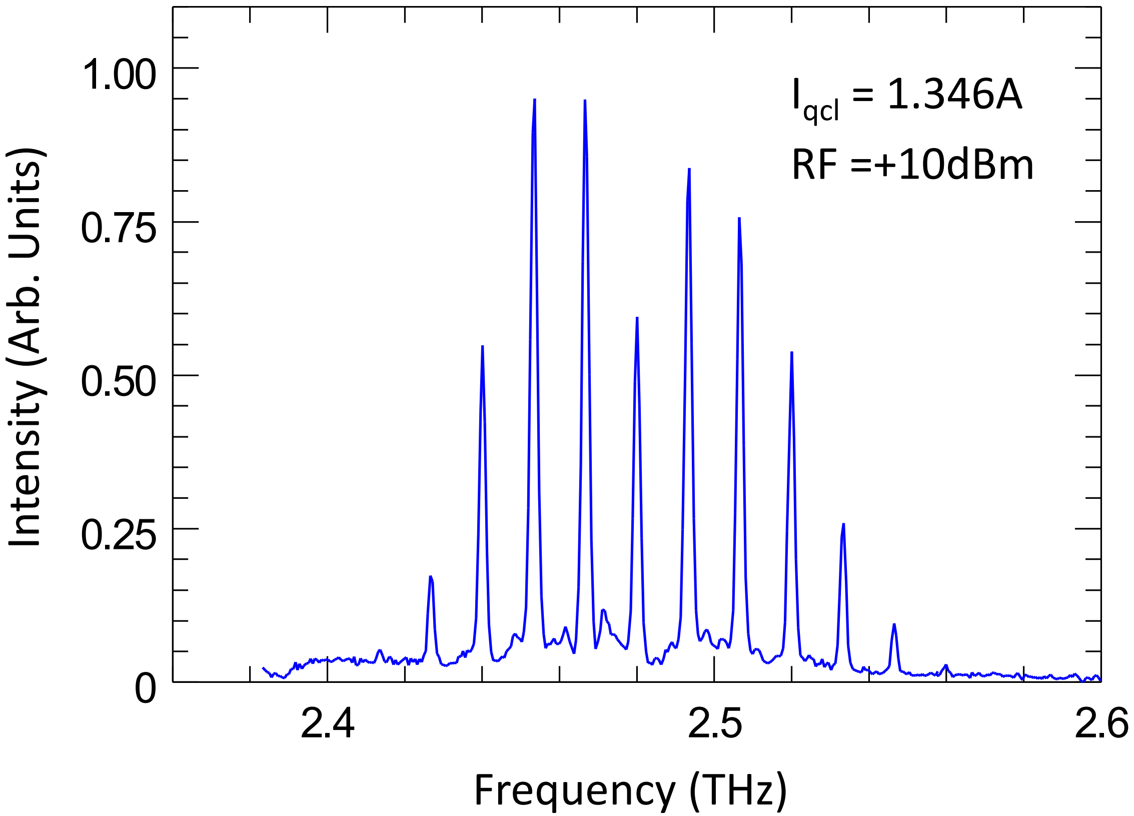
Free running



Locked

Injected optical spectrum

The spectrum has several modes due to the RF injection at the round trip

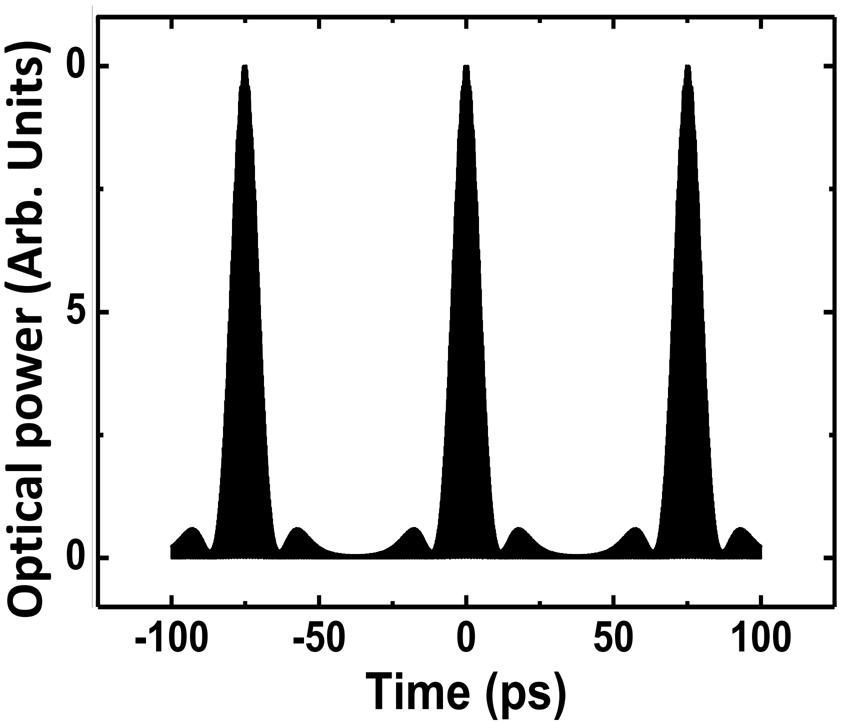


S. Barbieri *et al.* Nature Photon. **5**, 306 (2011)

C. Sirtori, *et al.* Nature Photon. **7**, 691 (2013)

Coherent detection of THz QC laser mode-locking

- Active THz QCL mode-locking measured by an asynchronous optical sampling



Pulse width: **10ps**

Measured pulse train

Pulse train **calculated by supposing** a negligible phase dispersion (*transform limited pulses*)

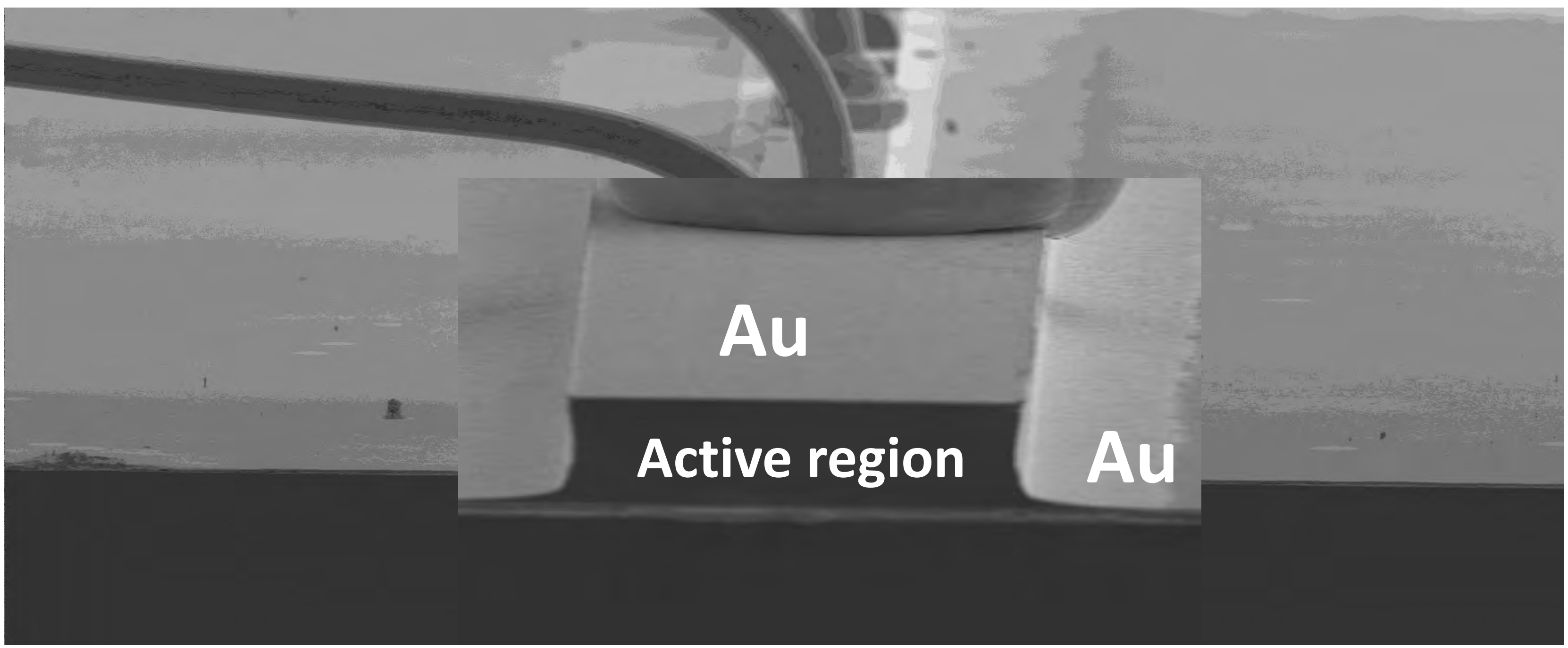
S. Barbieri *et al.* Nature Photon. **5**, 306 (2011)

C. Sirtori, *et al.* Nature Photon. **7**, 691 (2013)

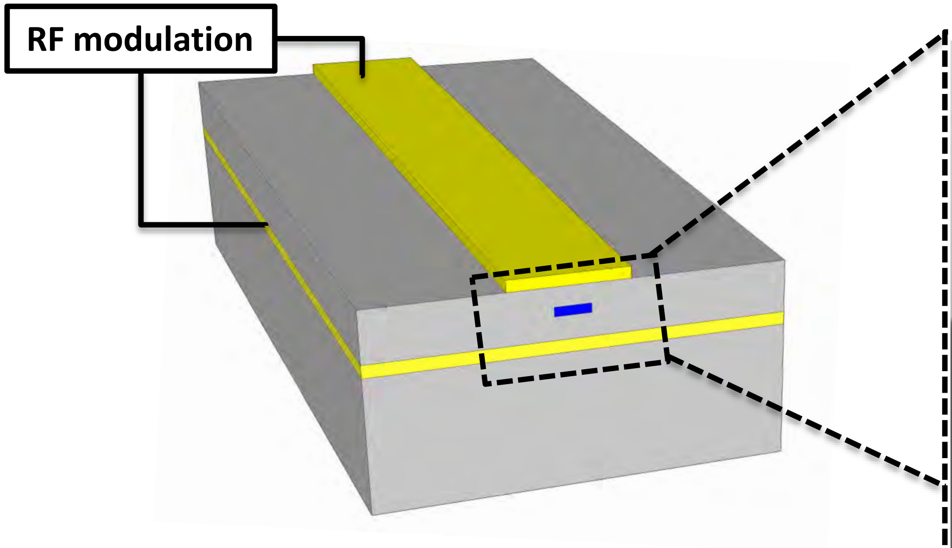
Intermodal (*round-trip*) injection locking in the mid-IR

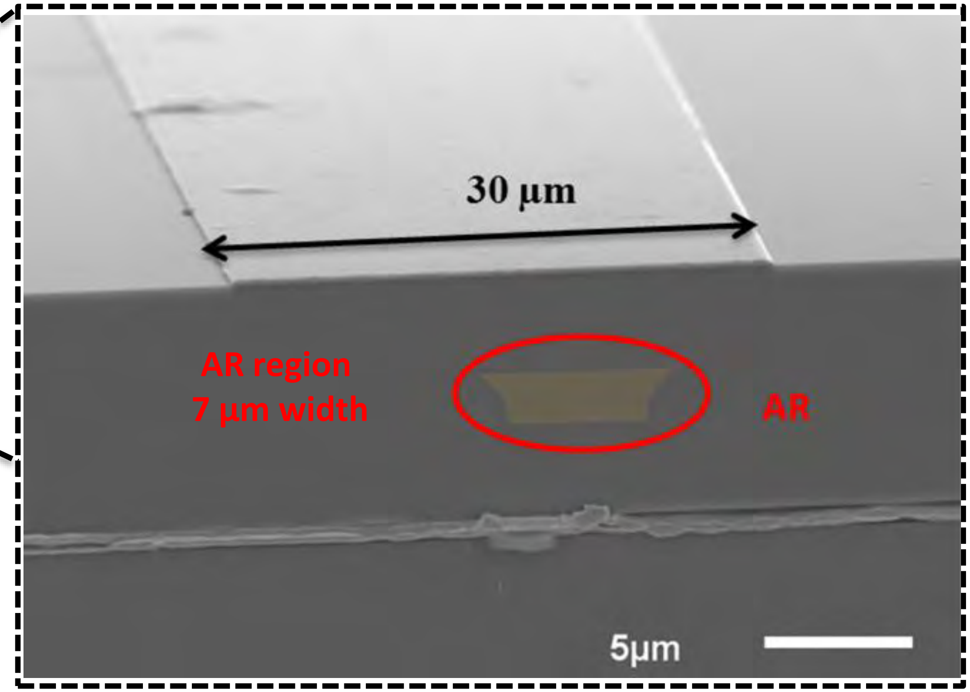
M. Amanti, A. Calvar, M. Renaudat

Let us copy ! …
THz quantum cascade laser



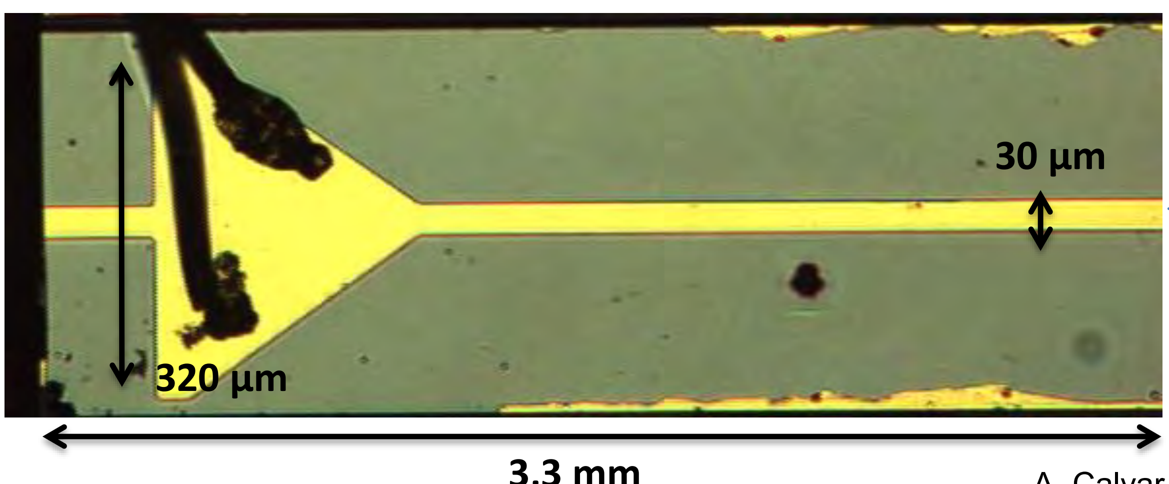
QC laser embedded within a microwave strip





In collaboration with:

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich



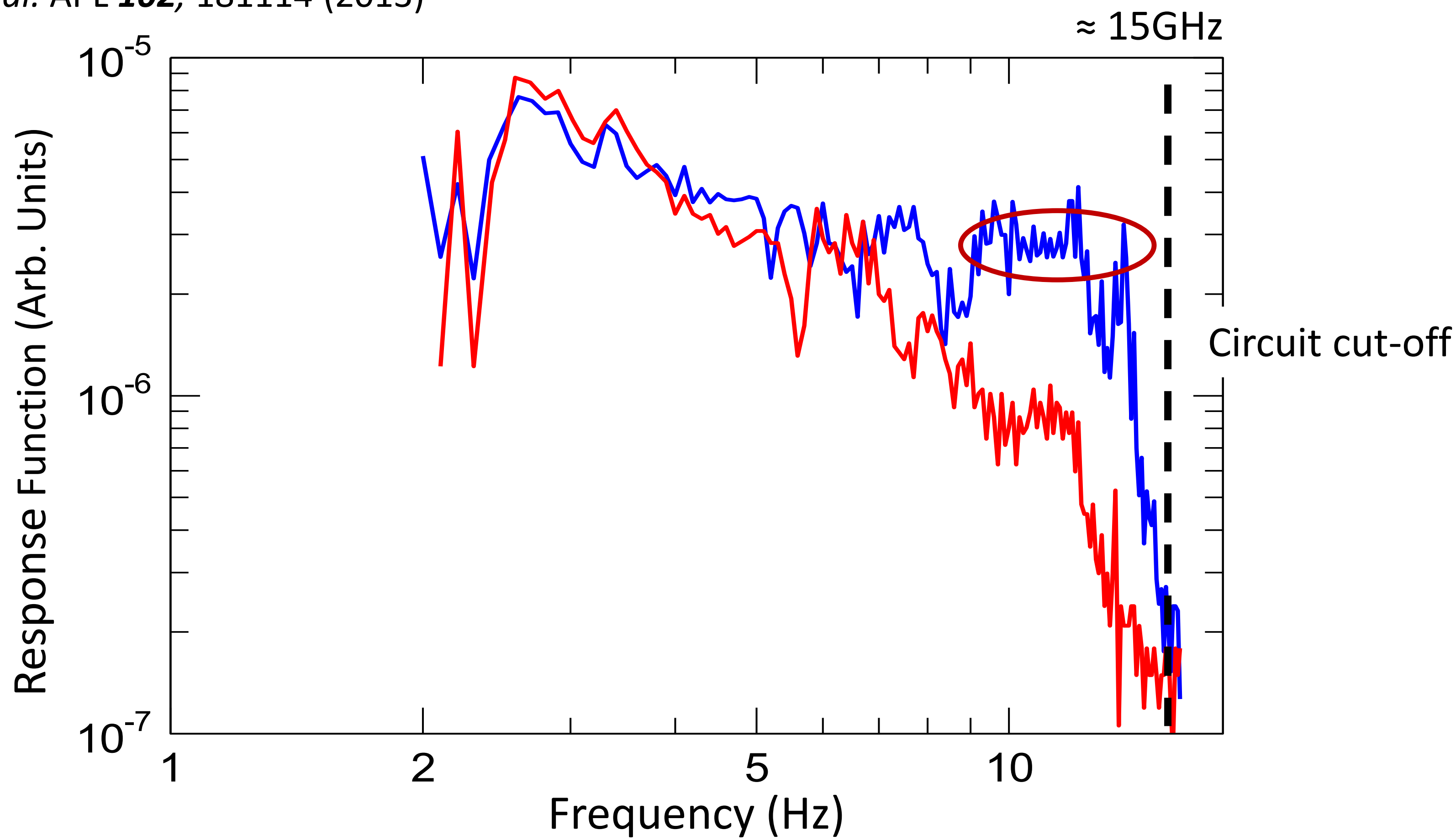
Geometry for the top contact :

→ **AR not damaged** by bonding

A. Calvar et al., *Applied Physics Letters* **102,** 181114 (2013)

High frequency response (comparison)

Calvar et al. APL ***102***, 181114 (2013)

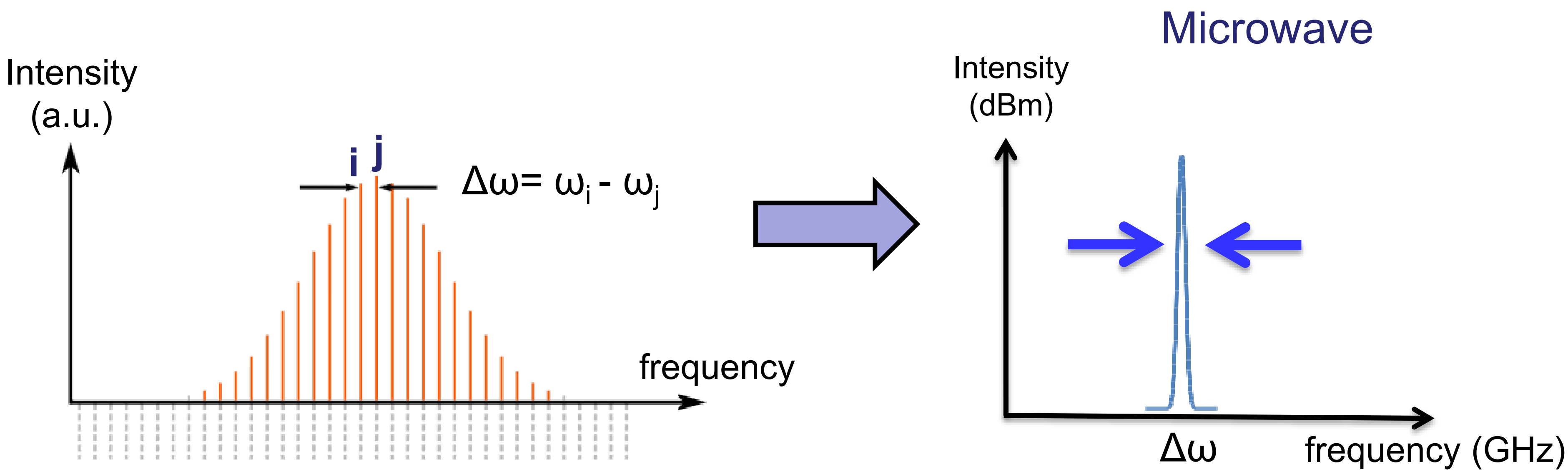


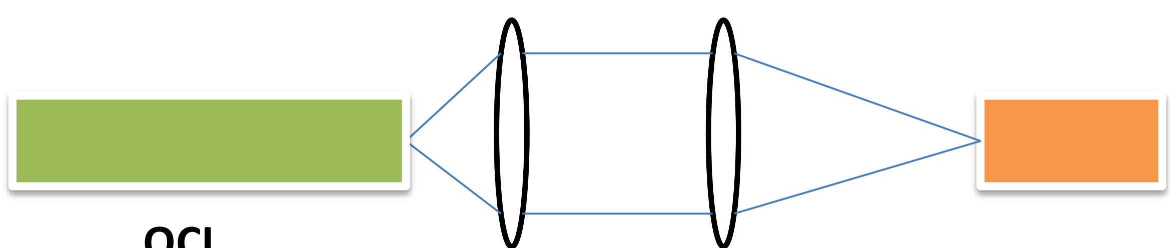
Comparison between a standard buried heterstructure (red) and the microawave-strip laser (blue)

Net improvement of the band pass up above 8GHz

Monitoring the laser modes separation

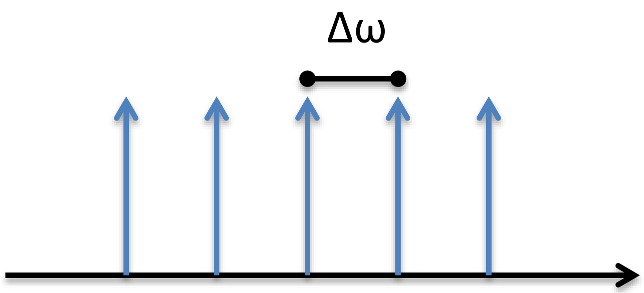
Optical spectrum is wide in QC lasers



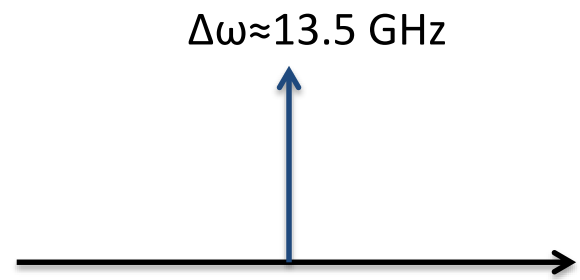


Stability of the cavity modes

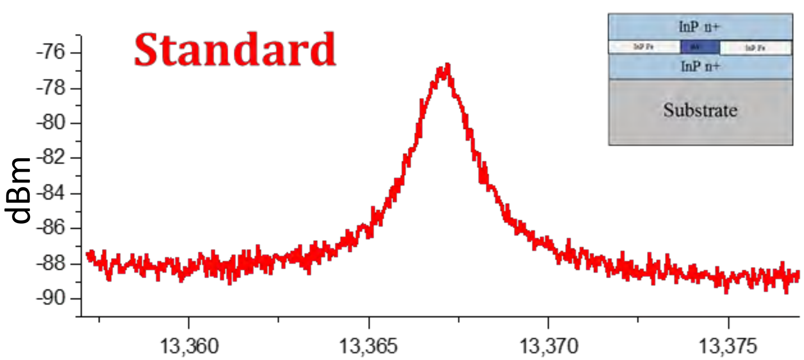
Optical spectrum :



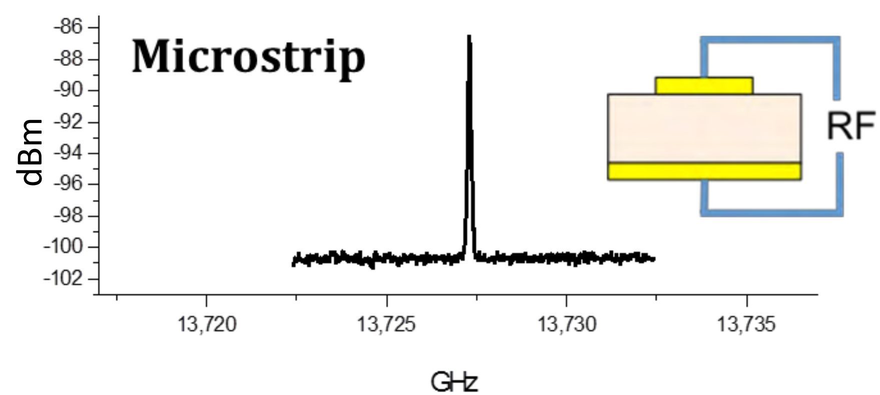
Microwave spectrum :



The shape of the beatnote gives an insight of the noise behavior of the laser modes



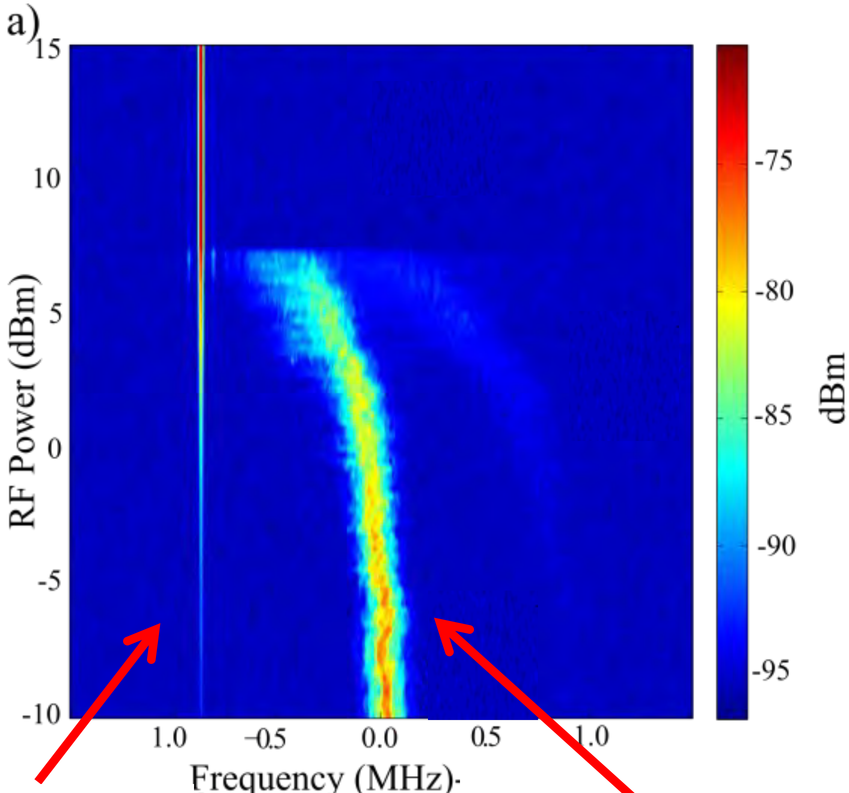
FWHM 1,3 MHz



FWHM 100 kHz

Beat note injection experimental data in the Mir

Power injection

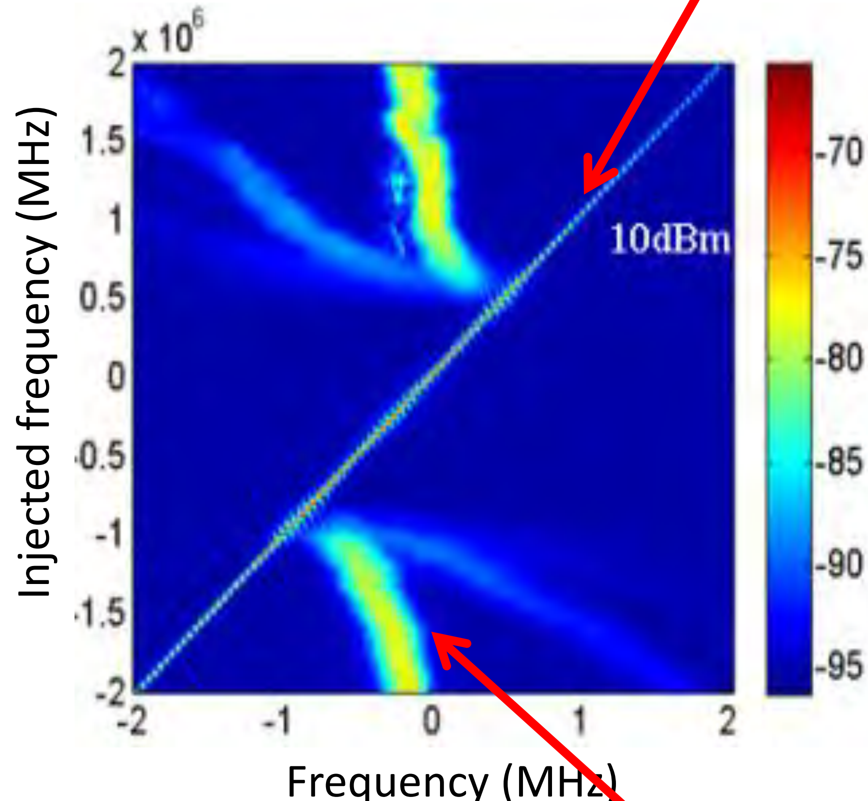


Injected microwave

Beating between the longitudinal modes

Frequency injection

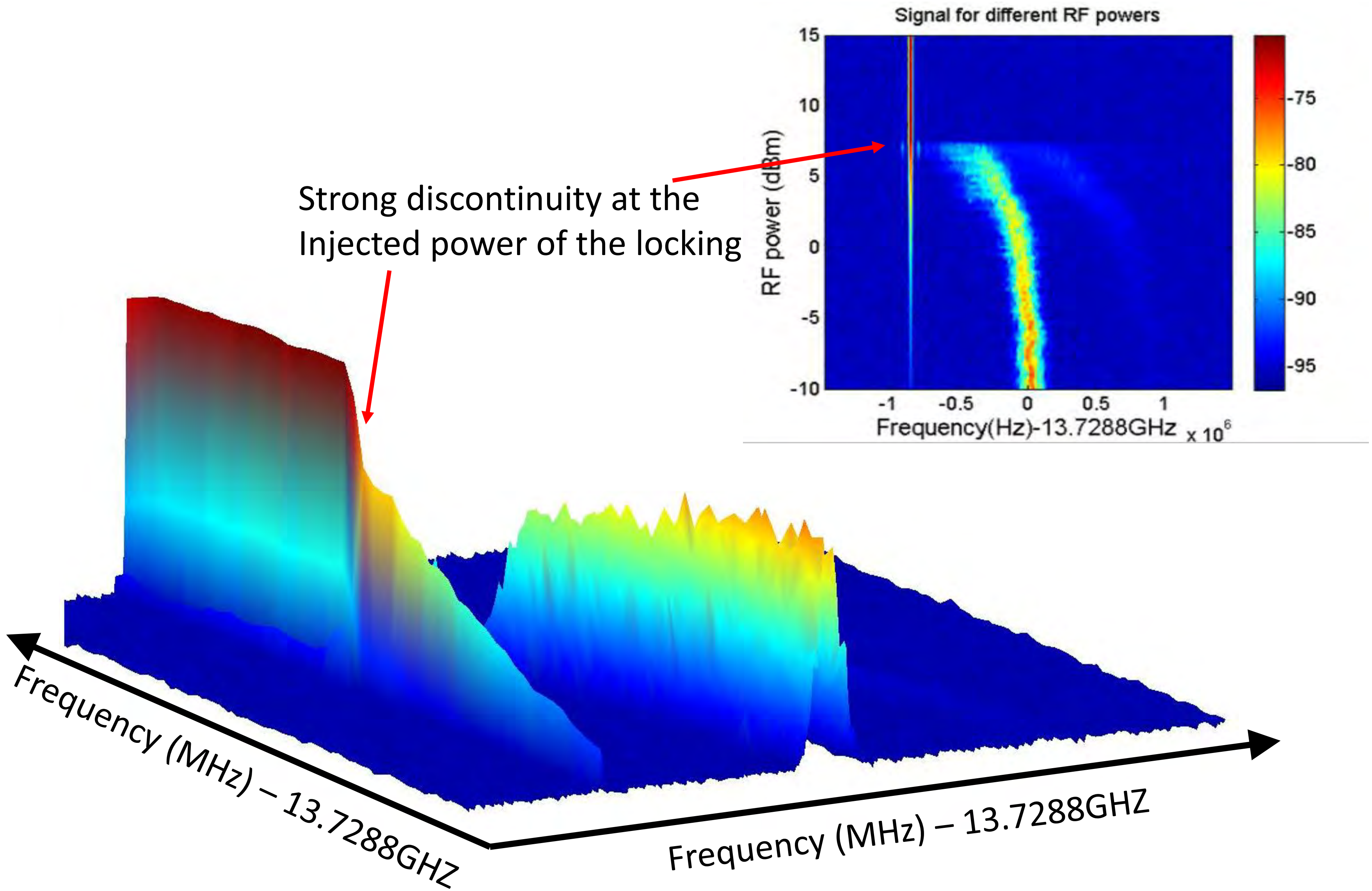
Injected microwave



Beating between the longitudinal modes

M. Renaudat et al., Laser Photonics Rev., (2014)

Beat note injection experimental data in the Mir



Mid-Infrared pulses?

No pulses have been measured!
(we have used a second order correlation using a two photon QWIPA)…

What is the difference between MIR and THz devices:

In the THz the upper state the lifetime can much longer than in the mid infrared

- @ THz (bound to continuum) ~ 10 - 20ps
- @MIR ~ 0.5 -1ps

Mode-locking of QCLs

ARTICLES
PUBLISHED ONLINE: 24 APRIL 2011 | DOI: 10.1038/NPHOTON.2011.49

nature photonics

Coherent sampling of active mode-locked terahertz quantum cascade lasers and frequency synthesis

Barbieri *et al.* Nature Photon. **5**, 306 (2011)

J. Freeman *et al.* OPEX. **21**, 16162 (2013)

LETTER

13 DECEMBER 2012 | VOL 492 | NATURE | 229
doi:10.1038/nature11620

Tomorrow talk of J. Faist

Mid-infrared frequency comb based on a quantum cascade laser

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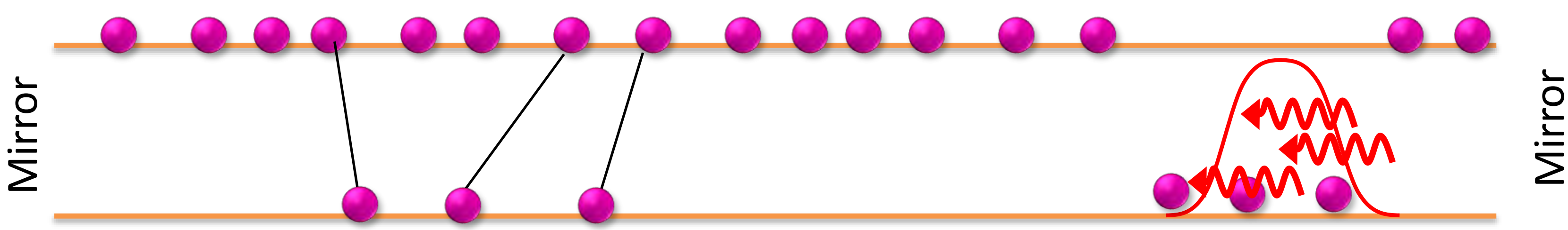
System not favourable for pulse generation
→ phase relation arising from FM

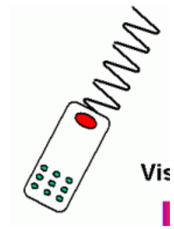


τ_{21}=1ps

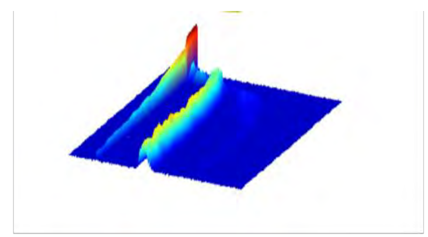
τ_{rt}=100ps

Conclusions

- Modulation of QC lasers has been measured above 30GHz



- QC lasers embedded in double metal waveguides can be easily injected at the round trip frequency and can give rise to frequency combs without generating pulses



- Mode-locking of QC lasers seems possible only if the lifetime exceeds tens of ps

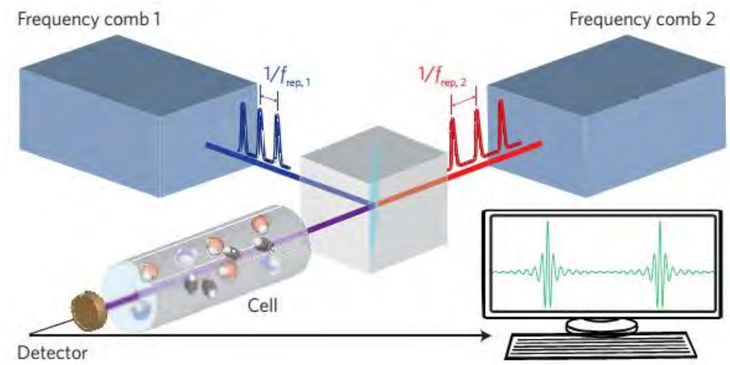
Frequency Comb Spectroscopy

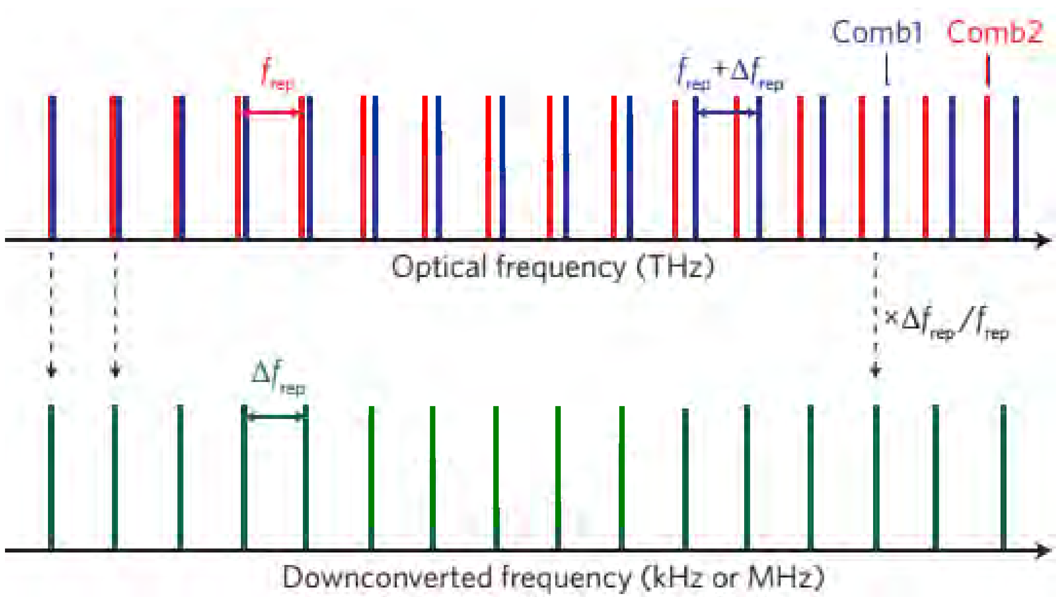
Dual comb spectroscopy:

2 lasers with two different repetition rates

⬇

2 combs slightly different mode separation





Optical spectrum

Microwave

- The optical absorption spectrum is mapped into the radiofrequency domain

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