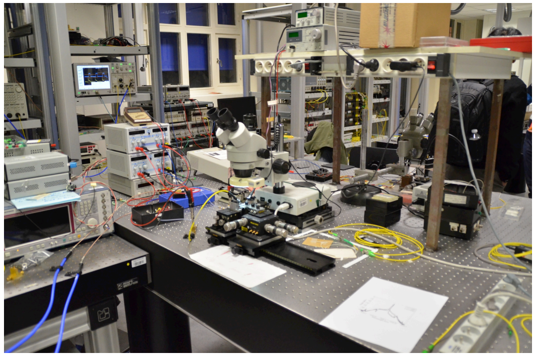
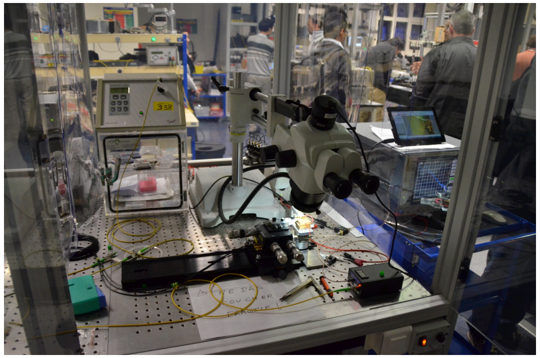
The optoelectronic team at a glance

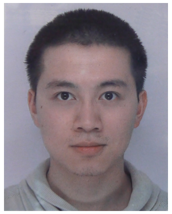
OPTOELECTRONICS LAB


F. Grillot (Head)


K. Schires (Postdoc)


C.Wang (PhD)

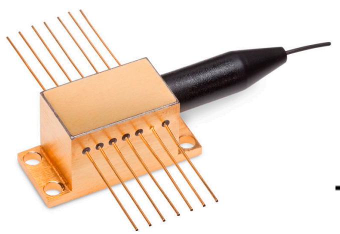

H. Huang (PhD)

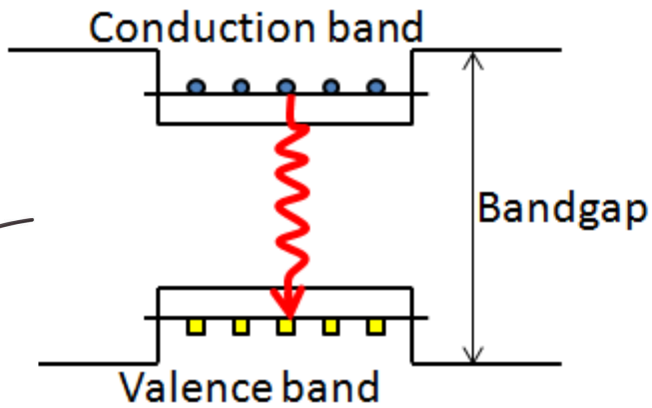

L. Jumpertz (PhD)

- Semiconductor Lasers
- Non-linear photonics and dynamics of Semiconductor lasers
- Physics and simulation of semiconductor lasers
- Advances quantum optoelectronics based on q-dot, q-cascade gain media as well as on micro-ring, plasmonics and hybrid silicon semiconductor lasers

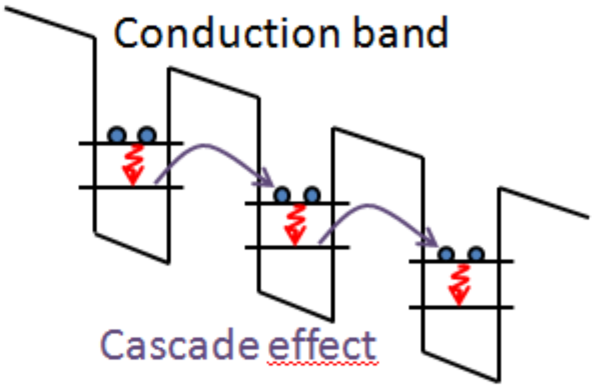
Quantum Cascade Lasers (QCLs)

- Ultrafast Intersubband transitions

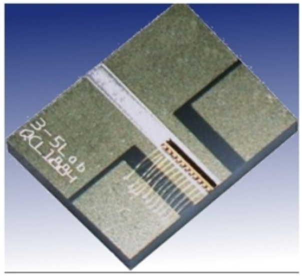




Interband lasers



Intersubband lasers (QCLs)

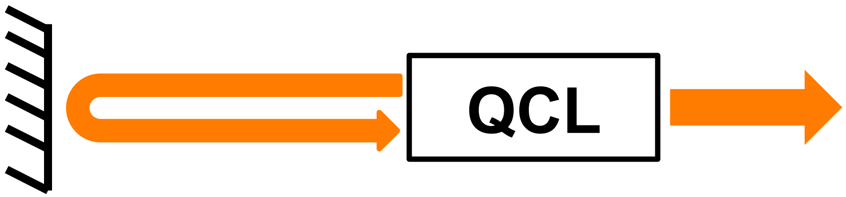


- Accessible wavelengths : mid-infrared (4-12µm) up to THz (30µm-1mm)
- Cascade effect : one electron produces several photons
- Ultrafast carrier dynamics
- **Motivations are to understand the nonlinear dynamical features of QCLs**

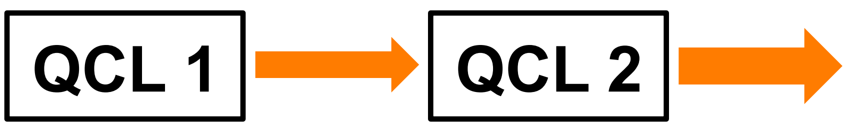
*Refs : C. Sirtori, C. R. Physique **4**, 639 (2003)*
*C. Gmalch et al., Rep. Prog. Phys. **64** ,1533 (2001)*

Forced Semiconductor Lasers

- **Self-Injection**

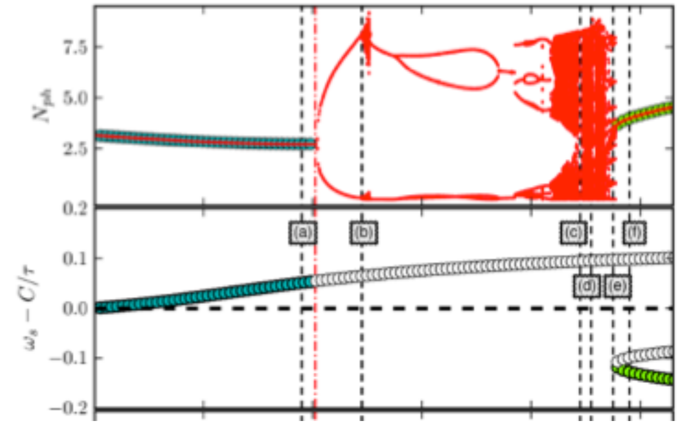


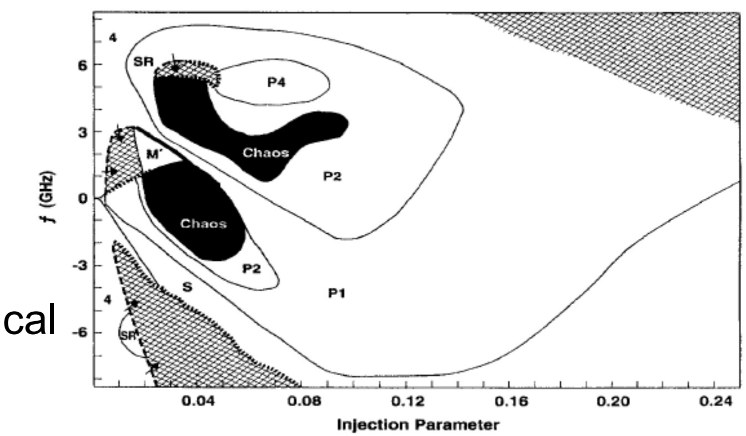
- **Injection-locking**



- **Improvements from nonlinear dynamics**
  - Single-mode operation
  - Reduced spectral linewidth
  - Ultra-low noise oscillator
  - Improved static (threshold, efficiency) and dynamical properties (modulation bandwidth)
  - Reduced filamentation
  - Four wave mixing

→ Applications in spectroscopy, DIRCM & free space communications





T.B. Simpson, J.M. Liu, K.F. Huang, and K. Tai,
"Nonlinear dynamics induced by external optical injection in semiconductor lasers,"
Quantum Semiclass. Opt., vol. 9, pp. 765-784, 1997

State-of-the-art

- Only a few studies on optical feedback mostly theoretical!
  - Extended cavity regime
  - Impact of the linewidth enhancement factor on optical feedback
  - Optical feedback & noise properties

TOPICAL REVIEW

External cavity quantum cascade laser

Andreas Hugi, Richard Maulini and Jérôme Faist

Institute of Quantum Electronics, ETH Zurich, Switzerland

E-mail: hugia@phys.ethz.ch and jerome.faist@phys.ethz.ch

Received 31 January 2009, in final form 14 February 2010
Published 2 July 2010
Online at stacks.iop.org/SST/25/083001

Intrinsic stability of quantum cascade lasers against optical feedback

F. P. Mezzapesa,[1,2,*] L. L. Columbo,[1,3] M. Brambilla,[1,2] M. Dabbicco,[1,2] S. Borri,[1] M. S. Vitiello,[4] H. E. Beere,[5] D. A. Ritchie,[5] and G. Scamarcio[1,2]

[1]CNR-IFN UOS Bari, via Amendola 173, I-70126 Bari, Italy
[2]Dipartimento Interateneo di Fisica, Università degli Studi e Politecnico di Bari, via Amendola 173, I-70126 Bari, Italy
[3]Dipartimento di Scienza ed Alta tecnologia, Università dell'Insubria,via Valleggio 11, 22100 Como, Italy
[4]NEST, CNR - Istituto Nanoscienze and Scuola Normale Superiore, Piazza San Silvestro 12, 56127 Pisa, Italy
[5]Cavendish Laboratory, University of Cambridge, J. J. Thomson Avenue, Cambridge CB3 0HE, UK
*francesco.mezzapesa@uniba.it

Quantum cascade laser intensity noise under external feedback conditions estimated from self-mixing method

T. Inoue, K. Tsushima, S. Mori and K. Kasahara

Experimental investigation of high-frequency noise and optical feedback effects using a 9.7 μm continuous-wave distributed-feedback quantum-cascade laser

Damien Weidmann, Kevin Smith, and Brian Ellison

Outline

- Delayed equations for self-injected QCLs
- Device characteristics
- Experimental results (optical spectra, regimes, etc.)
- Optical injection-locking
- Conclusions & perspectives

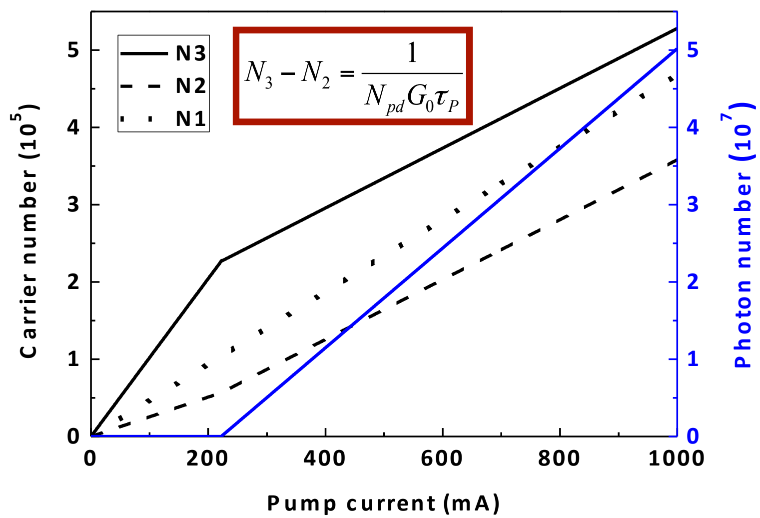
Rate Equation Model for QCLs

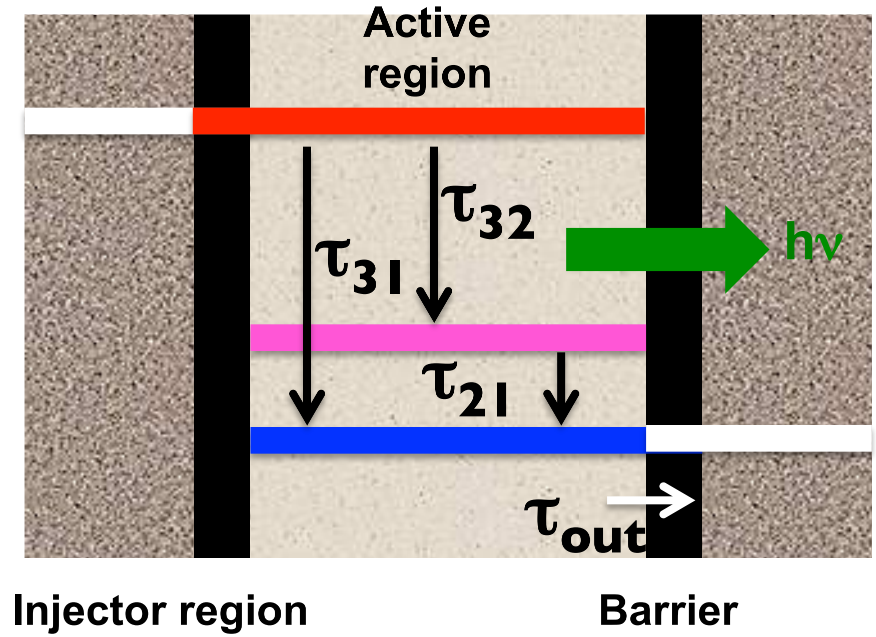
- Rate equation model (solitary)

$$\frac{dN_1}{dt} = \frac{N_3}{\tau_{31}} + \frac{N_2}{\tau_{21}} - \frac{N_1}{\tau_{out}} \qquad \Delta N = N_3 - N_2$$

$$\frac{dN_2}{dt} = \frac{N_3}{\tau_{32}} - \frac{N_2}{\tau_{21}} + G_0 \Delta N \left| E(t) \right|^2$$

$$\frac{dN_3}{dt} = \eta \frac{I}{q} - \frac{N_3}{\tau_{32}} - \frac{N_3}{\tau_{31}} - G_0 \Delta N \left| E(t) \right|^2$$





carrier lifetime < photon lifetime

$$\frac{dE(t)}{dt} = \frac{1}{2}\left(1 + j\alpha_H\right)\left(N_{pd} G_0 \Delta N - 1/\tau_p\right) E(t)$$

QCL's linewidth enhancement factor (LEF)

Ref: *Y. Petitjean et al., IEEE J. Sel. Top. Quantum Electron.* ***17,*** *22 (2011)*

Delayed Differential Equations

- Delay is incorporated into the electric field equation

$$\frac{dE(t)}{dt} = \frac{1}{2}\left(1 + j\alpha_H\right)\left(N_{pd}G_0\Delta N - 1/\tau_p\right)E(t) + k_c\sqrt{R_{ext}}\exp(-j\theta)E(t-\tau_{ext})$$

$$\frac{dS}{dt} = \left(N_{pd}G_0\Delta N - 1/\tau_P\right)S + \beta N_{pd}\frac{N_3}{\tau_{sp}} + 2k_c\sqrt{R_{ext}}\sqrt{S(t)S(t-\tau_{ext})}\cos\left(\theta + \phi(t) - \phi(t-\tau_{ext})\right)$$

$$\frac{d\phi}{dt} = \frac{\alpha_H}{2}\left(N_{pd}G_0\Delta N - 1/\tau_P\right) - k_c\sqrt{R_{ext}}\sqrt{\frac{S(t-\tau_{ext})}{S(t)}}\sin\left(\theta + \phi(t) - \phi(t-\tau_{ext})\right)$$

$$k_c = \frac{1}{\tau_{in}}\frac{1-R_1}{\sqrt{R_1}}$$

$$\phi(t) = (\omega_s - \omega_0)t$$

$$S(t) = \left|E_s\right|^2$$

τ_{in} → roundtrip time in the laser cavity
R_1 → the facet reflectivity
R_{ext} → feedback ratio
$\Theta = \omega_0 \times \tau_{ext}$ → feedback phase
ω_0 → solitary laser frequency at threshold
τ_{ext} → roundtrip delay of the external cavity

→ **Steady state, numerical integration, continuation methods**

Steady-State Solutions (I)

- Solutions → external cavity modes

$$S = \frac{N_{pd}}{1/\tau_p - 2k_c\sqrt{R_{ext}}\cos(\omega_s\tau_{ext})}\frac{1}{\tau_{32}(\tau_{31}+\tau_{21})}\left[\tau_{31}(\tau_{32}-\tau_{21})\frac{\eta I}{q} - \frac{\tau_{32}+\tau_{31}}{N_{pd}G_0}\left(\frac{1}{\tau_p} - 2k_c\sqrt{R_{ext}}\cos(\omega_s\tau_{ext})\right)\right]$$

$$N_3 = \frac{\tau_{31}\tau_{21}}{\tau_{31}+\tau_{21}}\left[\frac{\eta I}{q} + \frac{1}{N_{pd}G_0\tau_{21}}\left(\frac{1}{\tau_p} - 2k_c\sqrt{R_{ext}}\cos(\omega_s\tau_{ext})\right)\right]$$

$$N_1 = \tau_{out}\eta I / q$$

$$N_2 = \frac{\tau_{31}\tau_{21}}{\tau_{31}+\tau_{21}}\left[\frac{\eta I}{q} - \frac{1}{N_{pd}G_0\tau_{31}}\left(\frac{1}{\tau_p} - 2k_c\sqrt{R_{ext}}\cos(\omega_s\tau_{ext})\right)\right]$$

→ **Optimization of CW properties**
low threshold, high output power, high quantum efficiency

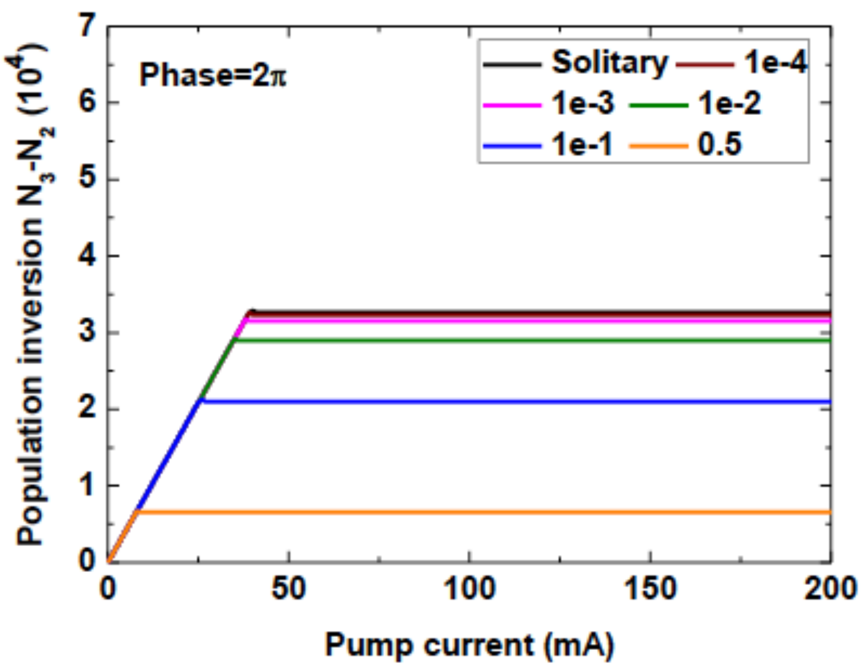
$$\omega_s - \omega_0 = -k_c\sqrt{R_{ext}}\left[\alpha_H\cos(\omega_s\tau_{ext}) + \sin(\omega_s\tau_{ext})\right]$$

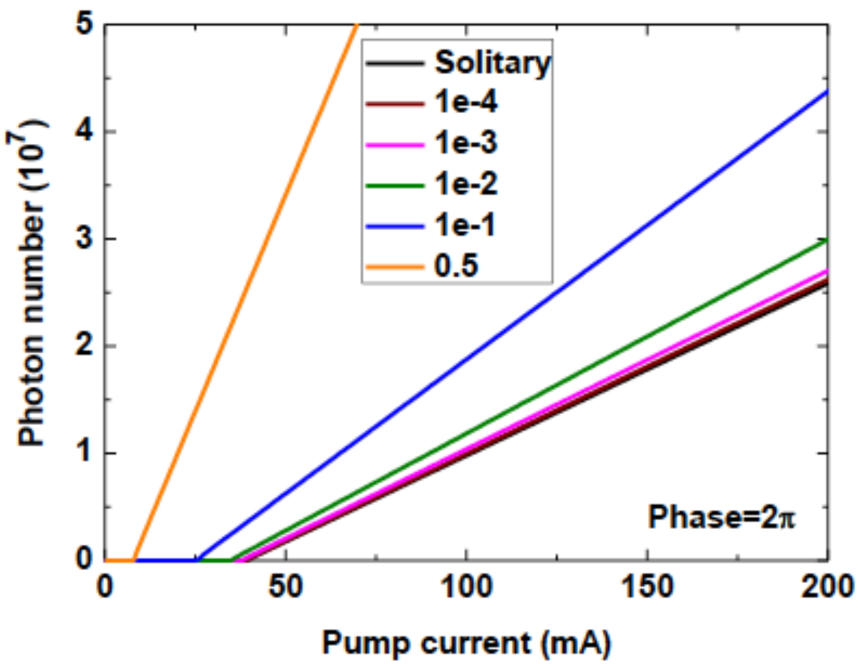
→ **Extraction of the above threshold Linewidth Enhancement Factor**

- Antimodes → destructive interference (unstable)
- Modes → constructive interference (stable)

Steady-State Solutions (II)

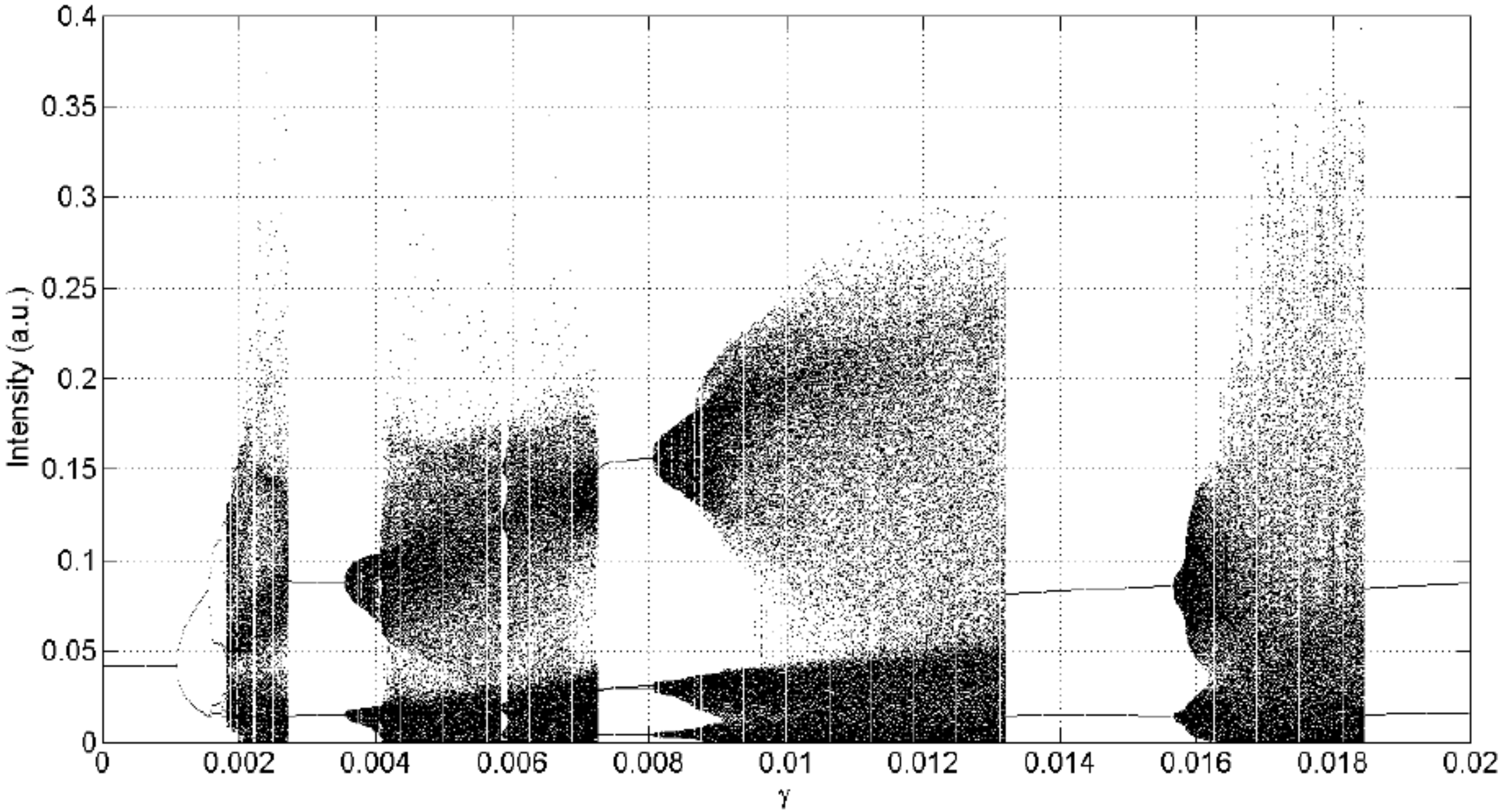
- L-I characteristics w/ optical feedback
  - Increase of optical power
  - Threshold reduction
  - Increase of the external quantum efficiency





A proper control of the feedback phase is required!

Route to chaos in a semiconductor laser



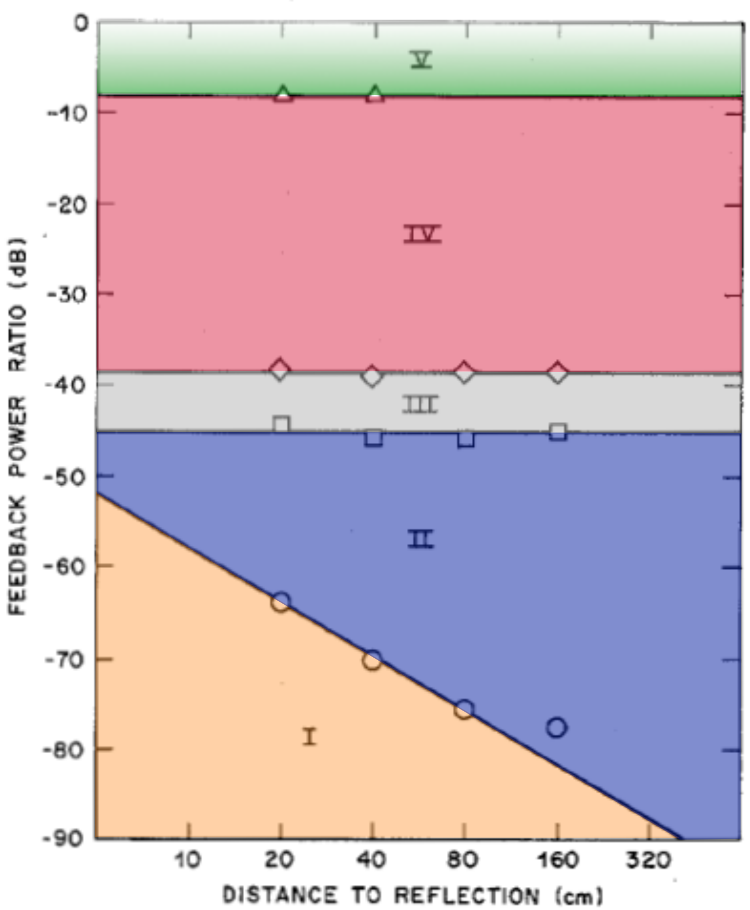
Complex cascade of bifurcation phenomena towards chaos

Chaos in Quantum Cascade Lasers?

Ref: A. Dal Bosco, PhD Thesis, Supelec, France (2013)

Feedback cartography

- The feedback regimes in interband lasers

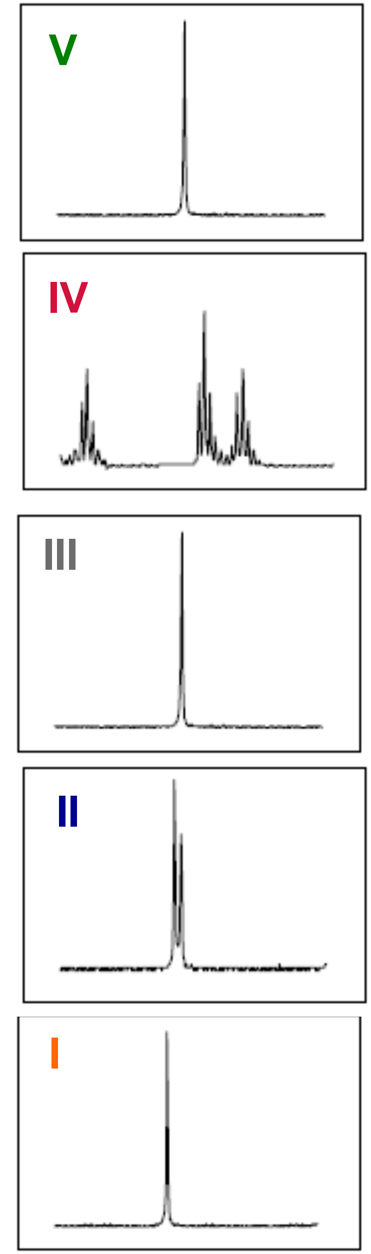


Extended cavity

Coherence Collapse

Mode hopping

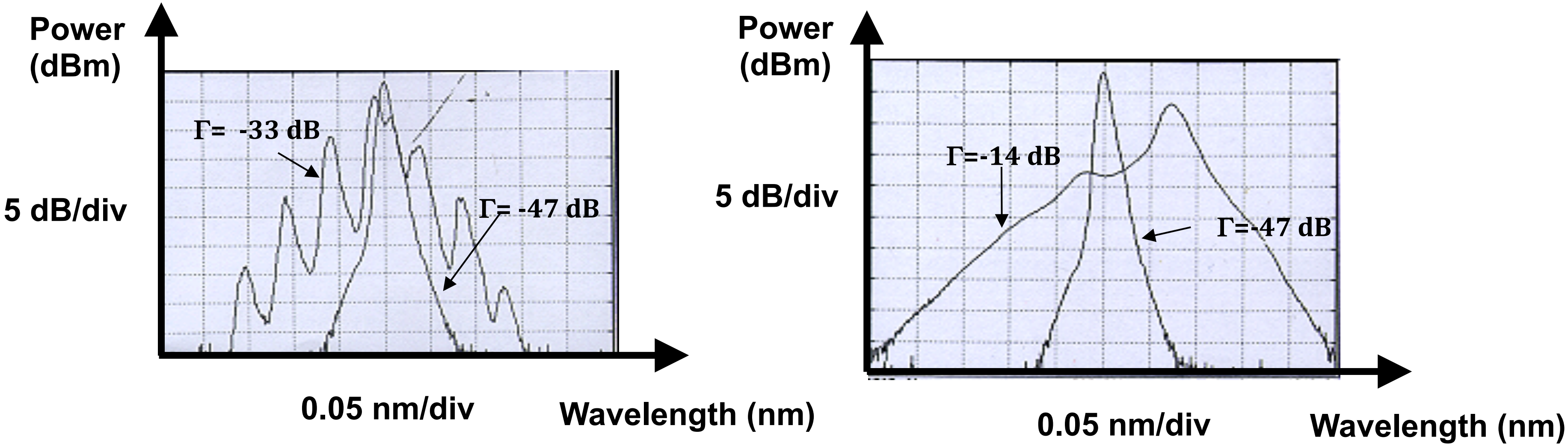
Stable & single mode



*Refs: R. W. Tkach and A. R. Chraplyvy. Journal of Lightwave Technology **4**, 1655 (1986)*
J. S. Lawrence, PhD Thesis (2000)

Coherence Collapse

- Self-injected interband lasers → spectral broadening (coherence collapse i.e chaos)



*Ref: F. Grillot et al. IEEE Photon. Technol. Letts. **14**, 101 (2002).*

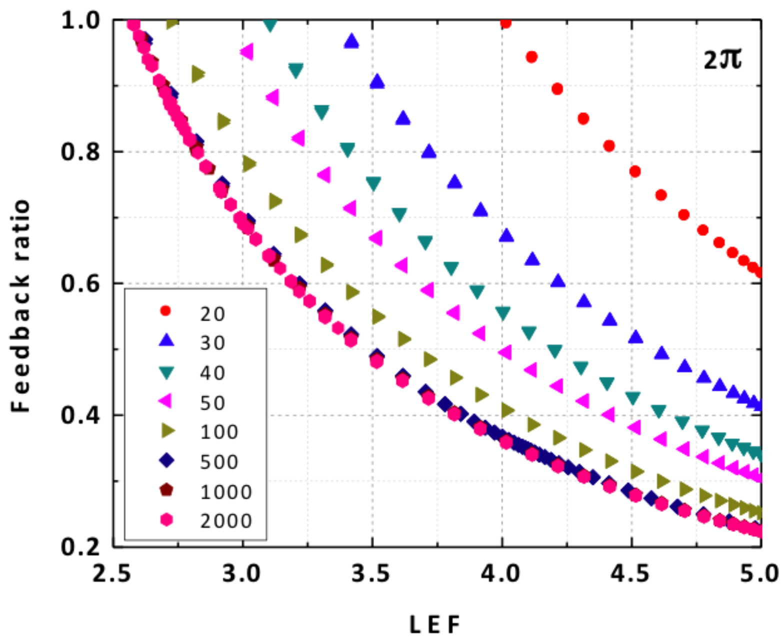
- Route to chaos through undamped ROs
- Increase of the spectrum pedestal
- The onset only depends on laser parameters

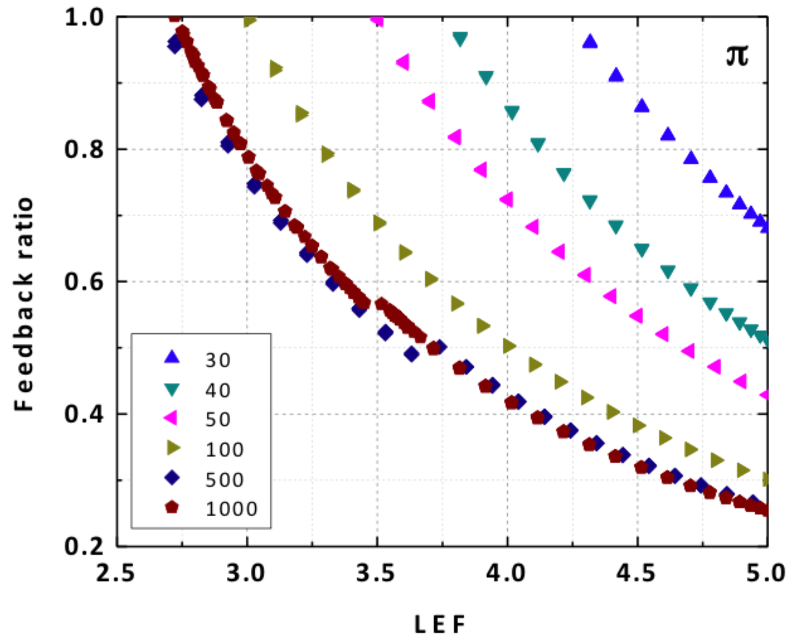
$$f_{ext,c} = \left[\frac{\omega_r \tau_{in}\sqrt{2}}{(1-R_2)}\right]^2 \frac{1}{1+\alpha^2}$$

No longer valid in class A quantum cascade lasers!

Hopf bifurcation line

- Route to chaos is ensured through the Hopf bifurcation that changes a fixed point to a limit cycle
- Hopf bifurcation is predicted with DDE-Biftool for various time delay



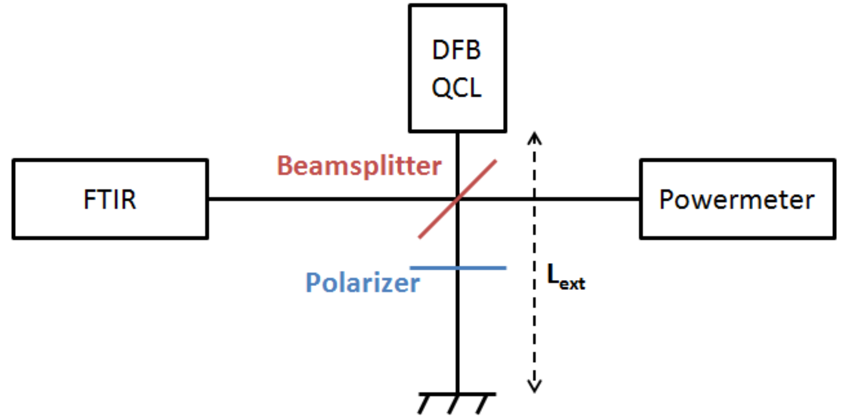


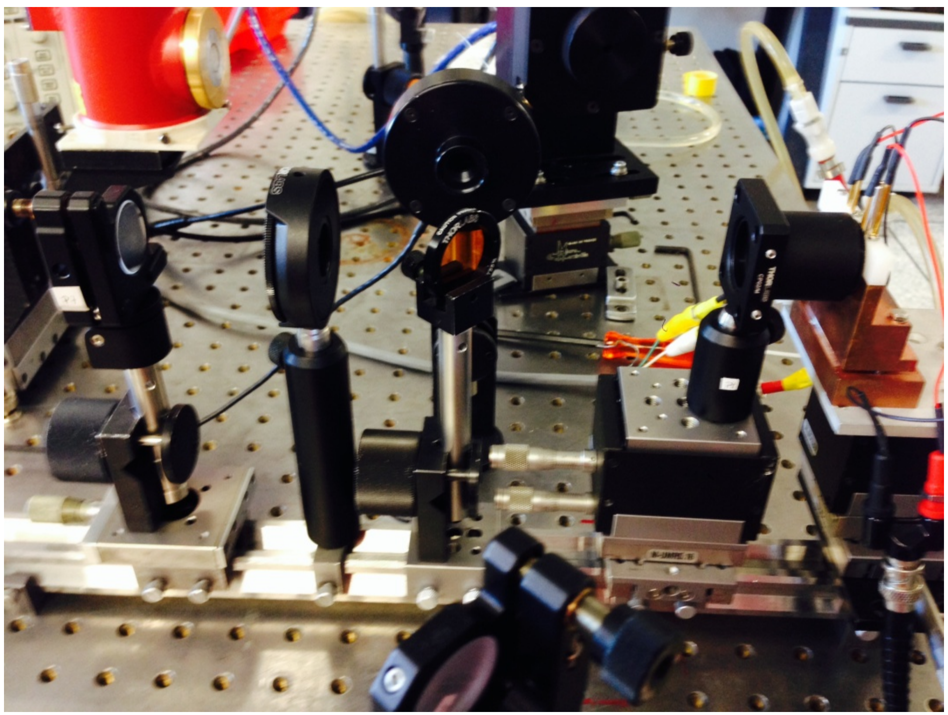
QCLs are much more stable than interband lasers!

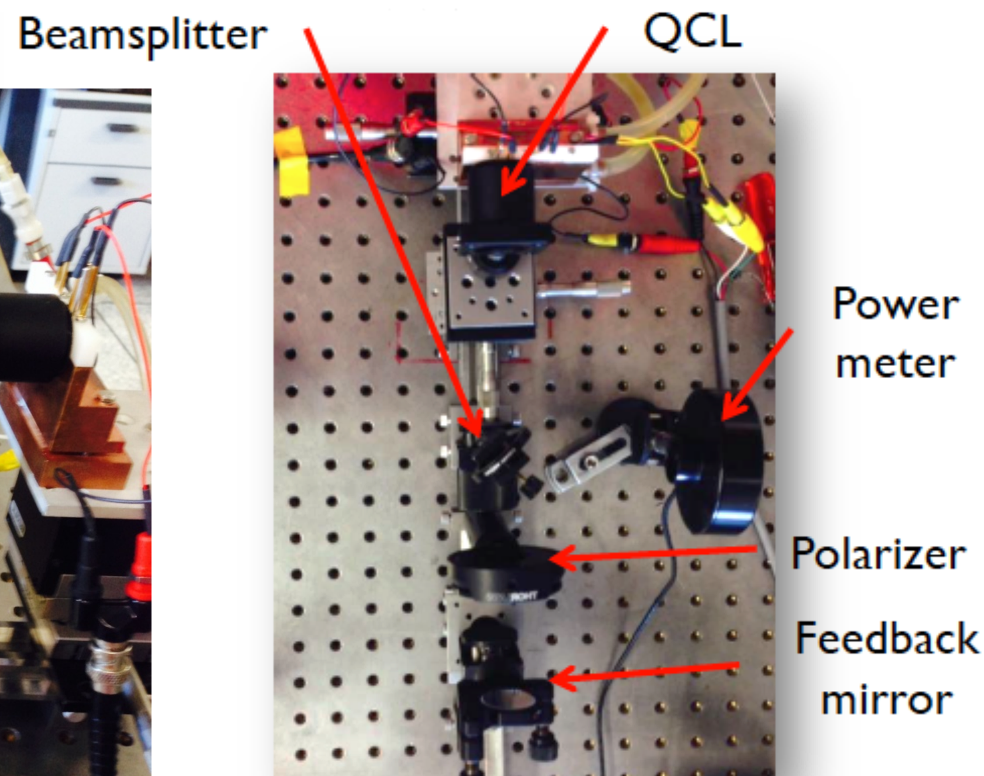
Experimental Set-up

- Feedback parameters:
  - External cavity length L_{ext}
  - Feedback rate f_{ext}

$$f_{ext} = \frac{P_{injected}}{P_{emitted}}$$

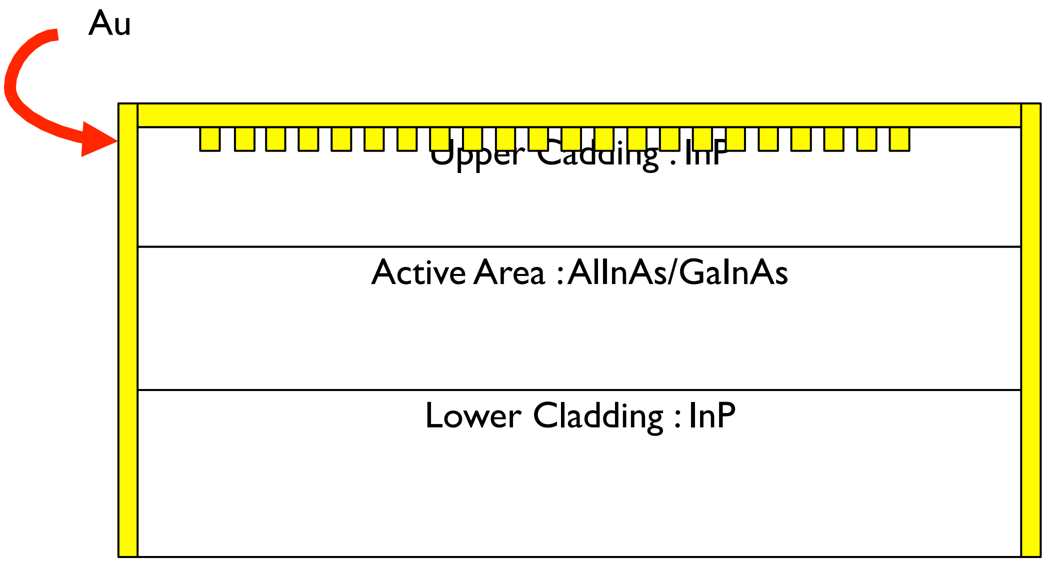


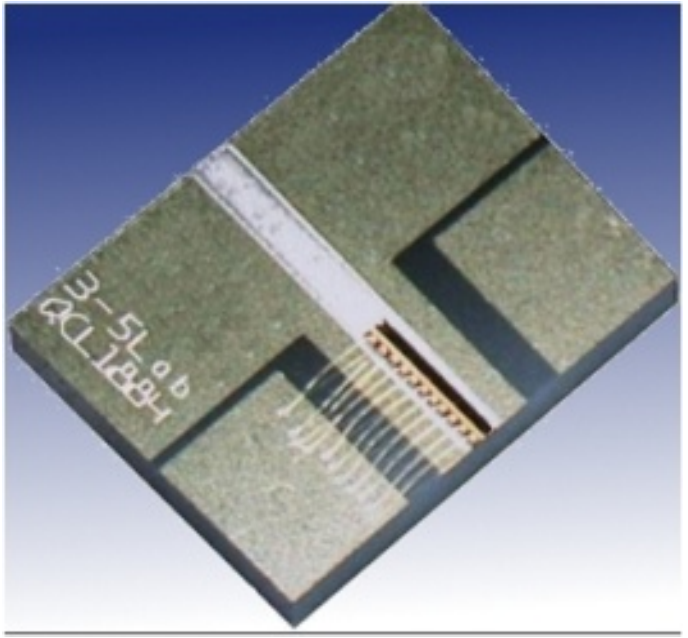




Device characteristics

- InAs/GaInAs/InP DFB laser@ 5.6 µm QCL
- Dimensions : 2 mm x 9 µm (R_{max}=99%, N_{pd}=30)
- Top metal grating for single-mode emission κ = 4 cm^{-1}
- I_{th}=433 mA ; η=0.23 mW/mA@283K



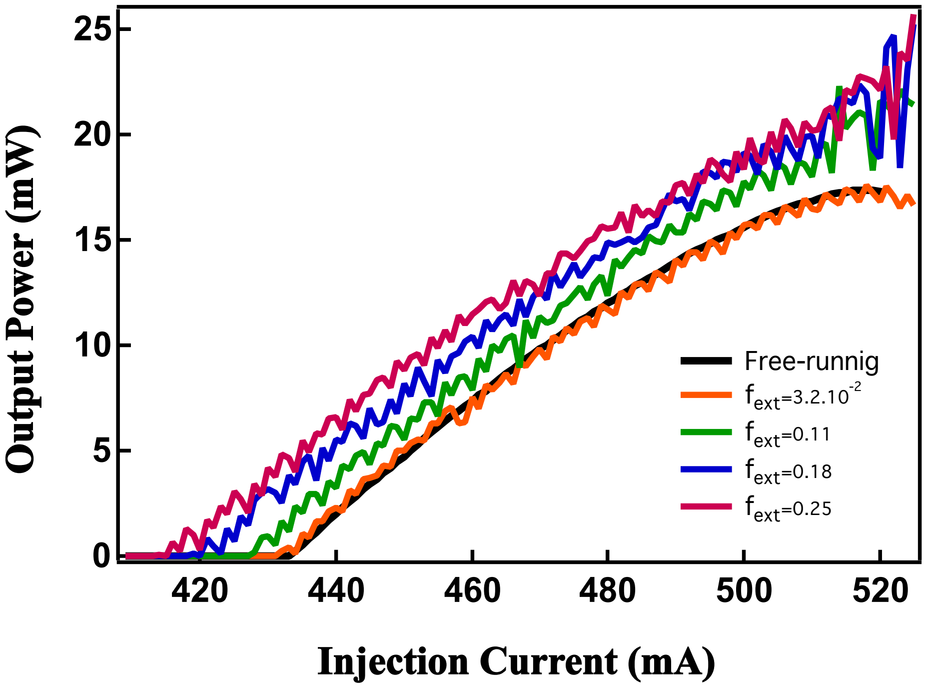


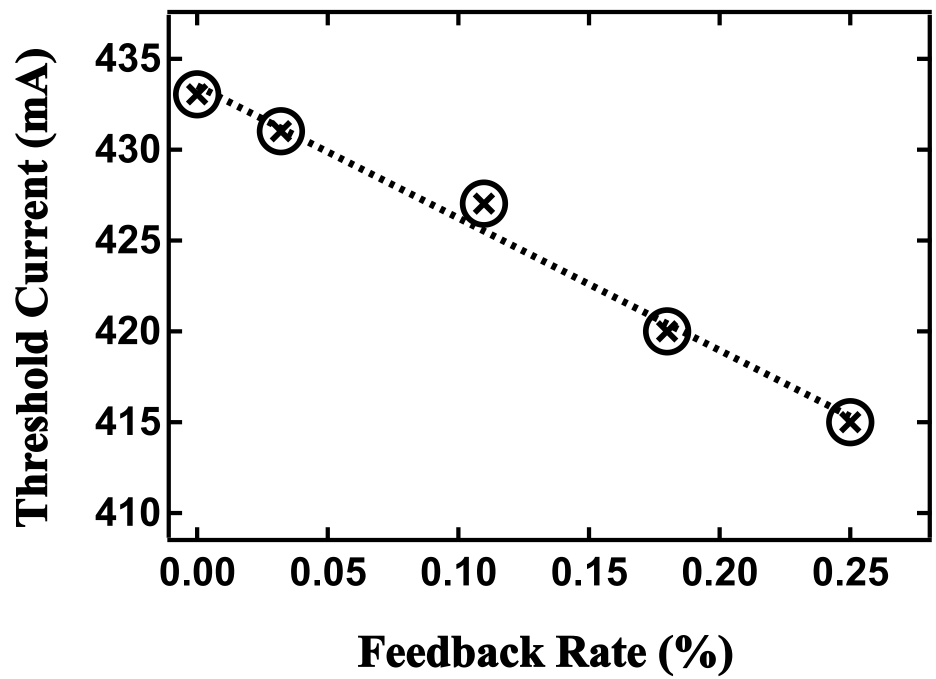
Courtesy of Dr. M. Carras (III-V Lab)

*Refs: A. Evans et al., Appl. Phys. Lett. **84**, 314 (2004)*
*M. Carras et al., Appl. Phys. Lett. **96**, 161105 (2010)*

Optical feedback on LCC

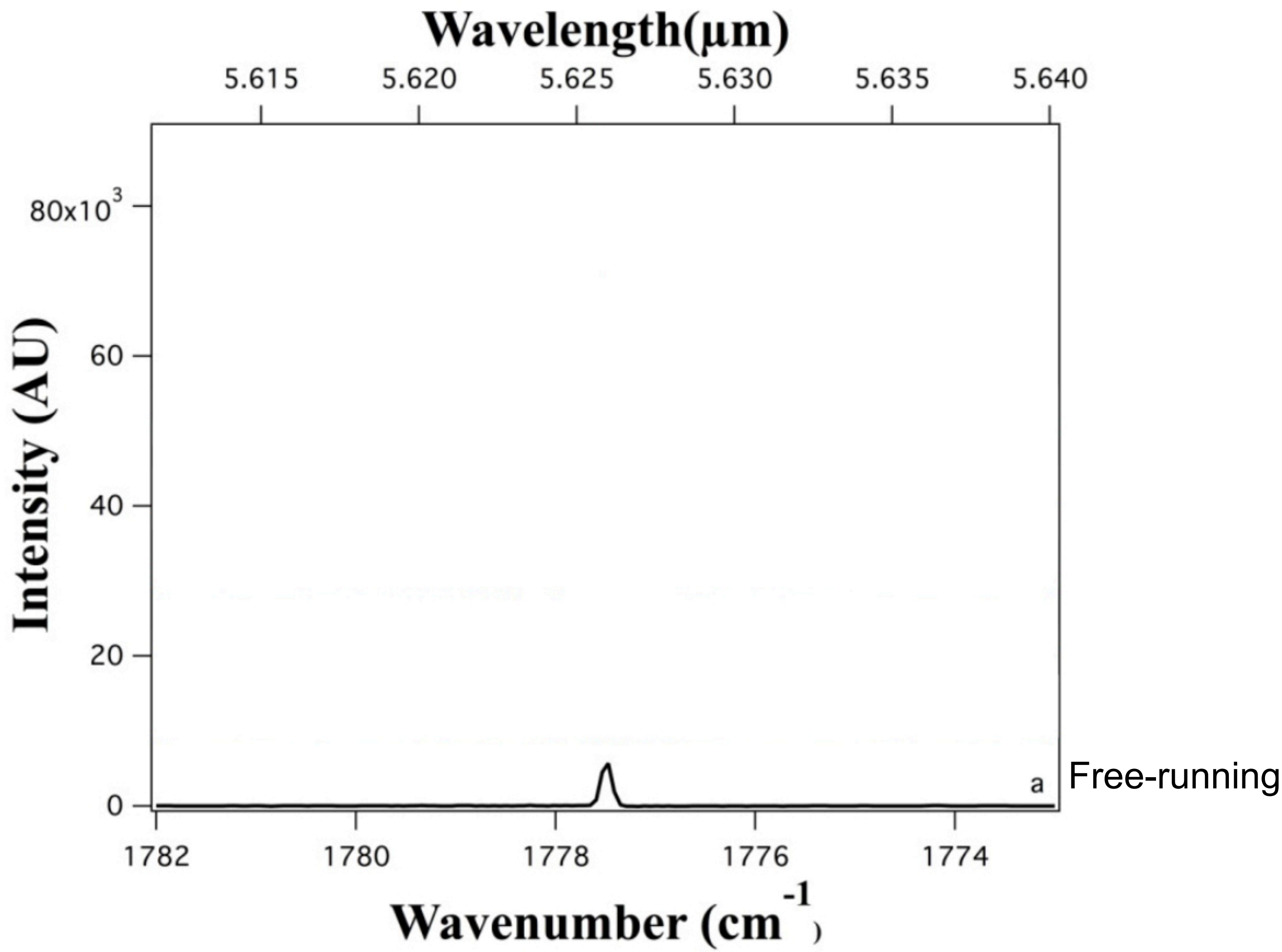
- Reduction of the laser threshold (up to 4% for the case under study)
- Larger optical output power under proper controlled feedback
- Increase of the injection current → modification of the refractive index → undulations due to interferences between ECMs with longitudinal modes of the laser cavity



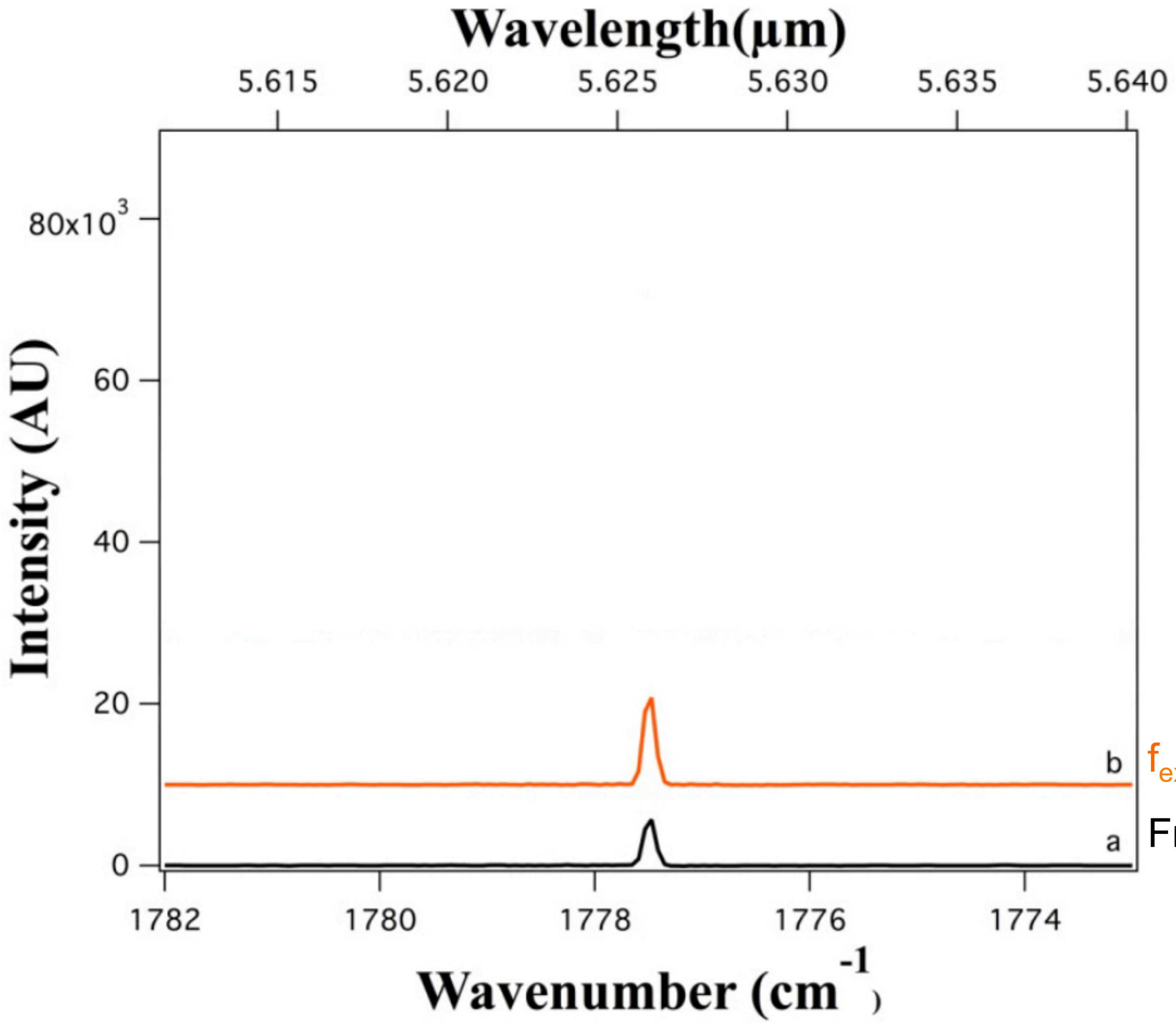


Ref : R. Lang and K. Kobayashi. IEEE J. Quantum Electron. ***16****, 347 (1980)*

FTIR observations (1)



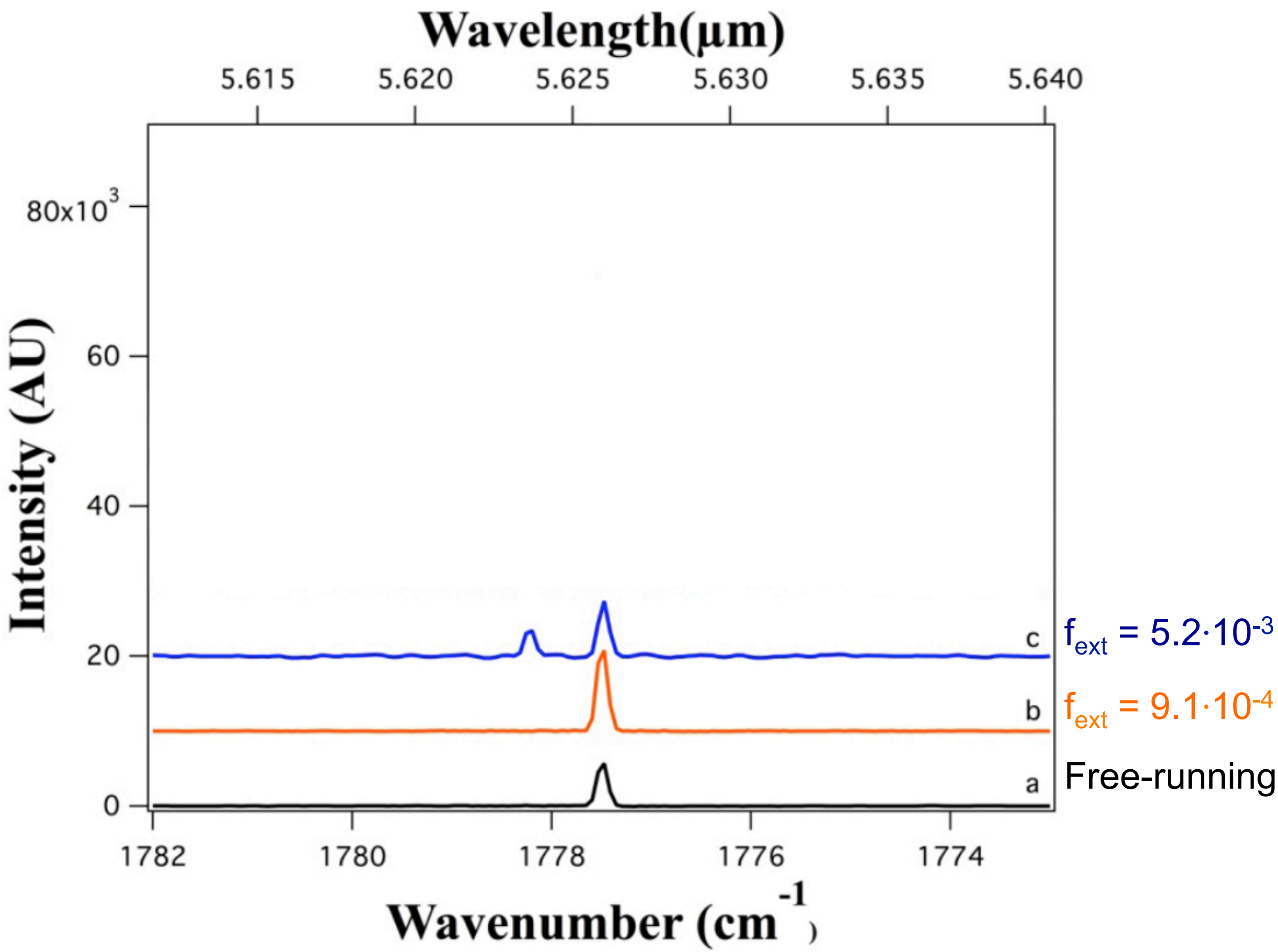
FTIR observations (2)



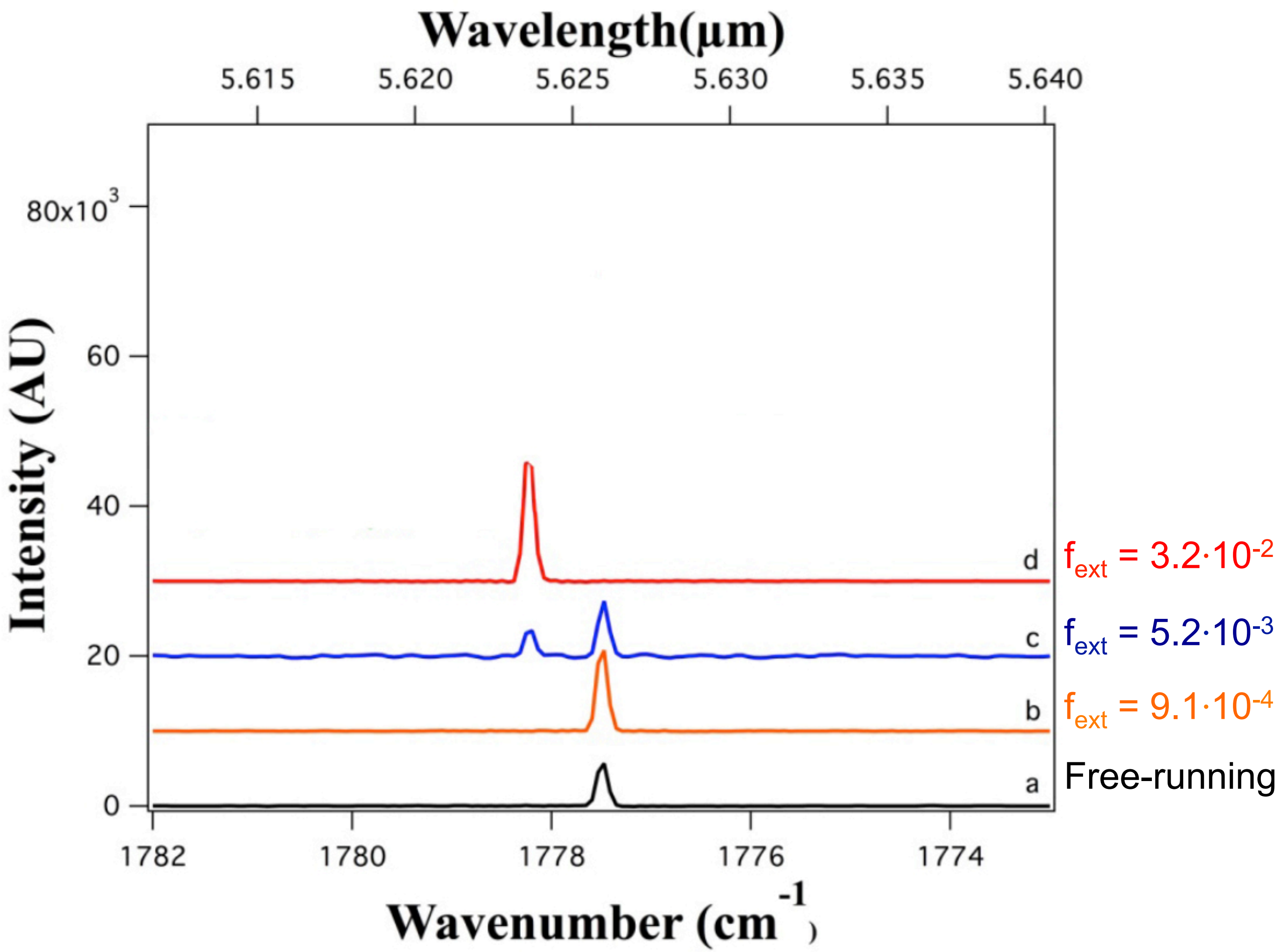
$f_{ext} = 9.1 \cdot 10^{-4}$

Free-running

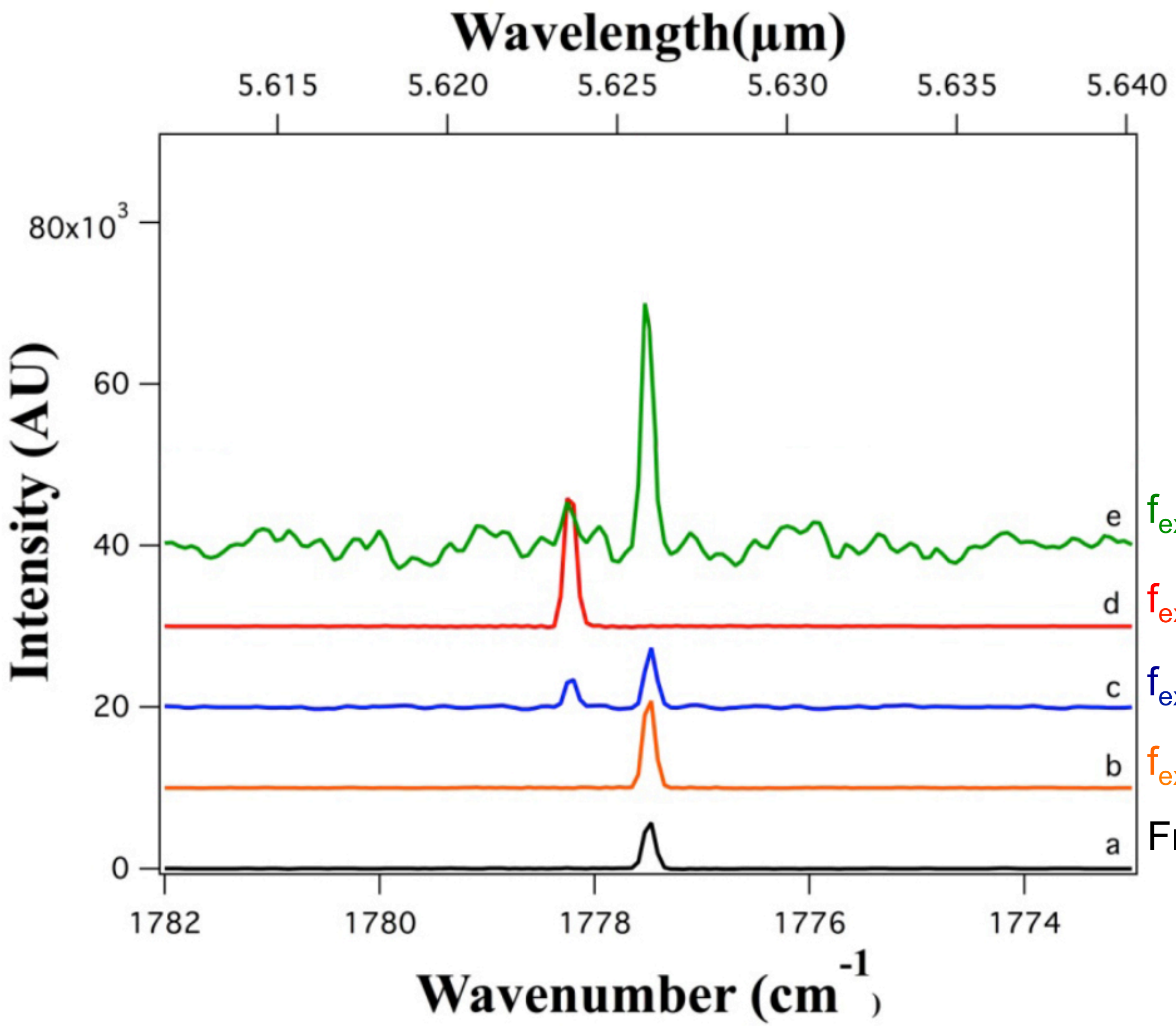
FTIR observations (3)



FTIR observations (4)



FTIR observations (5)



$f_{ext} = 0.13$

$f_{ext} = 3.2 \cdot 10^{-2}$

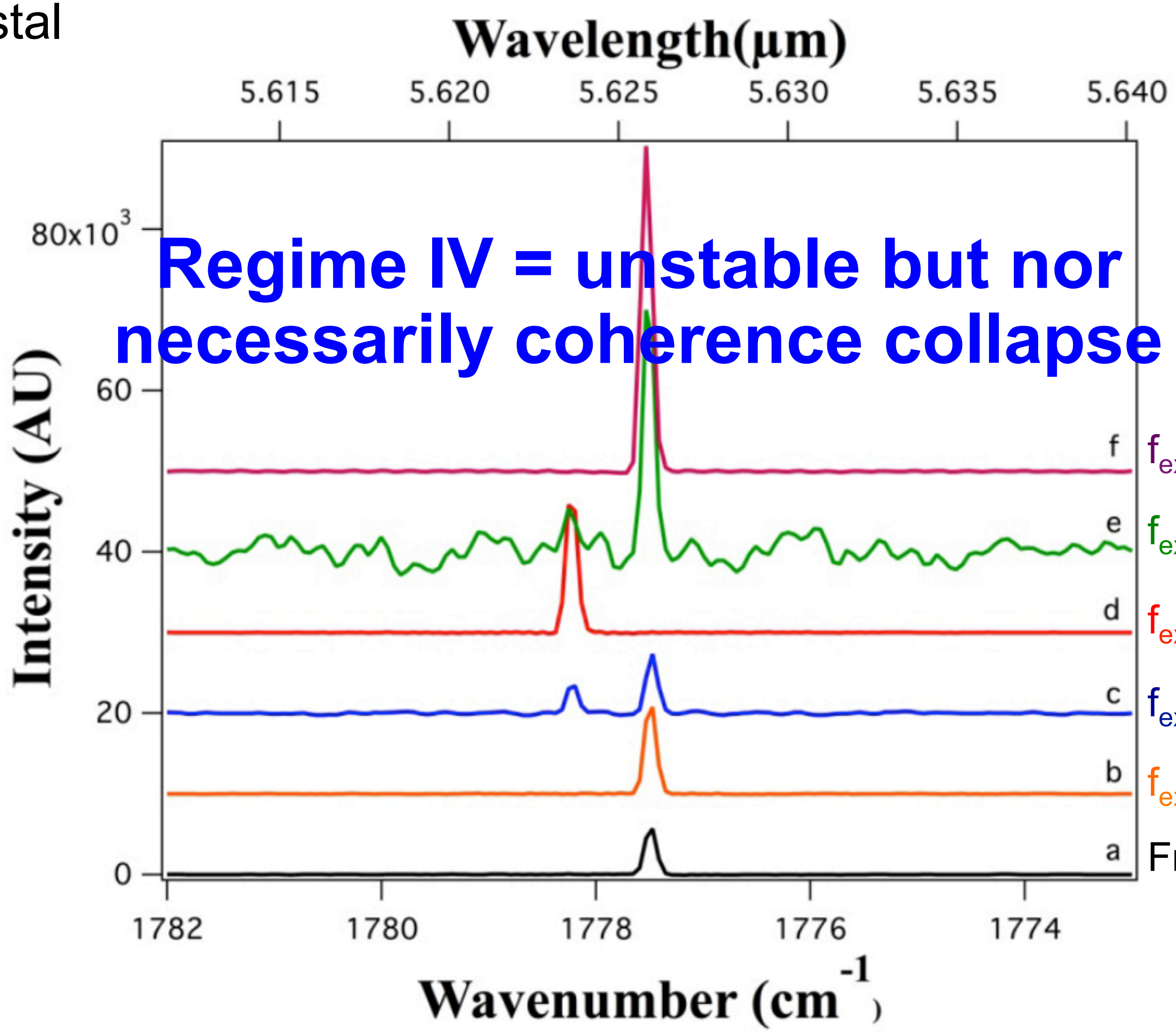
$f_{ext} = 5.2 \cdot 10^{-3}$

$f_{ext} = 9.1 \cdot 10^{-4}$

Free-running

FTIR observations (6)

- Regime IV is unstable and does exhibit a strong increase of the spectrum pedestal



$f_{ext} = 0.25$

$f_{ext} = 0.13$

$f_{ext} = 3.2 \cdot 10^{-2}$

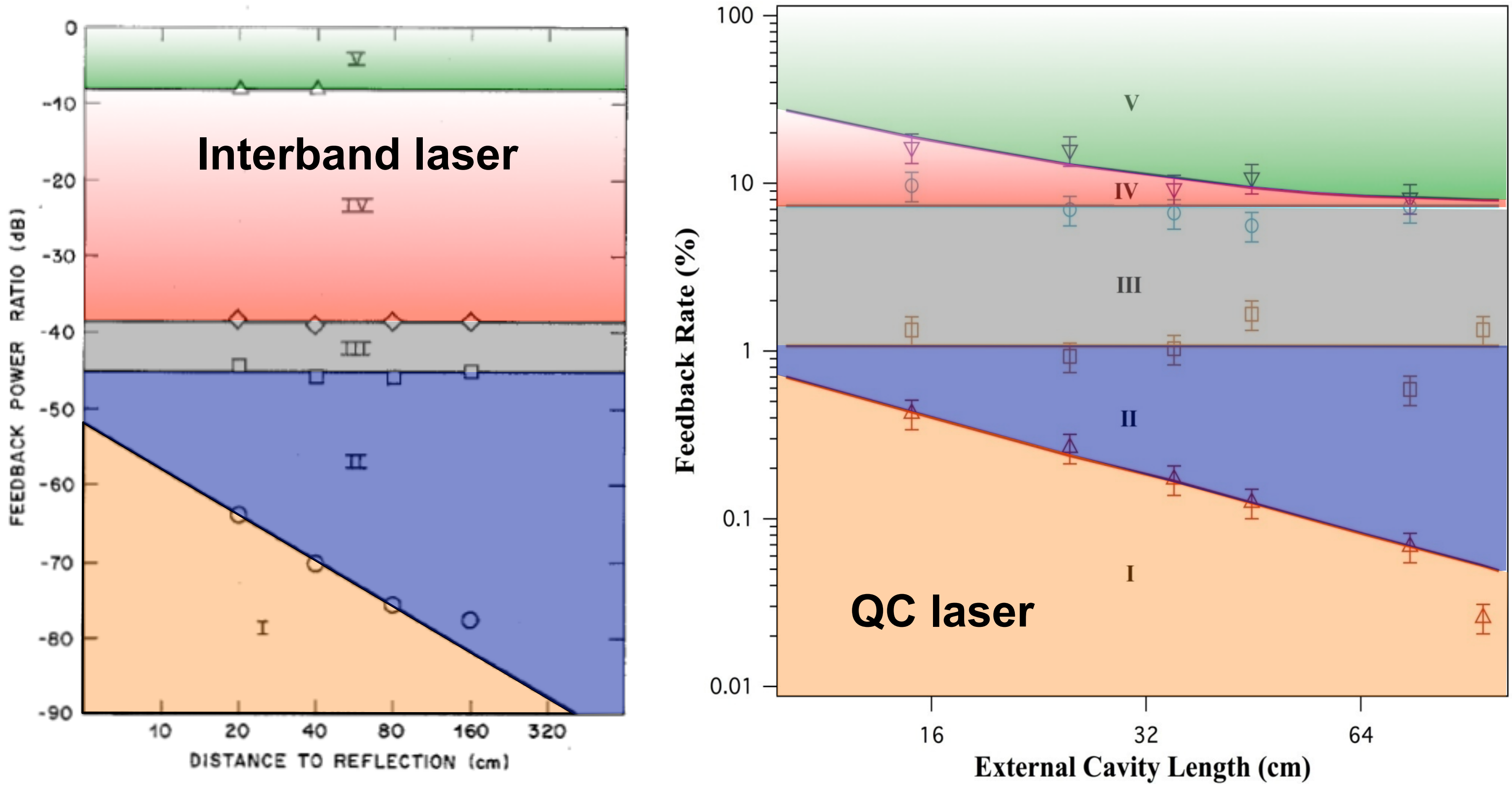
$f_{ext} = 5.2 \cdot 10^{-3}$

$f_{ext} = 9.1 \cdot 10^{-4}$

Free-running

The first cartography

- Transitions between regimes occur at higher feedback ratios in QCLs
- Range of feedback rates for regime IV is much narrower than in interband lasers



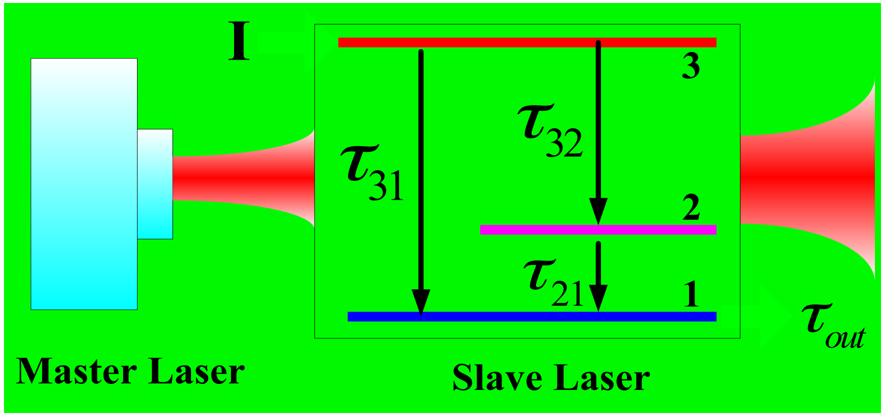
*Refs: R. W. Tkach and A. R. Chraplyvy. Journal of Lightwave Technology **4**, 1655 (1986)*
L. Jumpertz et al., paper accepted in Applied Physics Letters (2014)

Injection-locking rate equations

- Injected field is incorporated into the electric field equation

$$\frac{dS}{dt} = \left(N_{pd} G_0 \Delta N - 1/\tau_P\right) S + \beta N_{pd} \frac{N_3}{\tau_{sp}} + 2k_c \sqrt{S_{inj} S} \cos\phi$$

$$\frac{d\phi}{dt} = \frac{\alpha_H}{2}\left(N_{pd} G_0 \Delta N - 1/\tau_P\right) - \Delta\omega_{inj} - k_c \sqrt{\frac{S_{inj}}{S}} \sin\phi$$



Injection ratio:

$R_{inj} = S_{inj} / S_{FE}$

Detuning frequency:

$\Delta\omega_{inj} = \omega_{master} - \omega_{slave}$

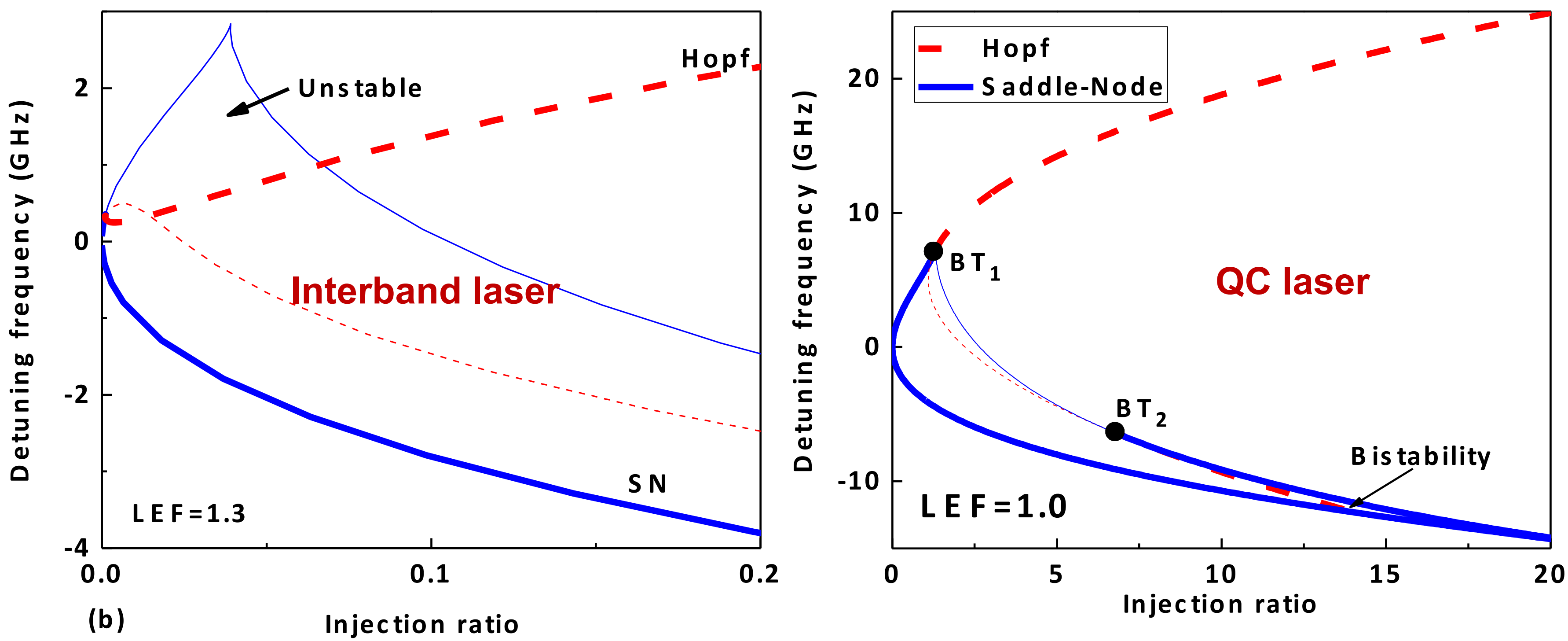
Phase difference:

$\Delta\phi = \phi_{slave} - \phi_{master}$

Steady state, numerical integration, continuation methods

Stable-locked regime

- Locking range is larger for QCLs w/ a zero detuning case always stable!



- Due to the ultrafast carrier lifetime, both bistable and unstable regimes exhibit in the injection-locking diagram

*Refs: C. Wang, F. Grillot, J. Even, Optics Letters, **38**, 1975, 2013*
*C. Wang, F. Grillot, J. Even, Journal of Applied Physics, **113**, 063104, 2013*

Small-signal analysis of the rate equation

$$I(t) = I + i_1 \exp(j\omega t) \qquad N_x(t) = N + n_x \exp(j\omega t)$$

$$S(t) = S + s_1 \exp(j\omega t) \qquad \phi(t) = \phi + \varphi_1 \exp(j\omega t)$$

$$\begin{bmatrix} \gamma_{11} + j\omega & -\gamma_{12} & 0 & -\gamma_{14} & 0 \\ -\gamma_{21} & \gamma_{22} + j\omega & 0 & -\gamma_{24} & 0 \\ -\gamma_{31} & -\gamma_{32} & \gamma_{33} + j\omega & 0 & 0 \\ -\gamma_{41} & -\gamma_{42} & 0 & \gamma_{44} + j\omega & -\gamma_{45} \\ -\gamma_{51} & -\gamma_{52} & 0 & -\gamma_{54} & \gamma_{55} + j\omega \end{bmatrix} \begin{bmatrix} n_3 \\ n_2 \\ n_1 \\ s_1 \\ \varphi_1 \end{bmatrix} = \frac{\eta i_1}{q} \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

$$H(\omega) = \frac{s_1(j\omega)}{i_1(j\omega)} = \frac{p_1 p_2 p_3 p_4 p_5}{z_1 z_2 z_3} \frac{\prod_{k=1}^{3}(j\omega - z_k)}{\prod_{k=1}^{5}(j\omega - p_k)}$$

$$z_1 = k_c \sqrt{S_{inj} / S}(\cos \Delta\phi - \alpha_H \sin \Delta\phi)$$

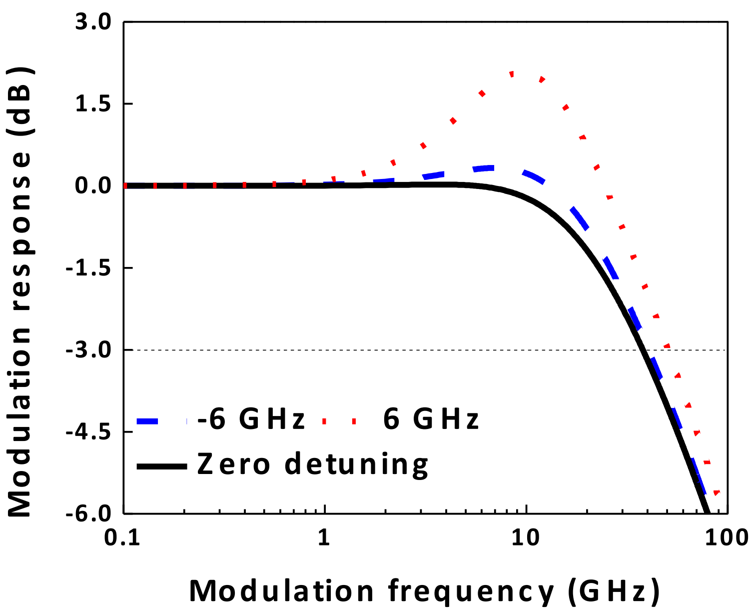
$$z_2 = 1/\tau_{32} - 1/\tau_{21}$$

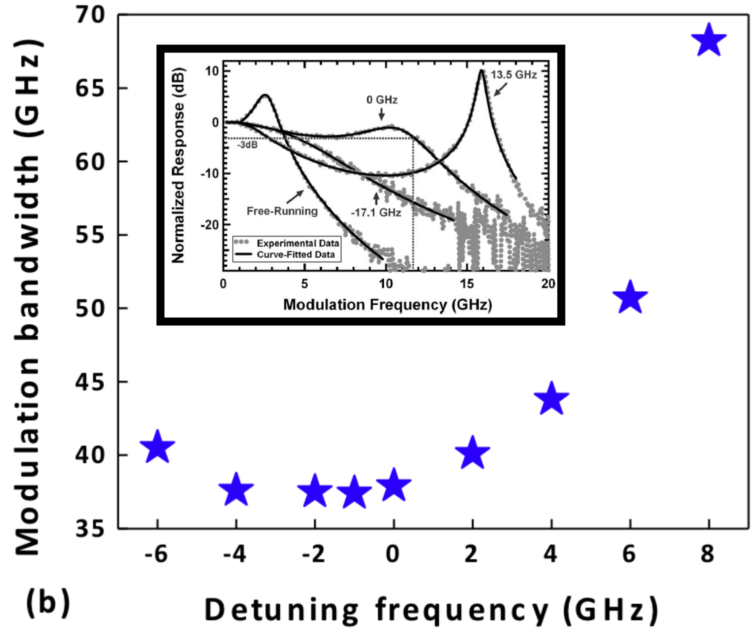
$$z_3 = -1/\tau_{out}$$

Refs: *C. Wang, F. Grillot, J. Even, Optics Letters, **38**, 1975, 2013*
*C. Wang, F. Grillot, J. Even, Journal of Applied Physics, **113**, 063104, 2013*

Modulation response

- Large injection strength & frequency detuning enhance the 3-dB bandwidth





(b)

- No dip exhibits in the modulation response
- Positive detuning leads to resonance behavior
- Optical injection-locked experiment is now needed for further investigations

→ but strong optical isolation of the master is required !

Main conclusions & perspectives

- Nonlinear dynamics of QCLs is at the early stages
- Self injected QCLs are much more stable (high feedback level for the first Hopf bifurcation)
- **Experimental study**
  - First spectral observation
  - First cartography of the feedback regimes
  - Regime IV is unstable with a smaller area
  - Broader areas for stable regimes
- **Future work**
  - Electrical spectra & time series to analyze regime IV (chaos)
  - Influence of the LEF
  - Laser linewidth
  - Comparison DFB and Fabry-Perot lasers
  - Optical injection-locking experiments

Thank you for your attention

Contact Information

grillot@telecom-paristech.fr