ETH zürich

Quantum Cascade laser for biophotonics

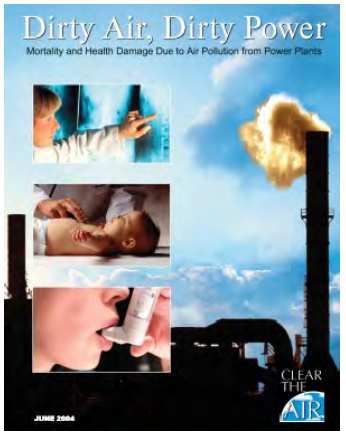
Jérôme Faist

Context and motivations

- Gas sensing

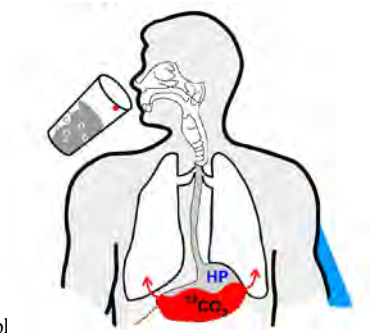
Control of air quality in urban areas

Monitoring and reducing production of pollutant gases



Study and limit the effects on human health

- Liquid solid

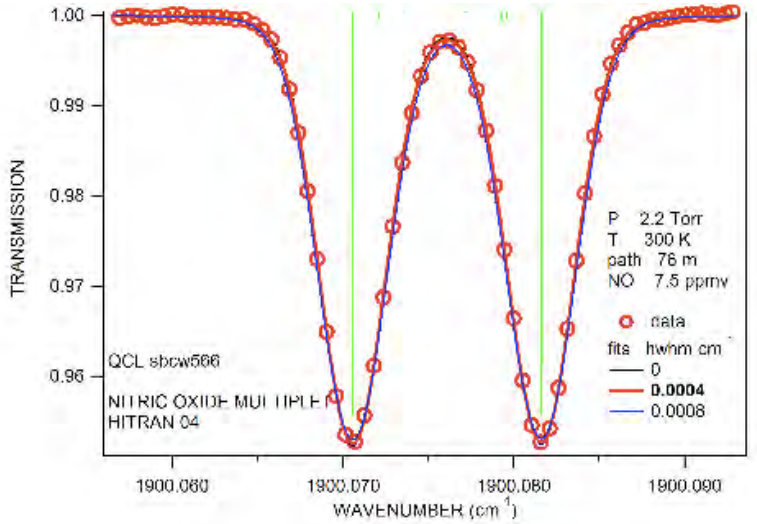


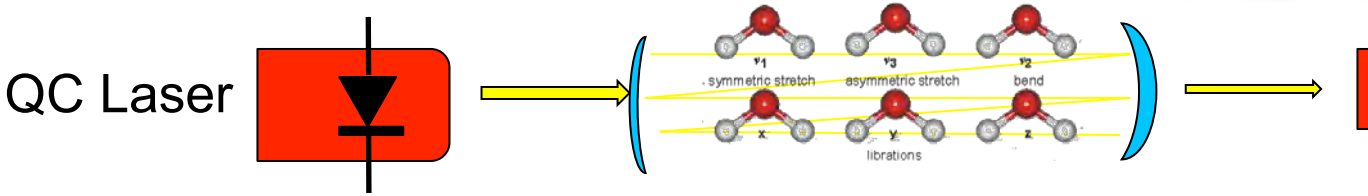
Health

Drug monitoring

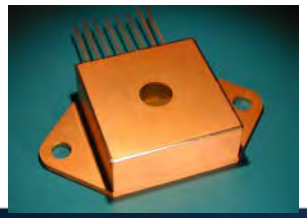
QCL application: optical chemical sensing

- Fundamental vibration modes of molecules are in the Mid-IR
  - Chemically and isotopically sensitive





Multipass cavity

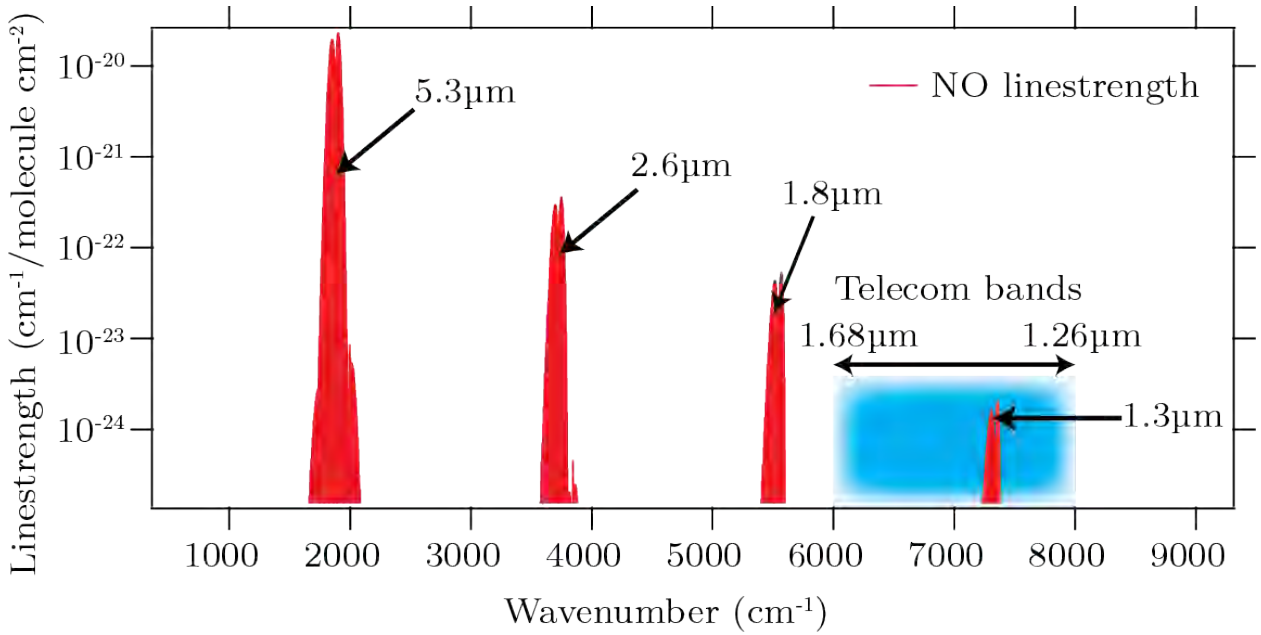


The mid-IR spectral range

- 2.5 µm < λ < 25 µm (4000 cm^{-1} – 400 cm^{-1})
- Access fundamental roto-vibrational states of molecules
- Atmospheric windows (3.5-4.8 µm / 8-12 µm)

Applications

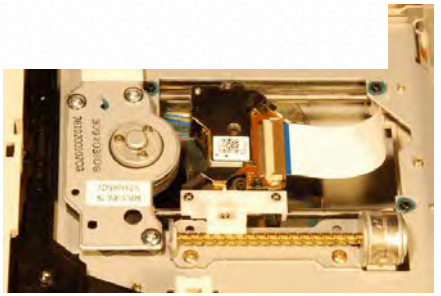
- Medicine
- Sensing
- Emission monitoring
- Process control
- Free-space communication
- Defense
- Homeland security



Photonics: an expensive solution?

Preconception #1: Optics means lenses, alignement, and therefore

Contains a single mode laser, lens Detector(s). Retail price: ~10CHF



Contains a single laser, high NA lens, tracking mechanism, detector, etc..
Retail price: ~50CHF

Mid-Infrared: immature?

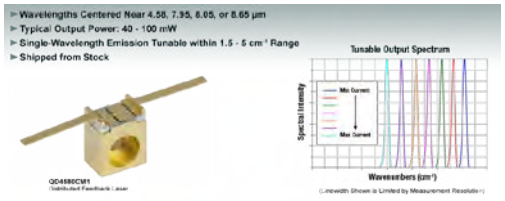
Preconception #2: Mid-Infrared is not mature, no lenses, no fibers, bad detectors, expensive lasers

Detector:

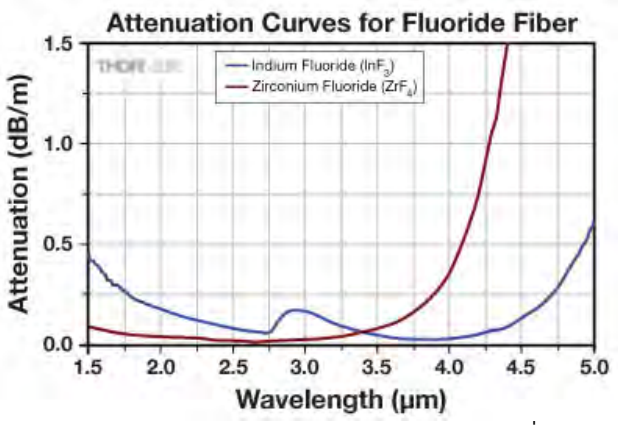
20pW NEP
TEC cooled

Aspheres with NA up to 0.8

Quantum cascade lasers

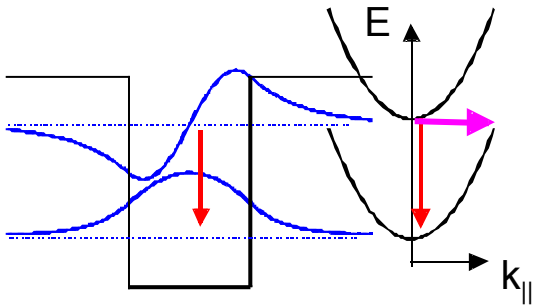


Fibers

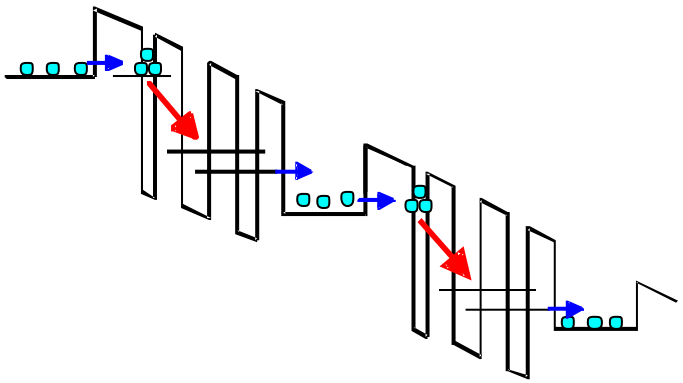


Quantum cascade laser: fundamental concepts

- Intersubband transitions
  - Transition energy depends only on layer thickness
  - The population inversion must be engineered



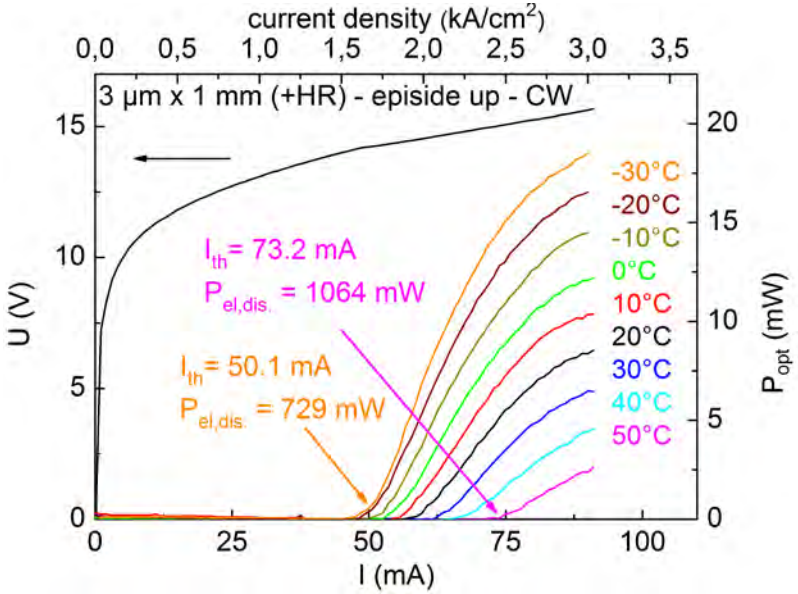
- Cascade active region period

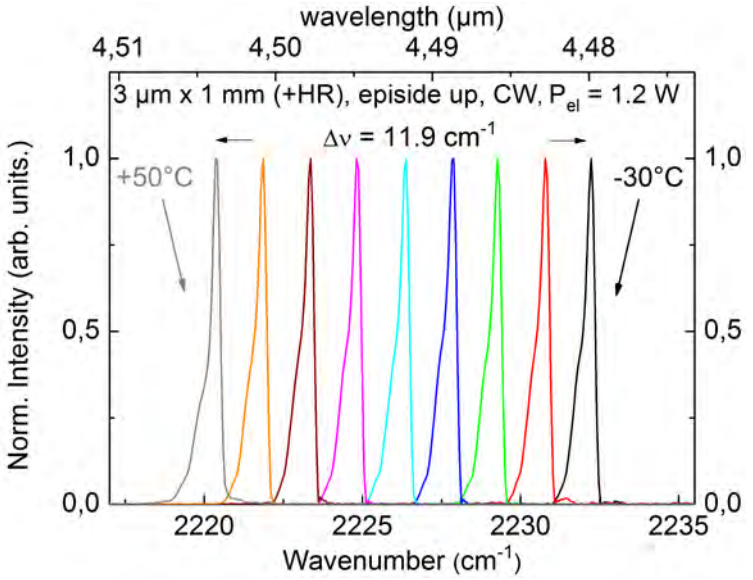


J. Faist, F. Capasso, D. L. Sivco, C. Sirtori, A.L. Hutchinson, A. Y. Cho, Science **264**, 553 (1994)

Single frequency, low dissipation DFBs

Narrow ridges, short device <1 W dissipation





- Narrow buried heterostructure, for portable sensors

B. Hinkov et al., Electron Lett. (2012)

Biomedical application in the THz

APPLIED PHYSICS LETTERS **88**, 153903 (2006)

Biomedical terahertz imaging with a quantum cascade laser

Seongsin M. Kim,[a)] Fariba Hatami, and James S. Harris
Solid State Photonics Laboratory, Stanford University, Stanford, California 94305

Allison W. Kurian and James Ford
School of Medicine, Division of Oncology, Stanford University, Stanford, California 94305

Douglas King
Hansen Experimental Physics Laboratory, Stanford University, Stanford, California 94305

Giacomo Scalari, Marcella Giovannini, Nicolas Hoyler, and Jerome Faist
Institute of Physics, University of Neuchâtel, Neuchâtel CH-2000, Switzerland

Geoff Harris
University of California, Davis Medical Center, Sacramento, California 95817

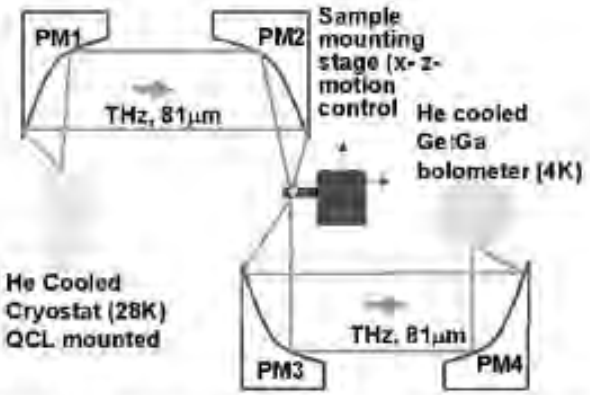
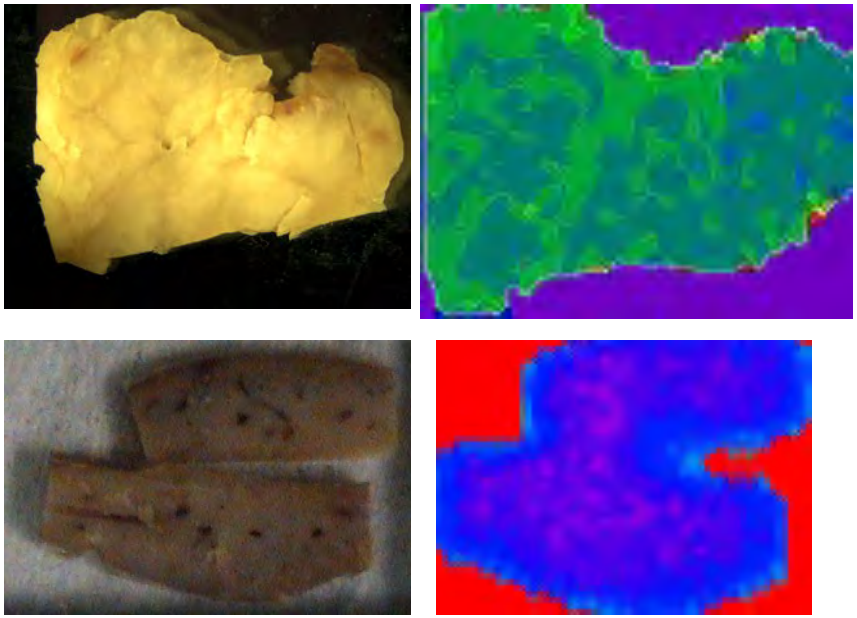


FIG. 1. Schematic diagram of terahertz imaging system using a quantum cascade laser at 3.7 THz.



Outline

- Mid-Infrared spectroscopy:
  - The key application for quantum cascade lasers
- Broadly tunable QCLs
- Comb operation in broadband QCL devices
- Dual comb spectroscopy
- IRSENS project: detecting Cocaine in saliva
- Conclusion

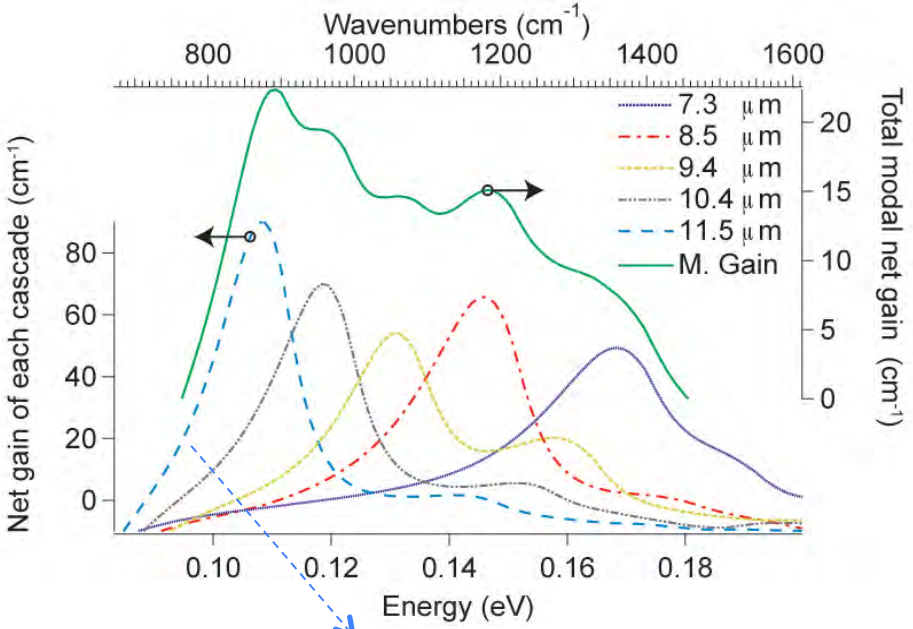
Outline

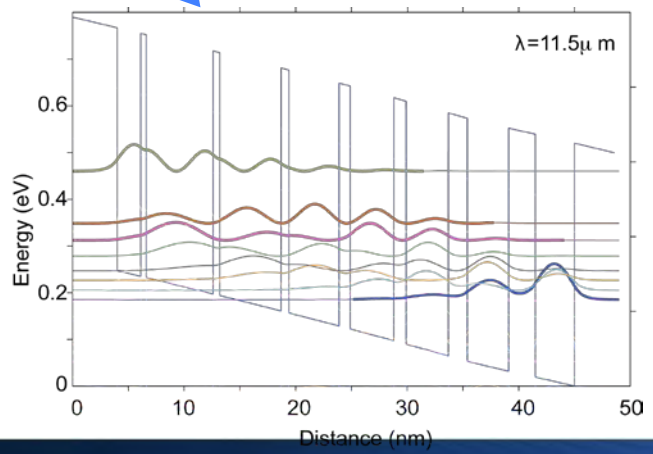
- Mid-Infrared spectroscopy:
  - The key application for quantum cascade lasers
- Broadly tunable QCLs
- Comb operation in broadband QCL devices
- Dual comb spectroscopy
- IRSENS project: detecting Cocaine in saliva
- Conclusion

Broadly tunable devices

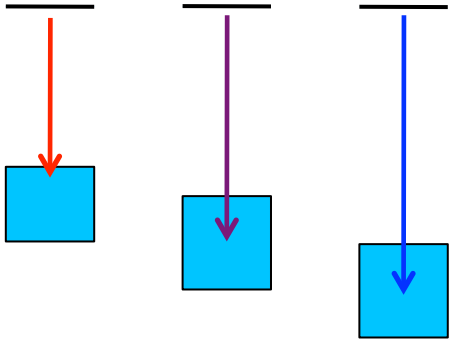
- Sensing many gases simultaneously
- Liquid and solids (broad absorption features)
  - Glucose
  - Explosives
  - Chemical weapons
- Ultimately, could replace the FTIR?
- Take advantage of the “designability” of quantum cascade lasers

Multiple colors

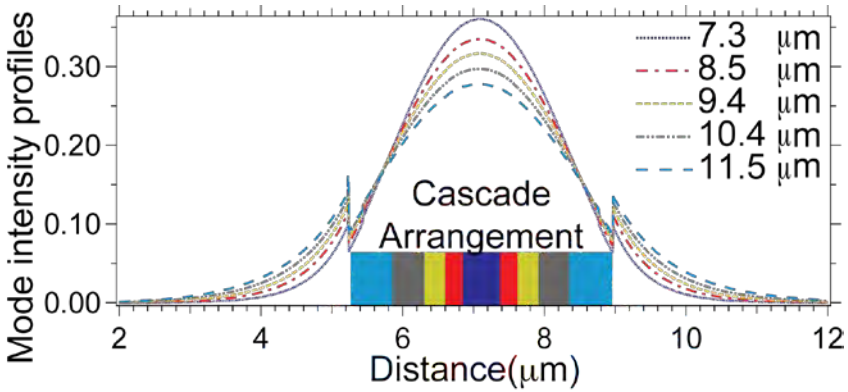




Design inherent broad stages

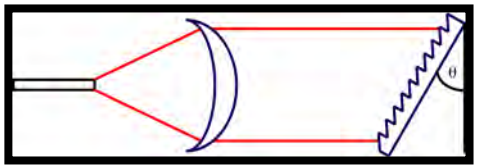


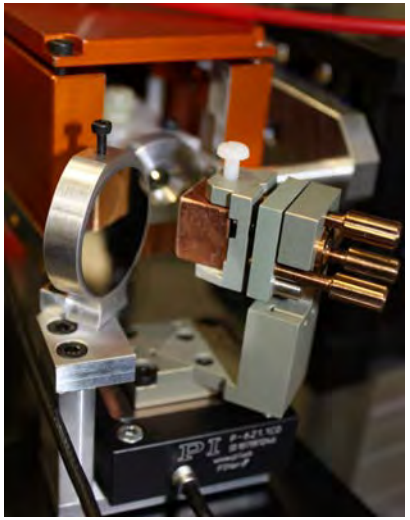
5 active regions



Pulsed operation: tuning curves

External cavity:
tuning with grating

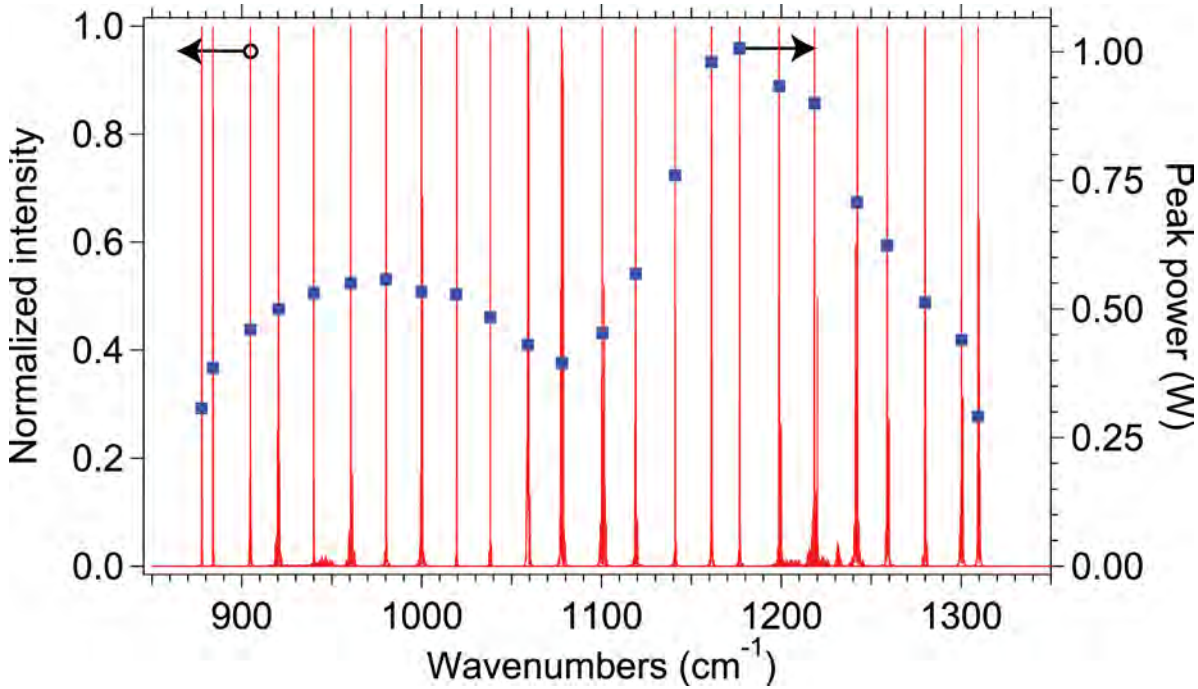




Pulsed operation:

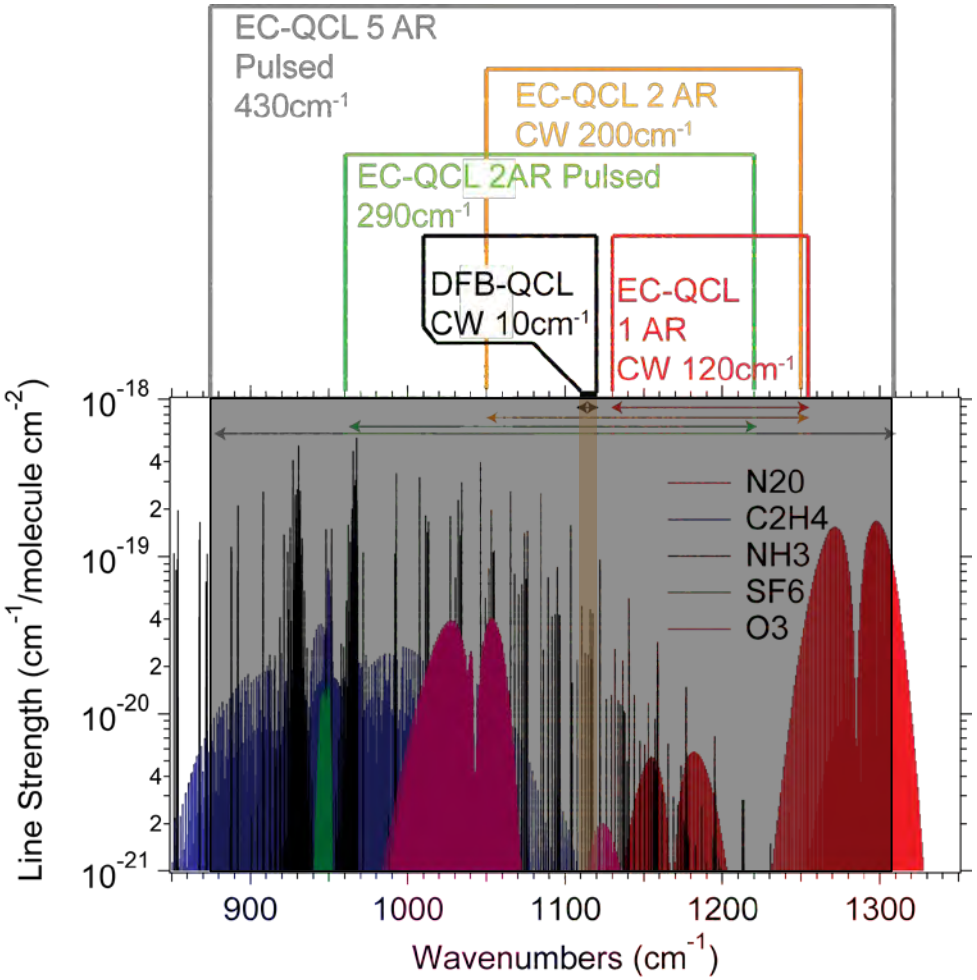
432 cm^{-1} tuning (7.5μm – 11.4μm)

1 W peak power



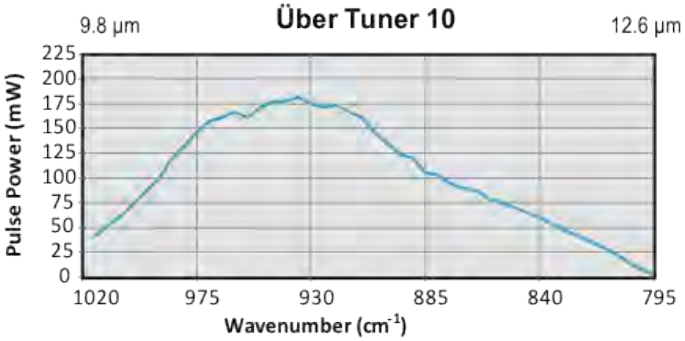
A.Hugi et al., Appl. Phys. Lett. **95, 061103** (2009)

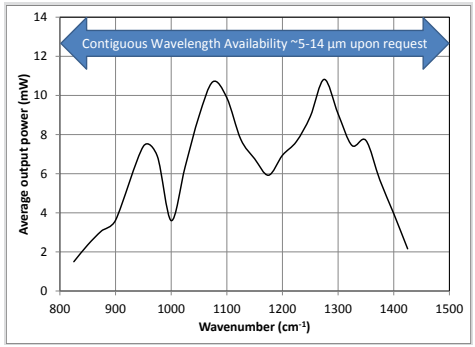
Tuning range



A.Hugi, R. Maulini, J. Faist, Semicond. Sci. Technol. **25 (2010) 083001**

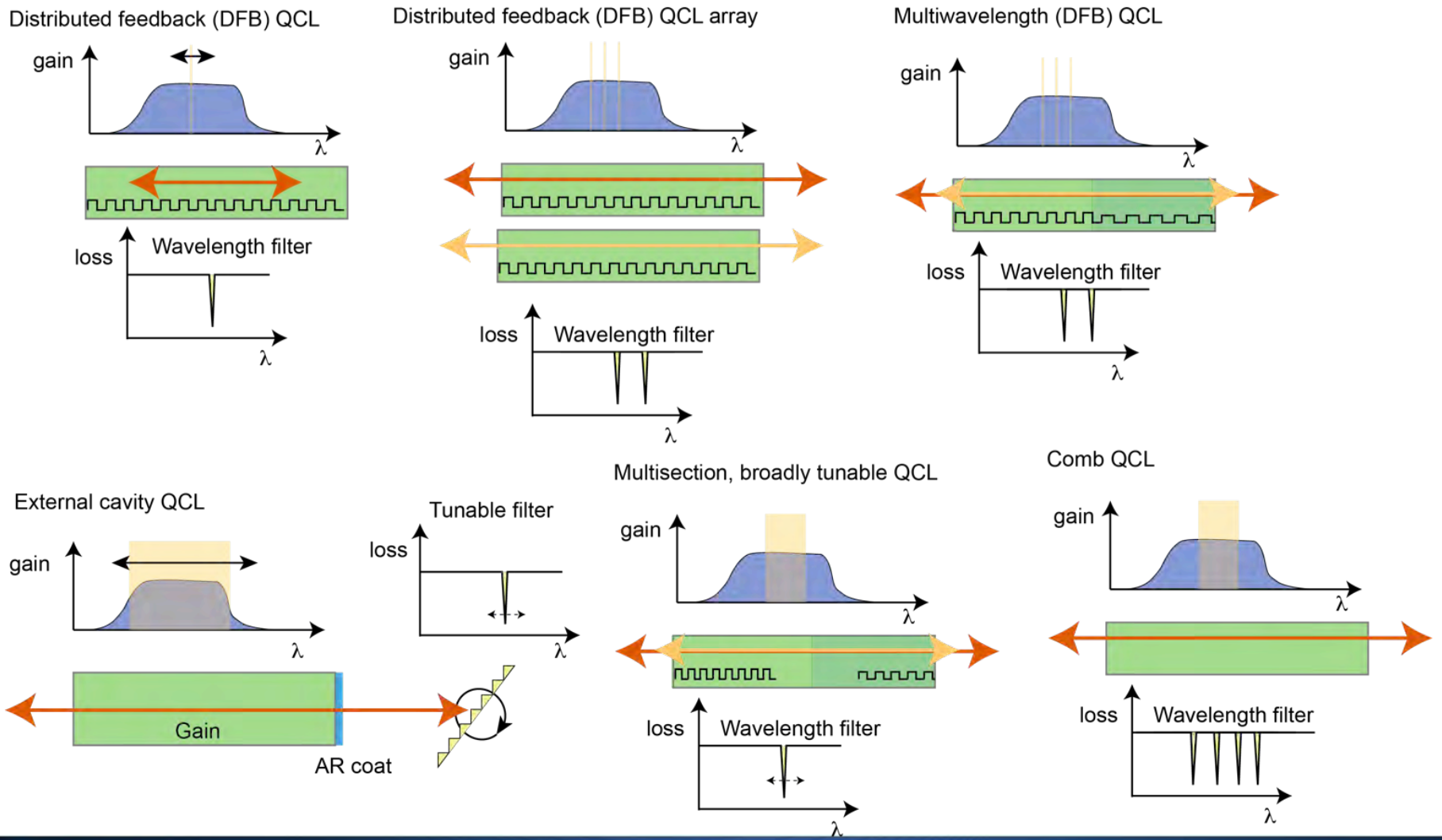
Commercial product (Daylight, Block..)





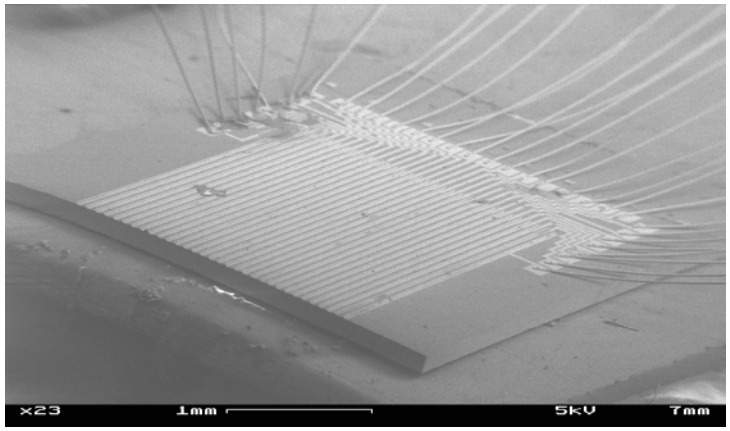
- Drawback: mechanical tuning necessary

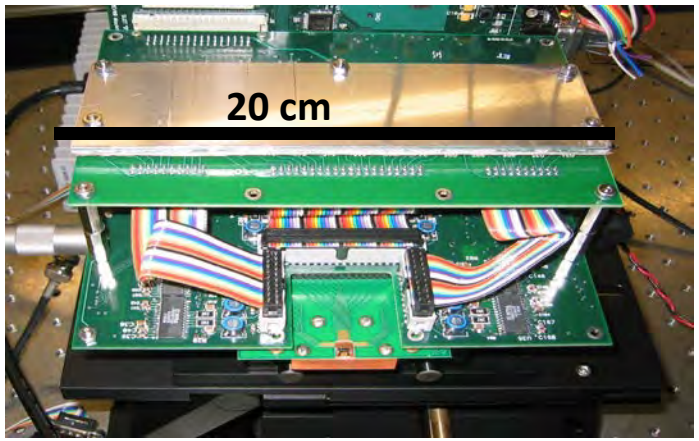
Spectrally agile QCLs



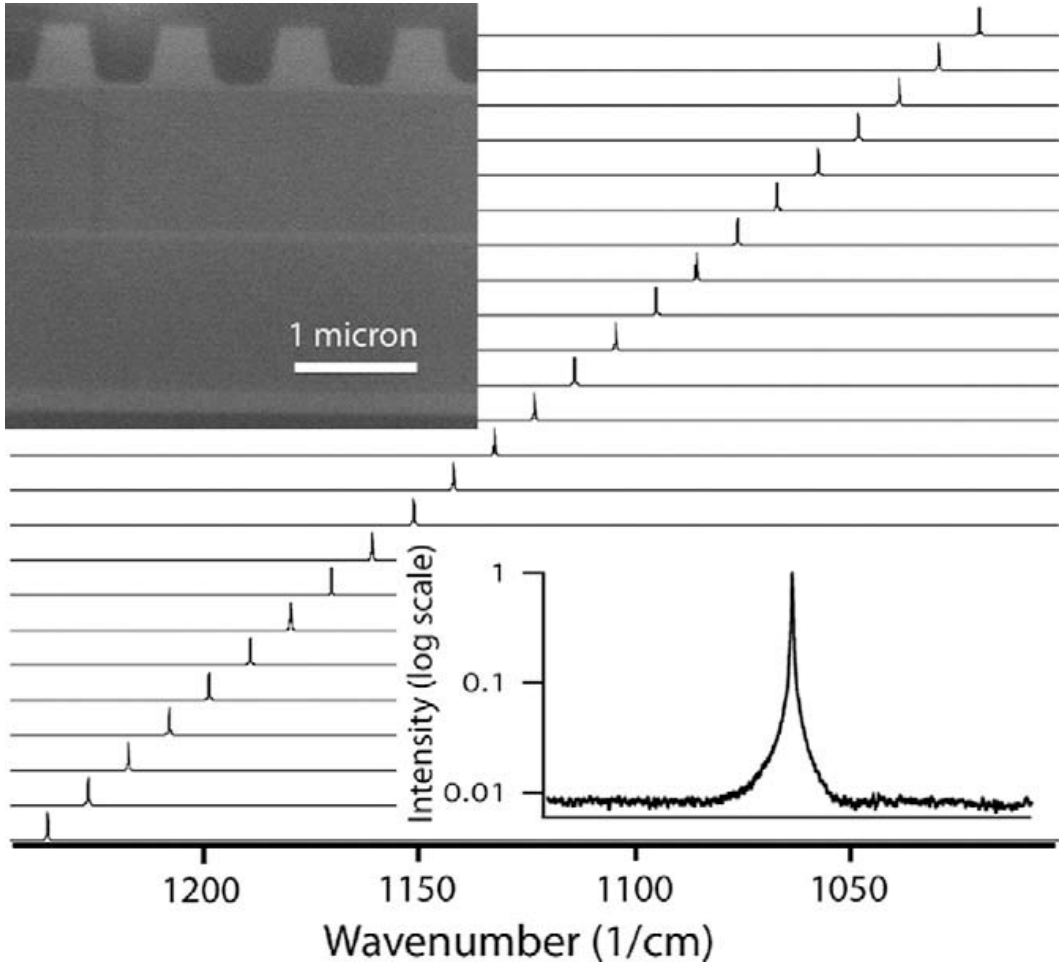
Multi-DFB on a wide gain active region

B.G. Lee et al., IEEE Photon. Technol. Lett. 21 (2009) 914.





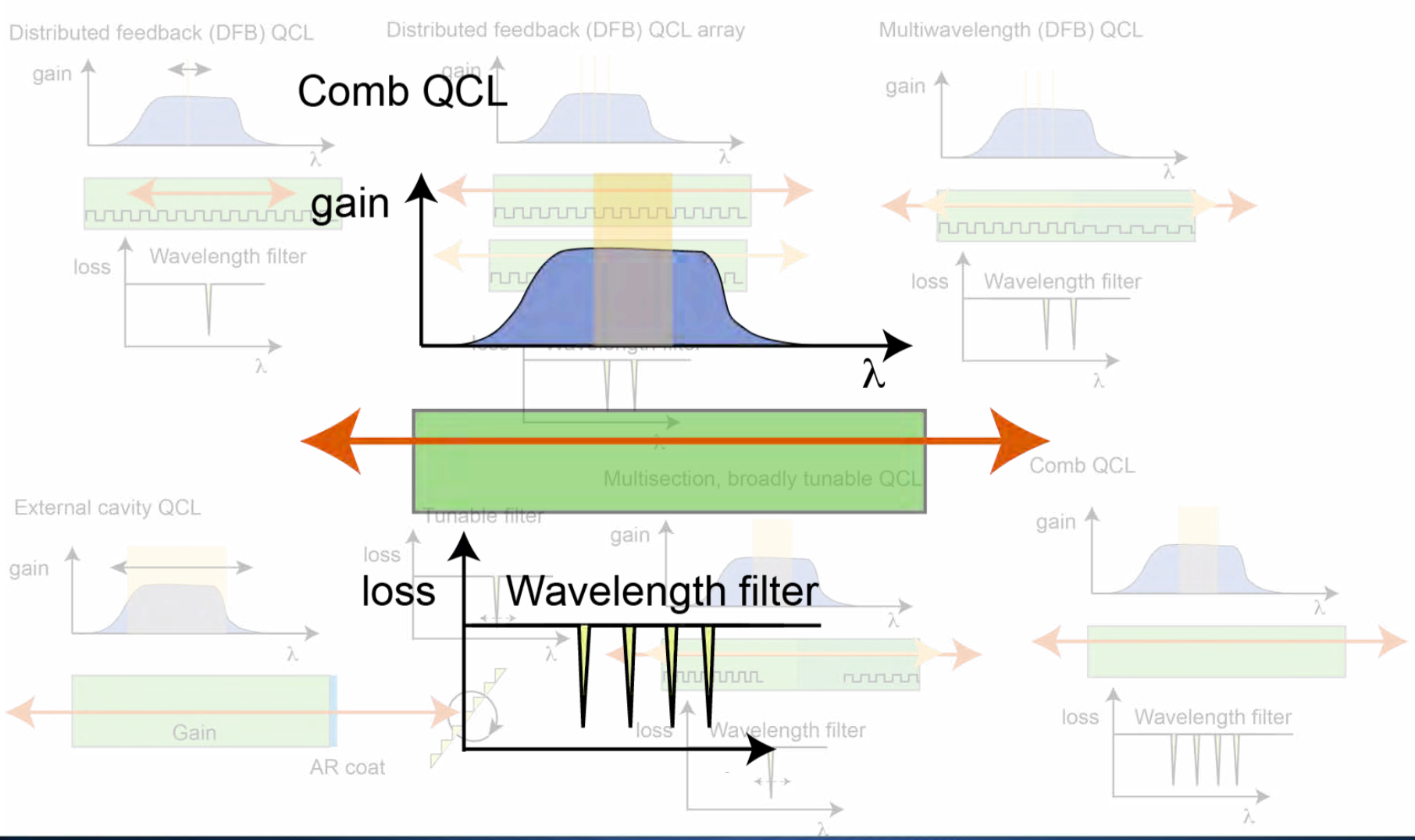
Emission spectrum of the array



Comparison with FTIR spectrometer

- Much higher S/N due to laser rather than thermal source: remote trace gas detection
- Higher spectral resolution due laser linewidth
- Compact

Spectrally agile QCLs

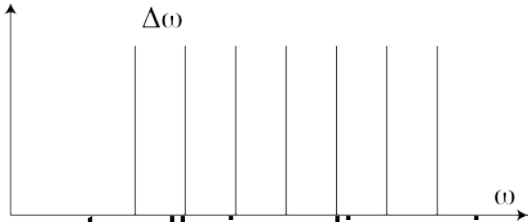


Outline

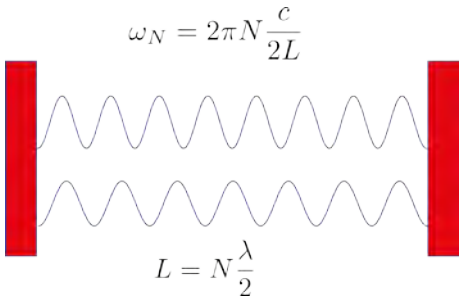
- Mid-Infrared spectroscopy:
  - The key application for quantum cascade lasers
- Broadly tunable QCLs
- Comb operation in broadband QCL devices
- Dual comb spectroscopy
- IRSENS project: detecting Cocaine in saliva
- Conclusion

Optical frequency comb

- Source with equidistant optical modes

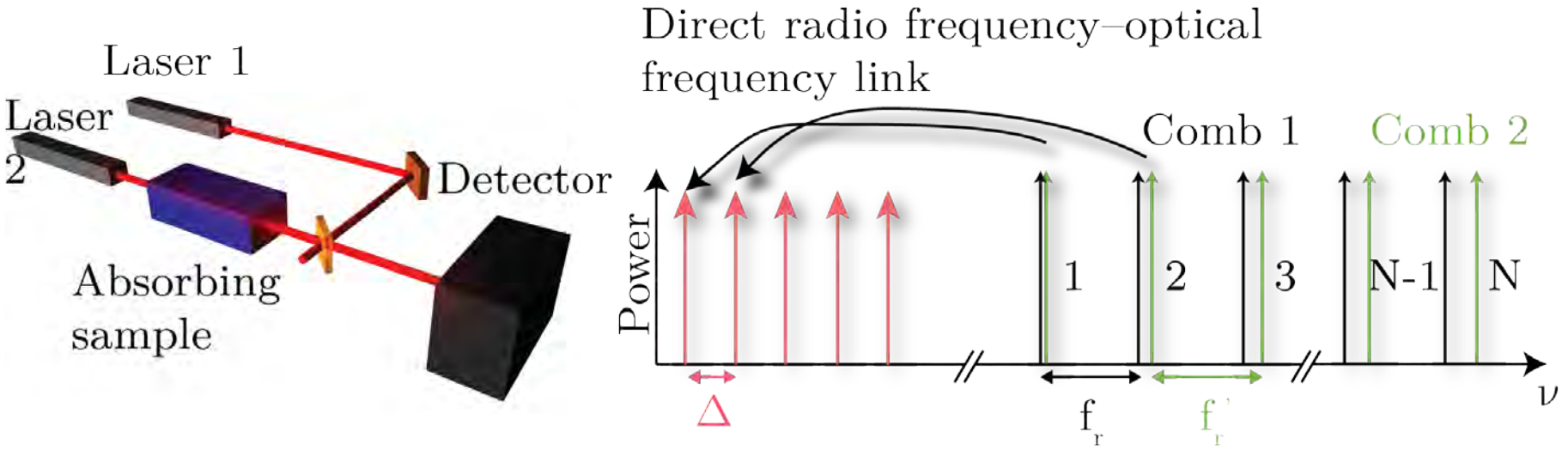


- Comes naturally in a dispersionless Fabry-Perot



- To fight dispersion, one needs a phase locking mechanism
  - Saturable absorber -> all equal phases, single pulses

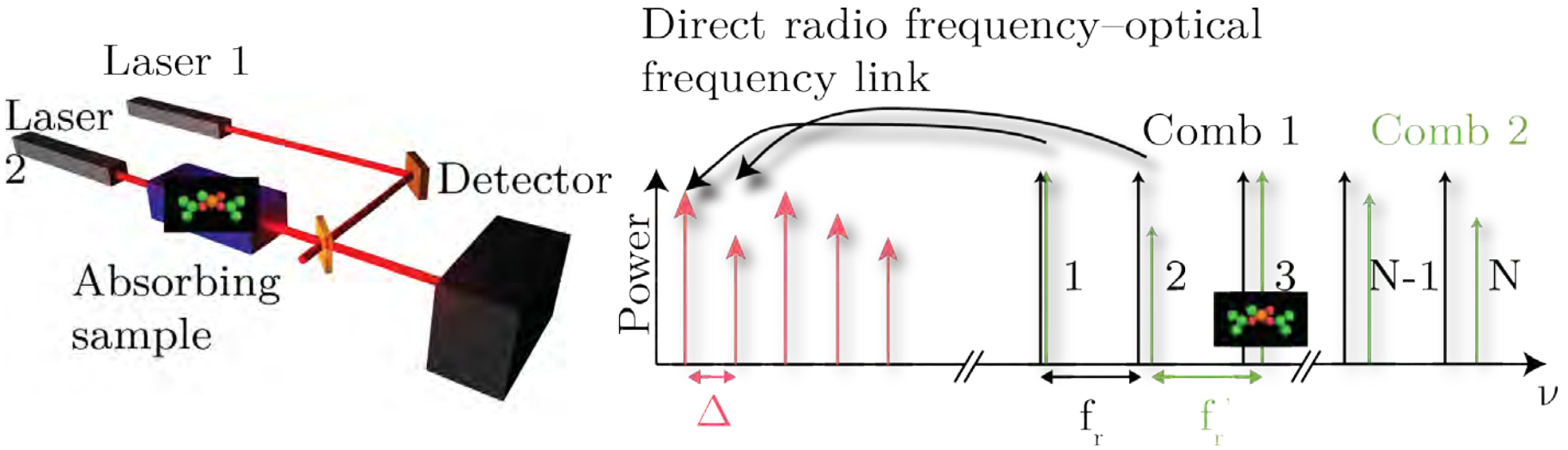
Dual comb spectroscopy



S. Schiller, “Spectrometry with frequency combs,” Opt Lett, vol. 27, no. 9, pp. 766–768, 2002.

Keilmann, F., et al. Time-domain mid-infrared frequency-comb spectrometer. Opt. Lett. 29, 1542–1544 (2004).

Dual comb spectroscopy



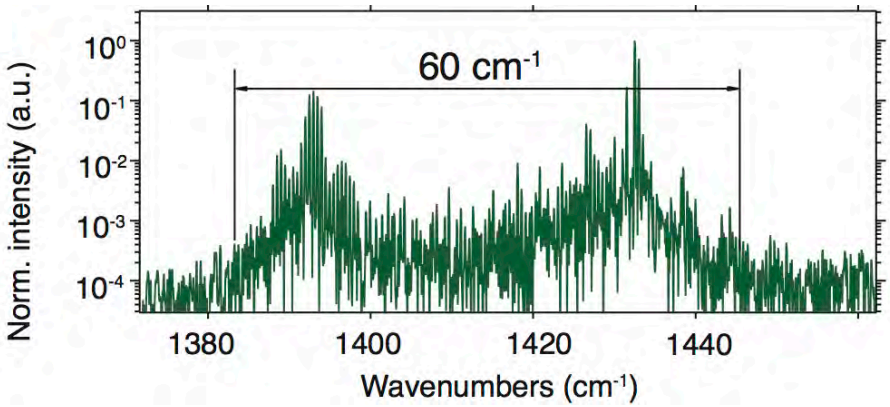
No moving parts, very fast!

S. Schiller, “Spectrometry with frequency combs,” Opt Lett, vol. 27, no. 9, pp. 766–768, 2002.

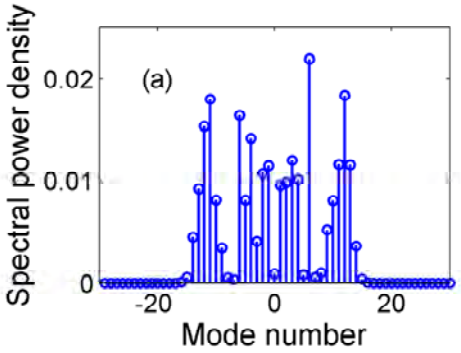
Keilmann, F., et al. Time-domain mid-infrared frequency-comb spectrometer. Opt. Lett. 29, 1542–1544 (2004).

Broadband active region

- Large dipole matrix element and short lifetimes
  - Large, fast non-linearity
- Low dispersion
  - Naturally low GVD
- Fast gain recovery time
  - Pulse generation is damped in favor of FM mode-locking

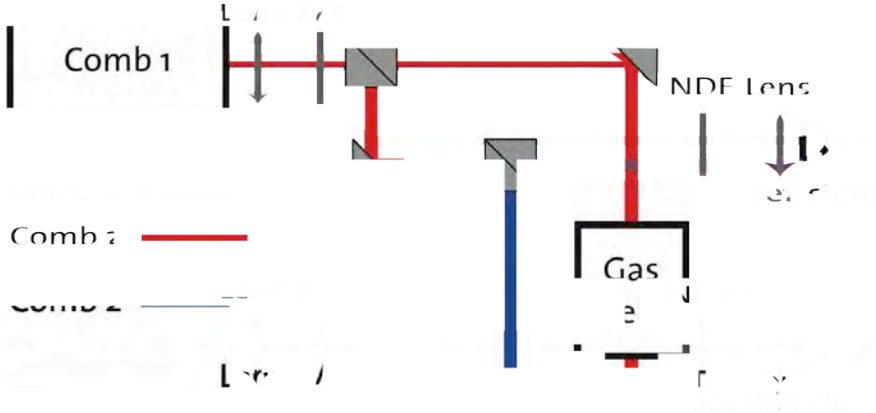


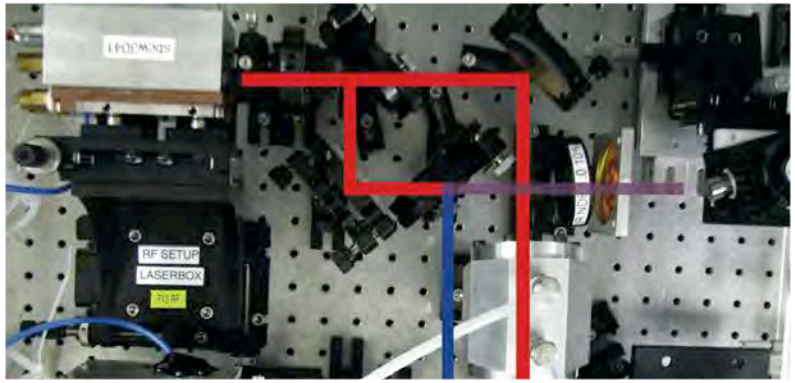
A. Hugi, et al., *Nature*, vol. **492**, 229–233 (2012)



J. Khurghin et al, Appl. Phys. Lett. (2014)

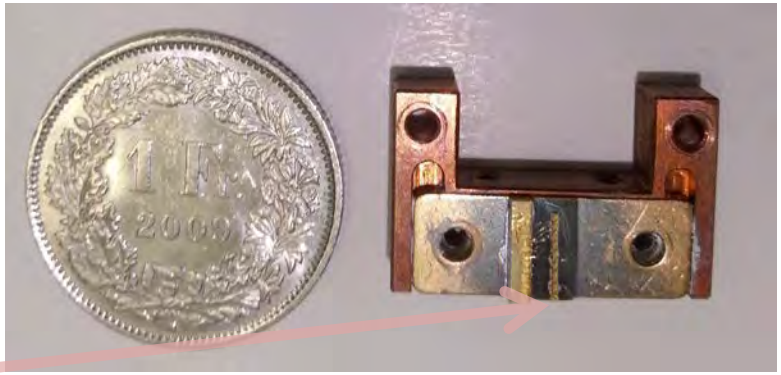
Setup: mid-IR dual comb spectroscopy





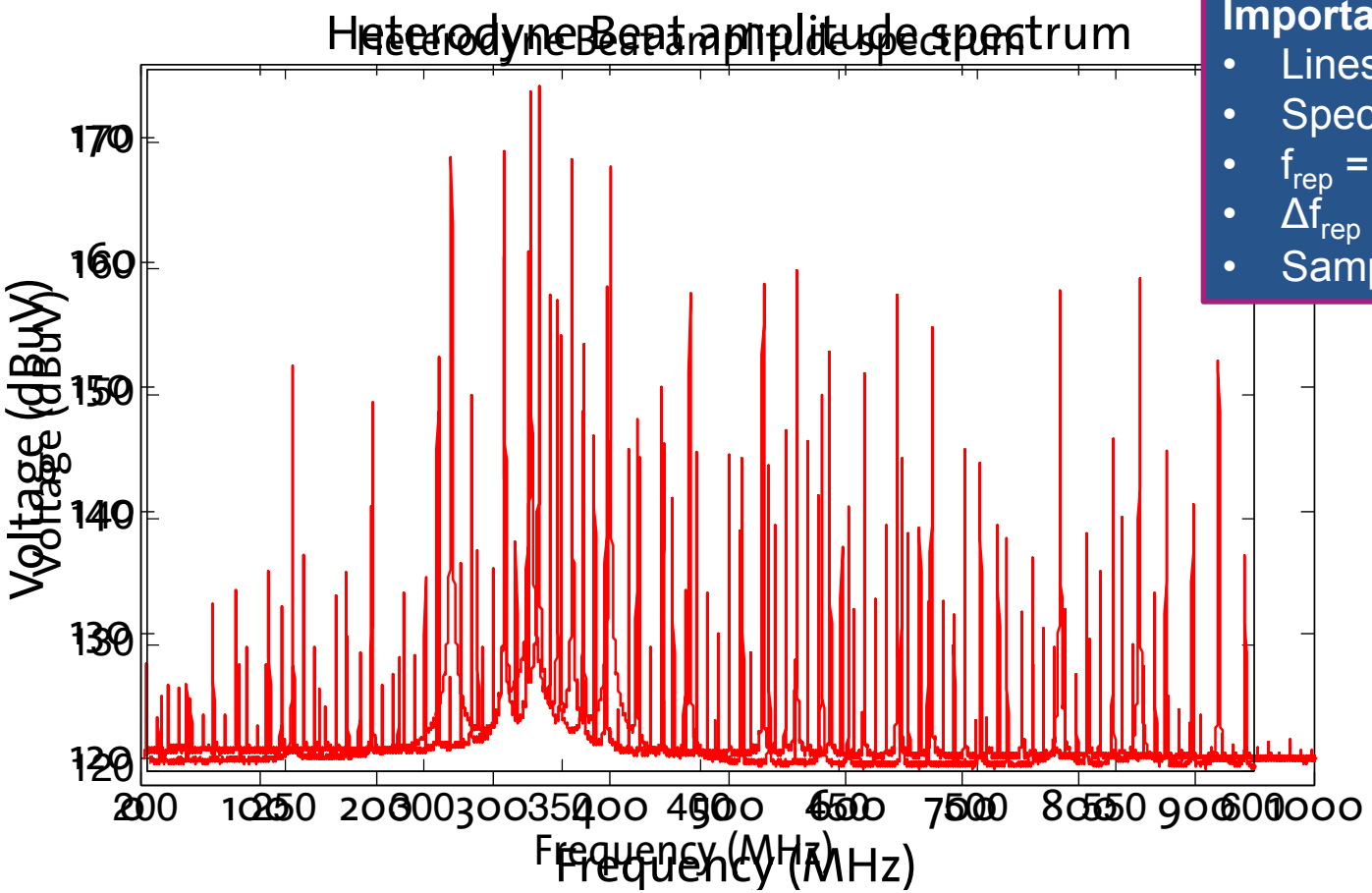
Characteristics

- Compact setup (65cm x 65cm x 25cm)
- No cryogenic cooling needed



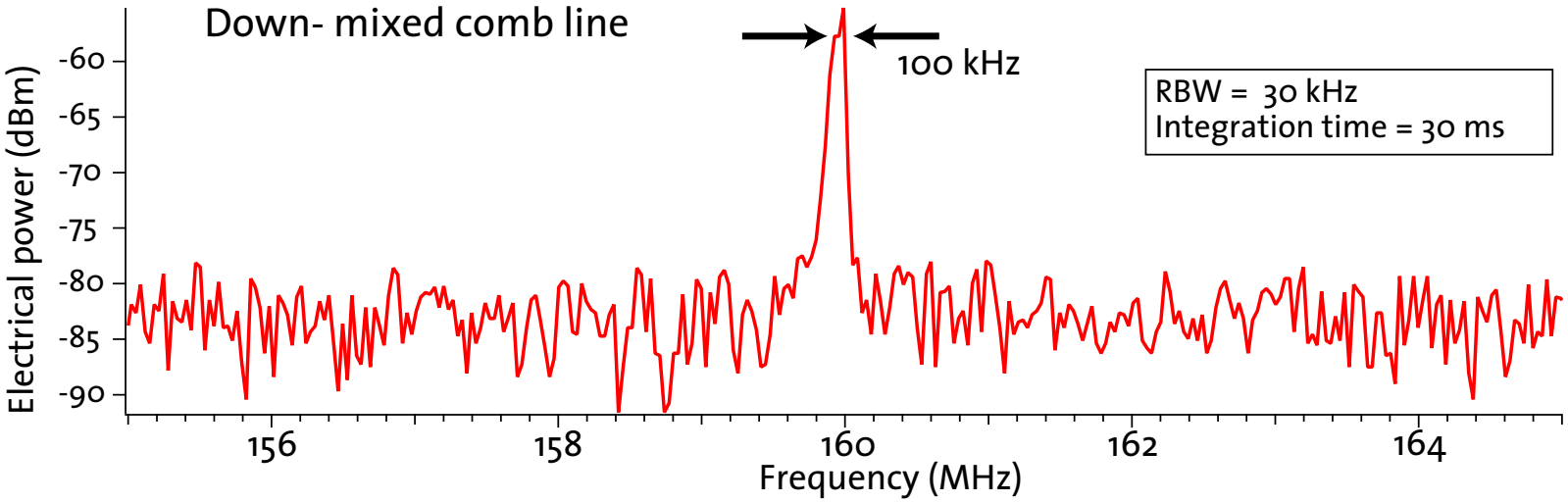
6 mm long

Free running heterodyne beat measurements



Important numbers:
- Lines = 100;
- Spectral coverage = 25 cm^{-1}
- f_{rep} = 7.5 GHz
- Δf_{rep} = 10 MHz
- Sampling = 0.25 cm^{-1}

Free running heterodyne beat measurements

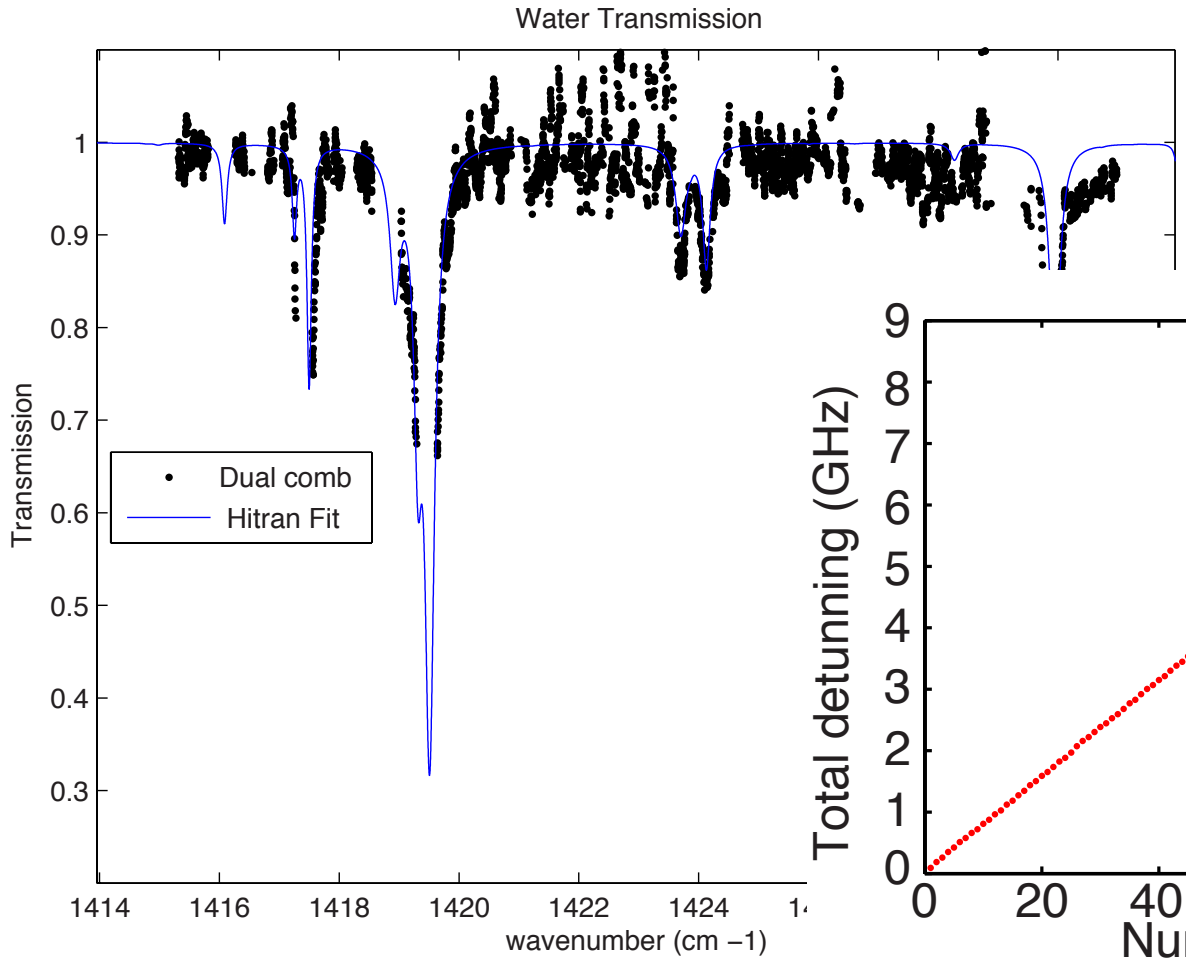


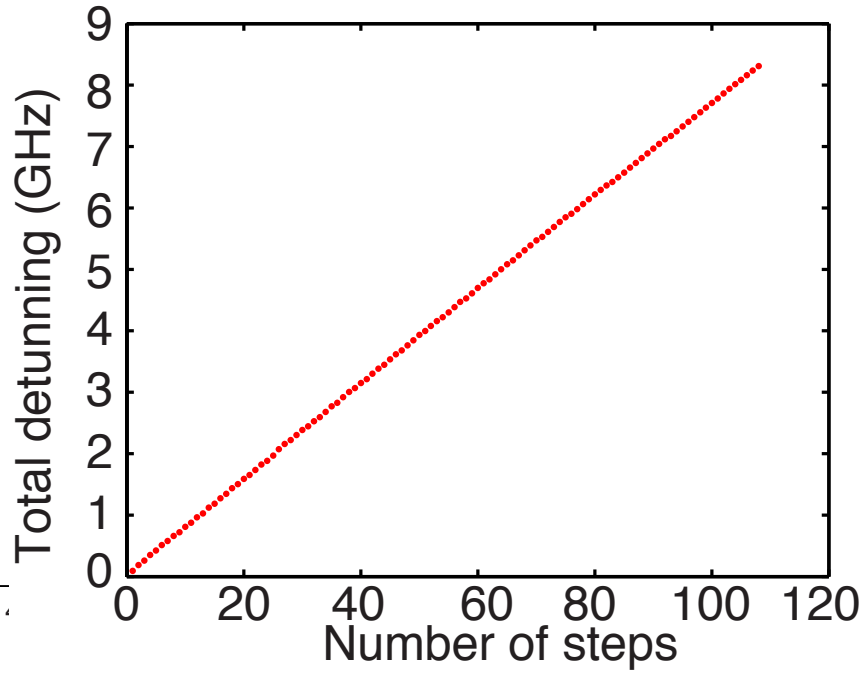
Comb tooth linewidth (free running)

- FWHM = 100 kHz

FTIR with a 1km long arm !

Water spectrum



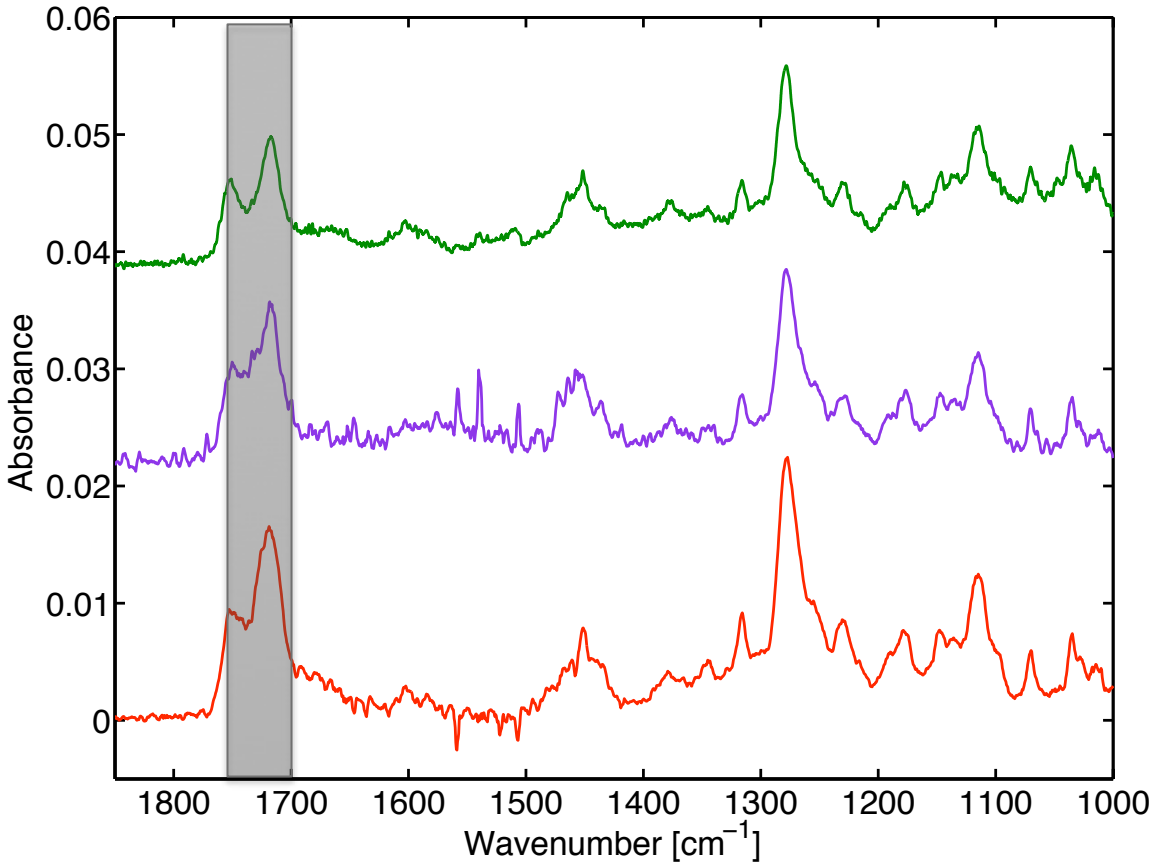


Sample spacing: 80 MHz
Bandwith: 16 cm^{-1}

NanoTera IRSENS

Measurements in Liquids: Cocaine in saliva

Measurements in liquids: benchmarking with FTIR

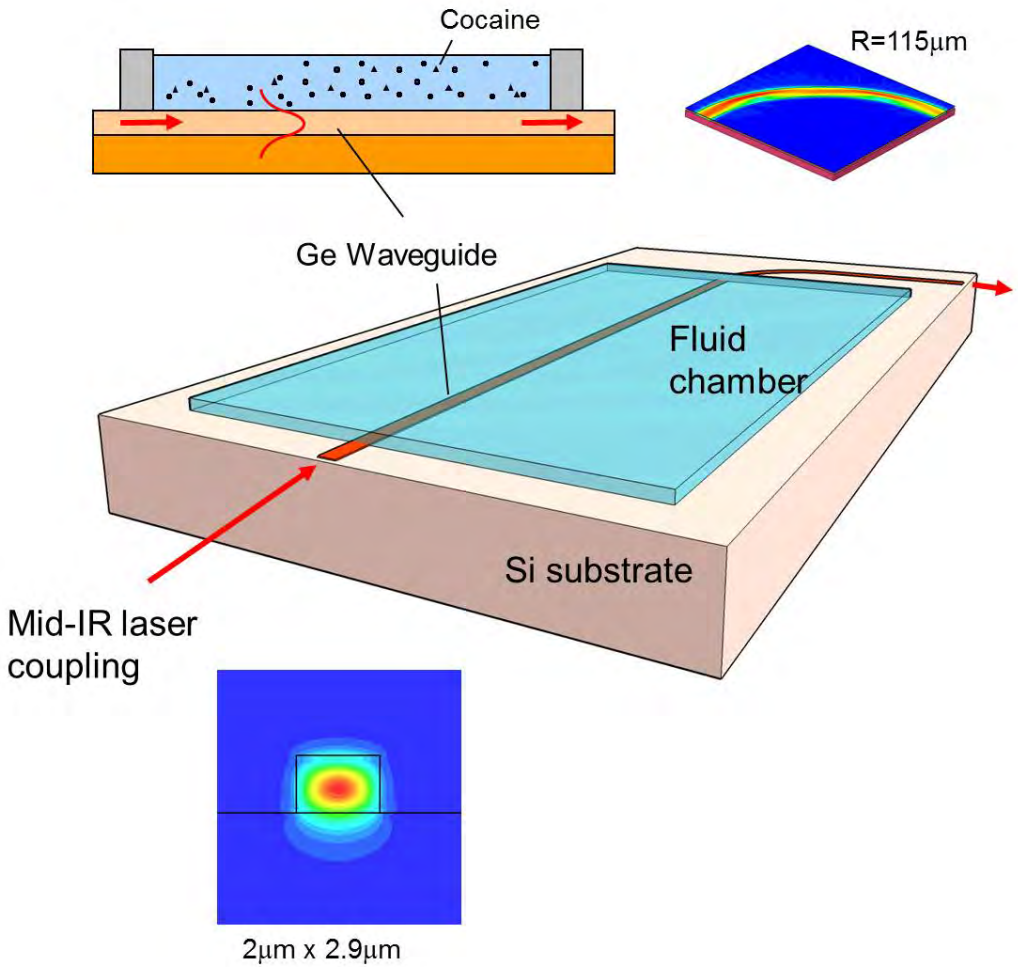


ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

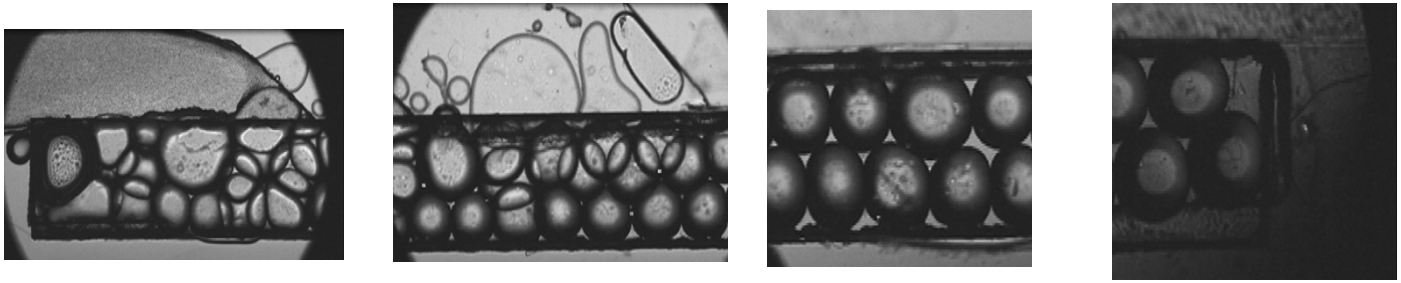
Comparison between spectra of pure cocaine, TCE phase of an extract from saliva spiked with pure cocaine and of an extract of saliva spiked with street cocaine (from the Forensic Science Institute Zurich)

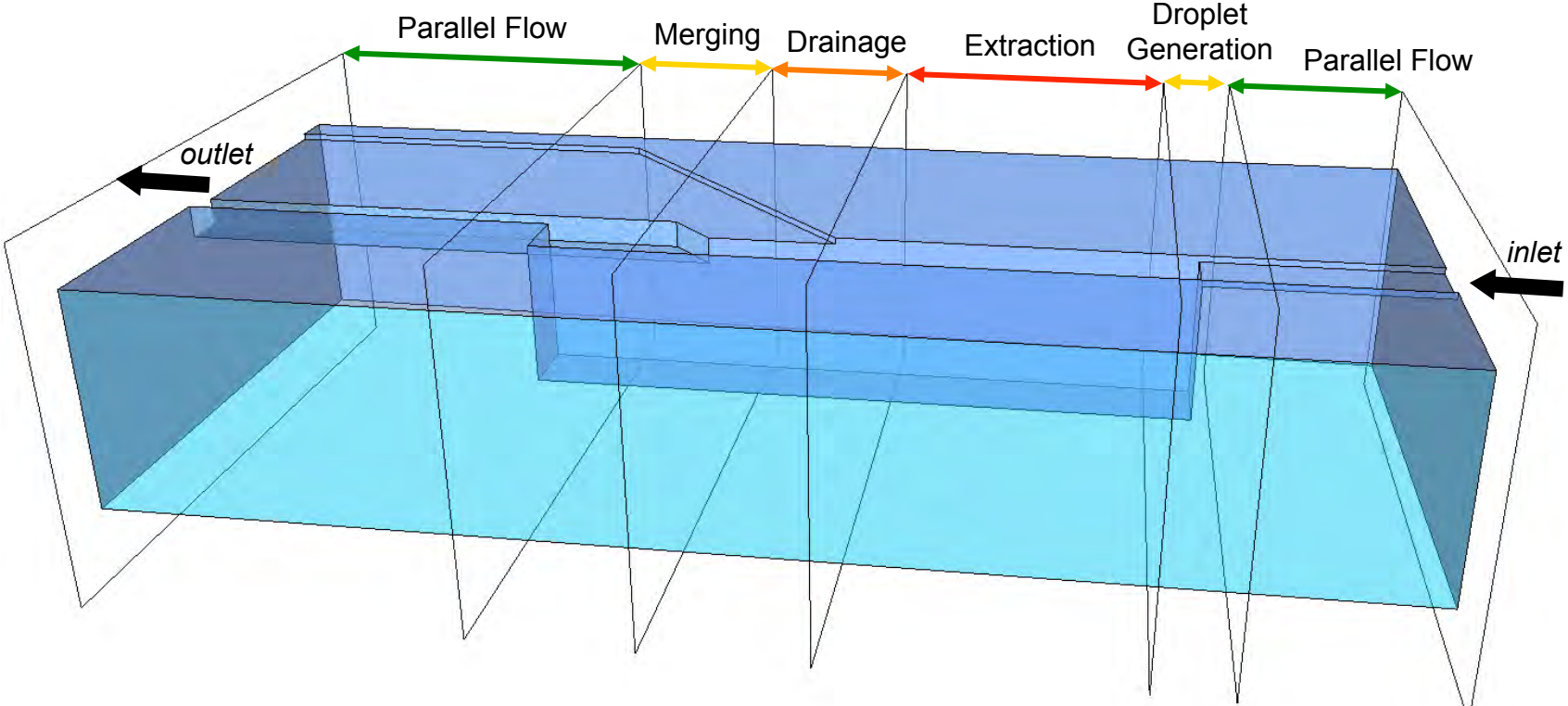
Measurements in liquids: Si/Ge waveguides

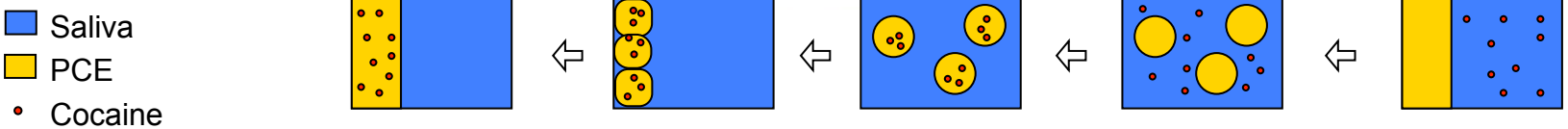
Evanescence interaction:

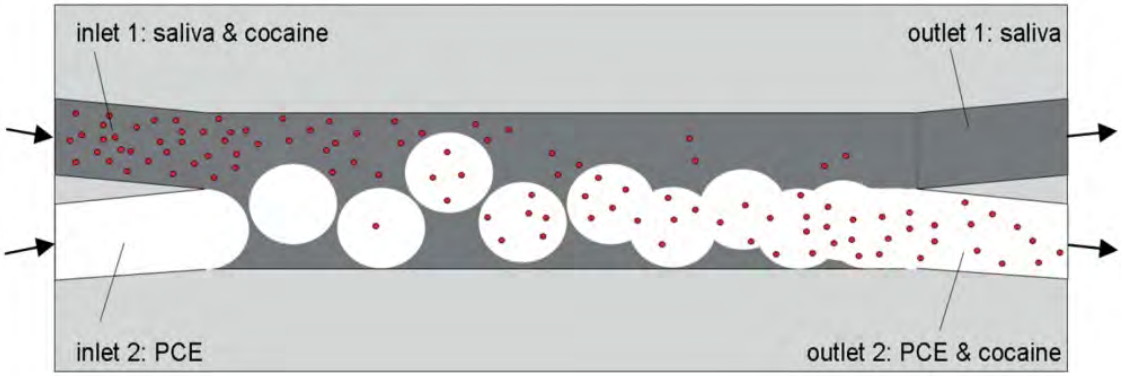


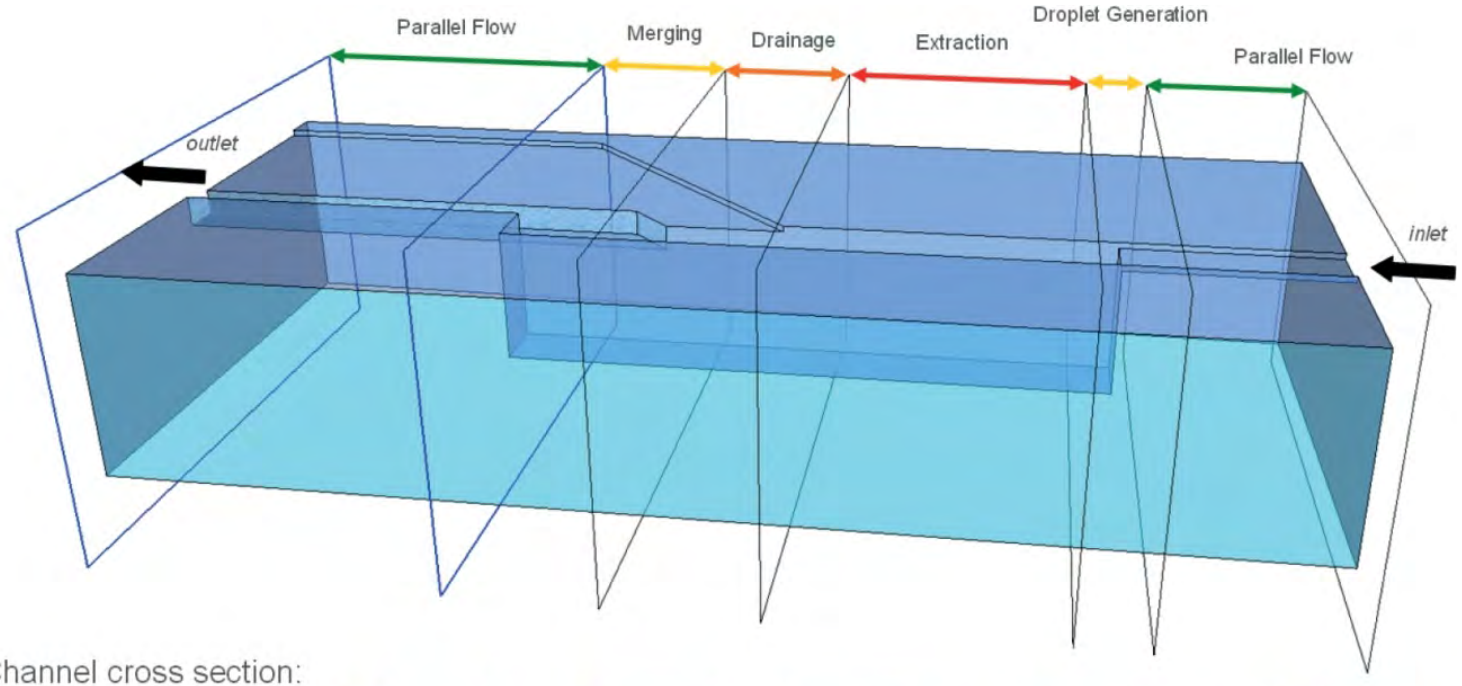
Measurements in liquids: real microfluidic extraction





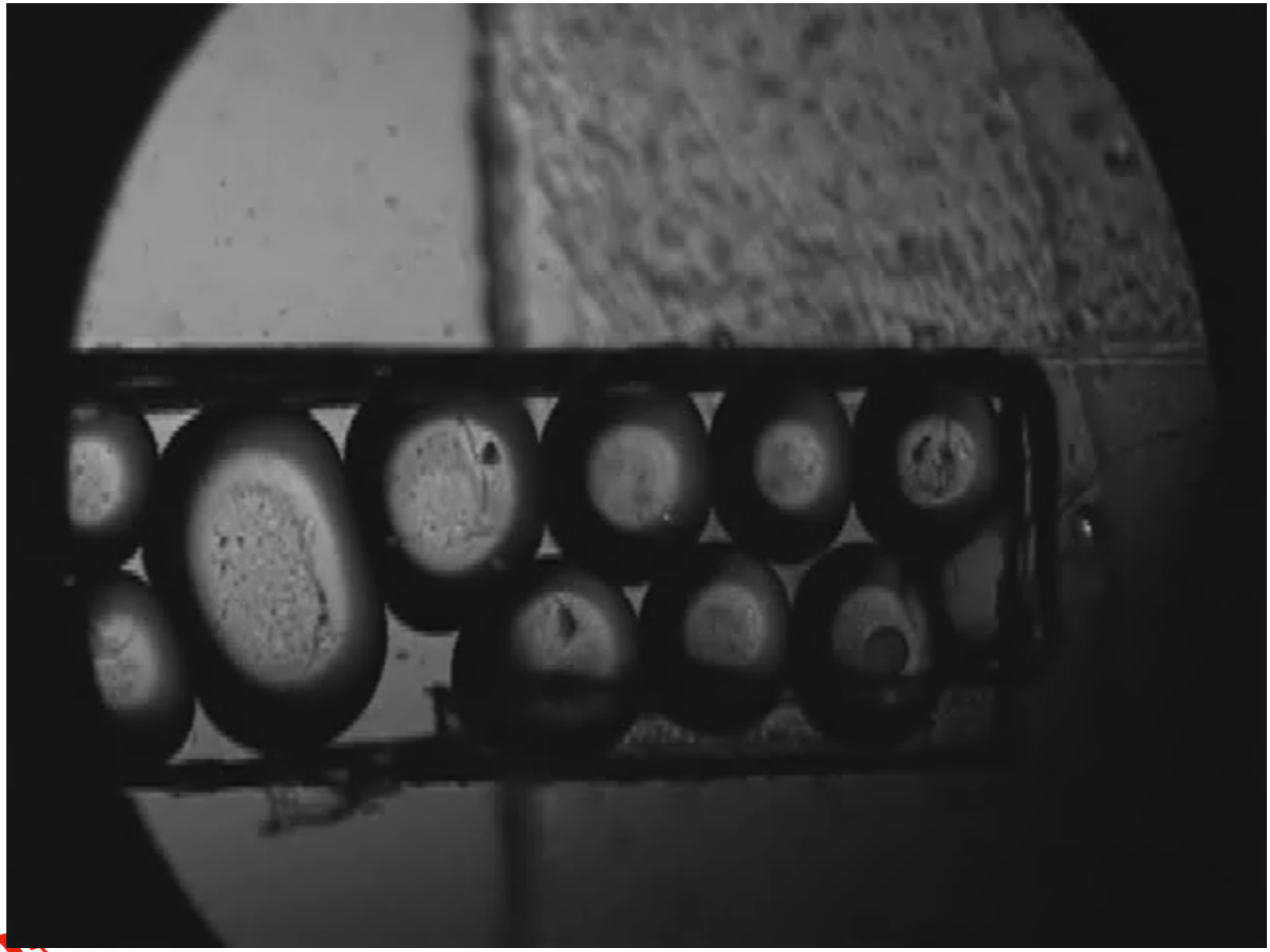






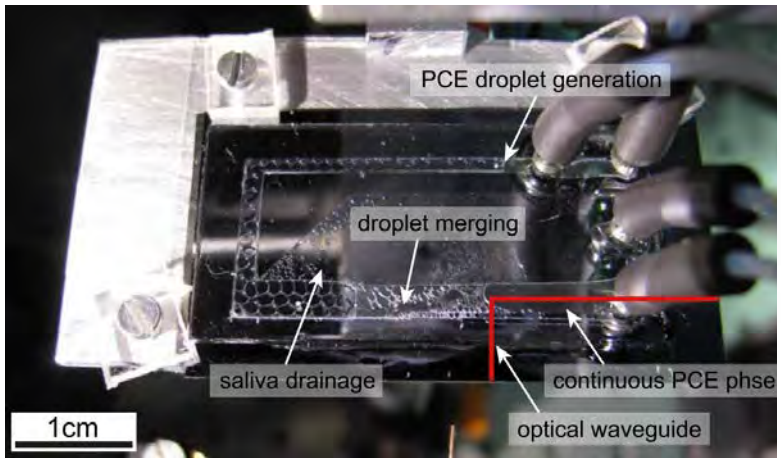
Channel cross section:

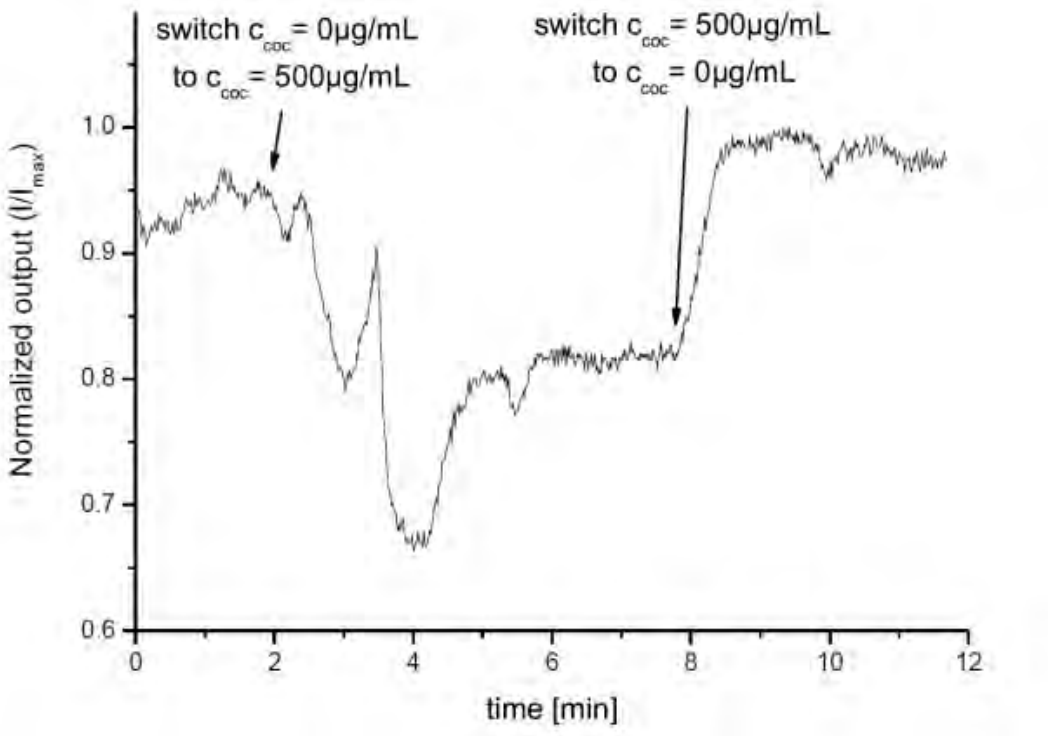
Droplet generation



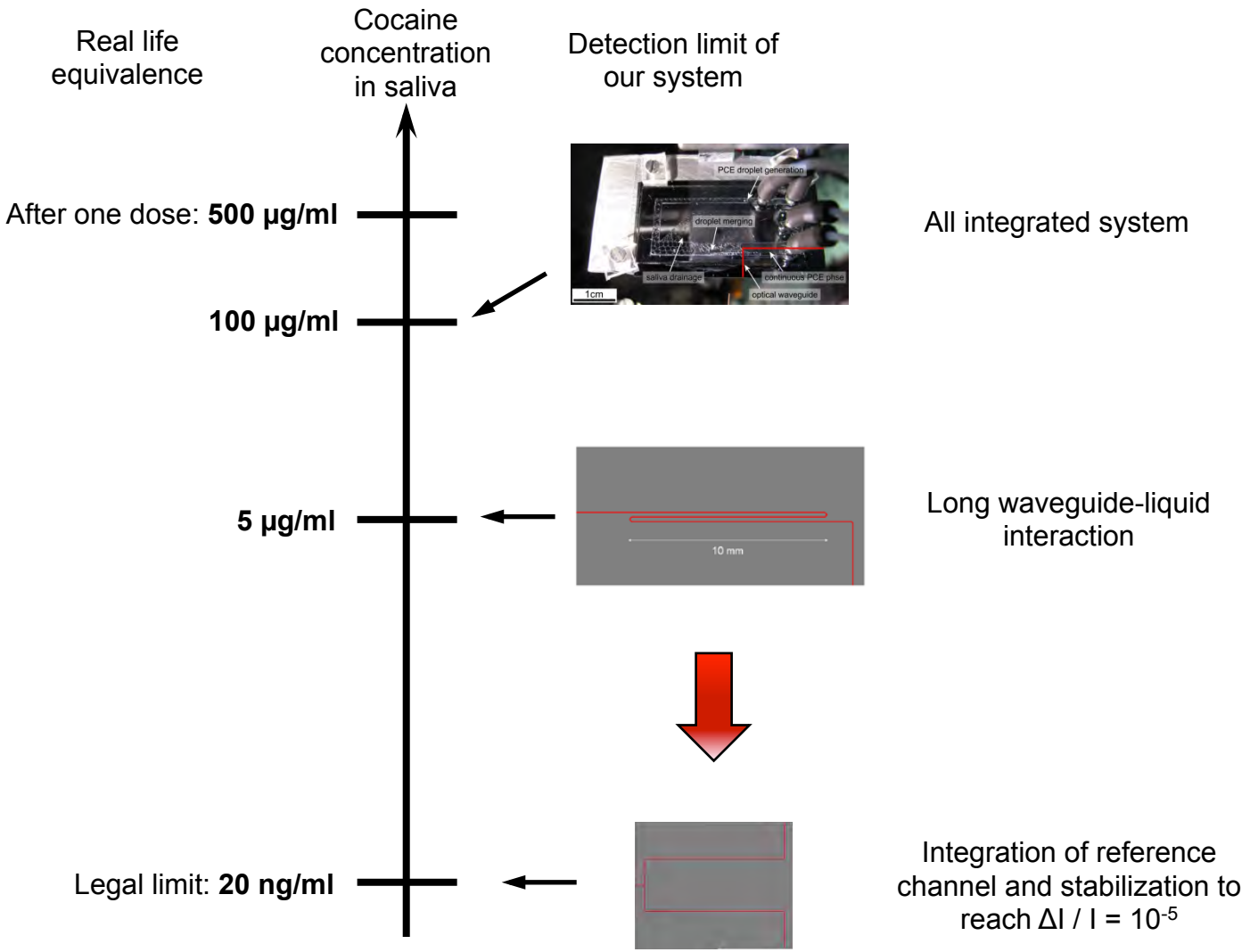
Measurements in liquids: all integrated system

Cocaine measurement in saliva using the all in one chip:



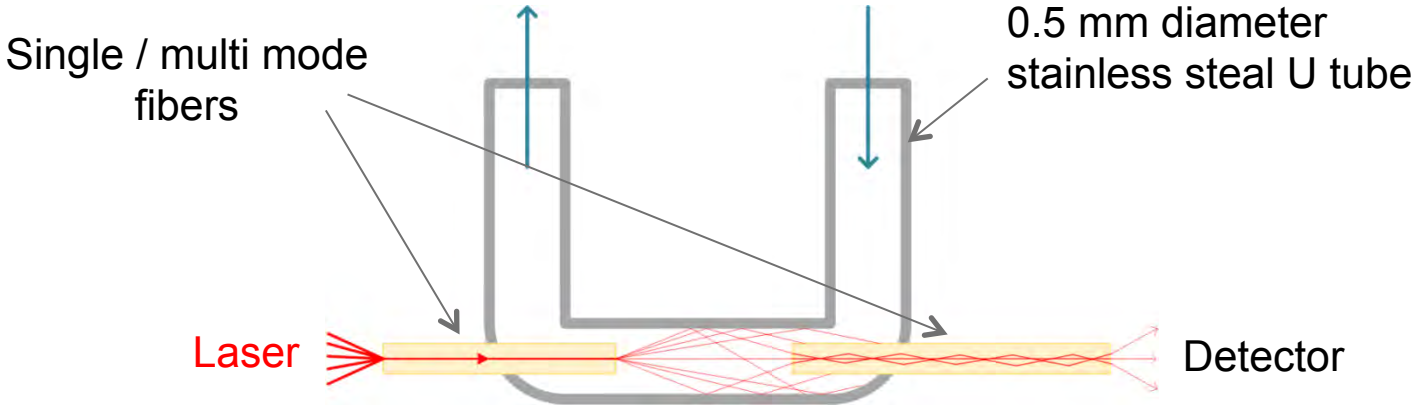


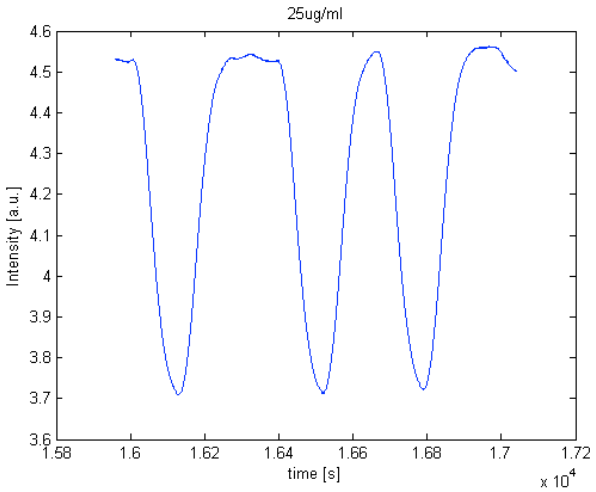
Measurements in liquids: status



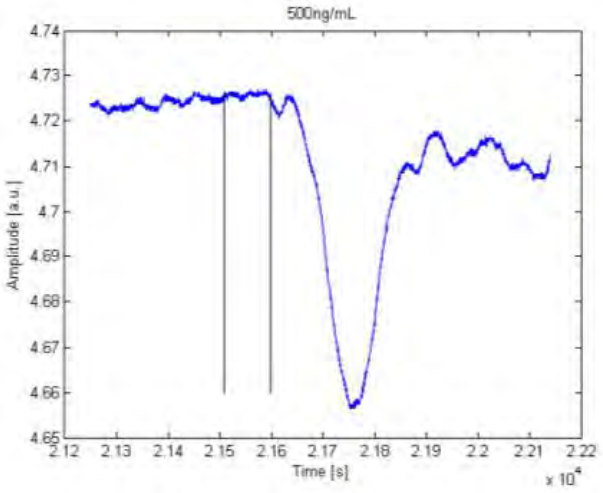
Fiber-based solution

Direct absorption in a tube with optical fibers:

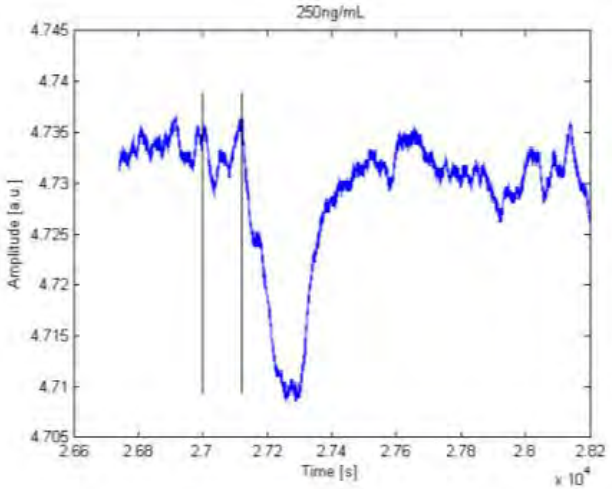




25 µg/mL

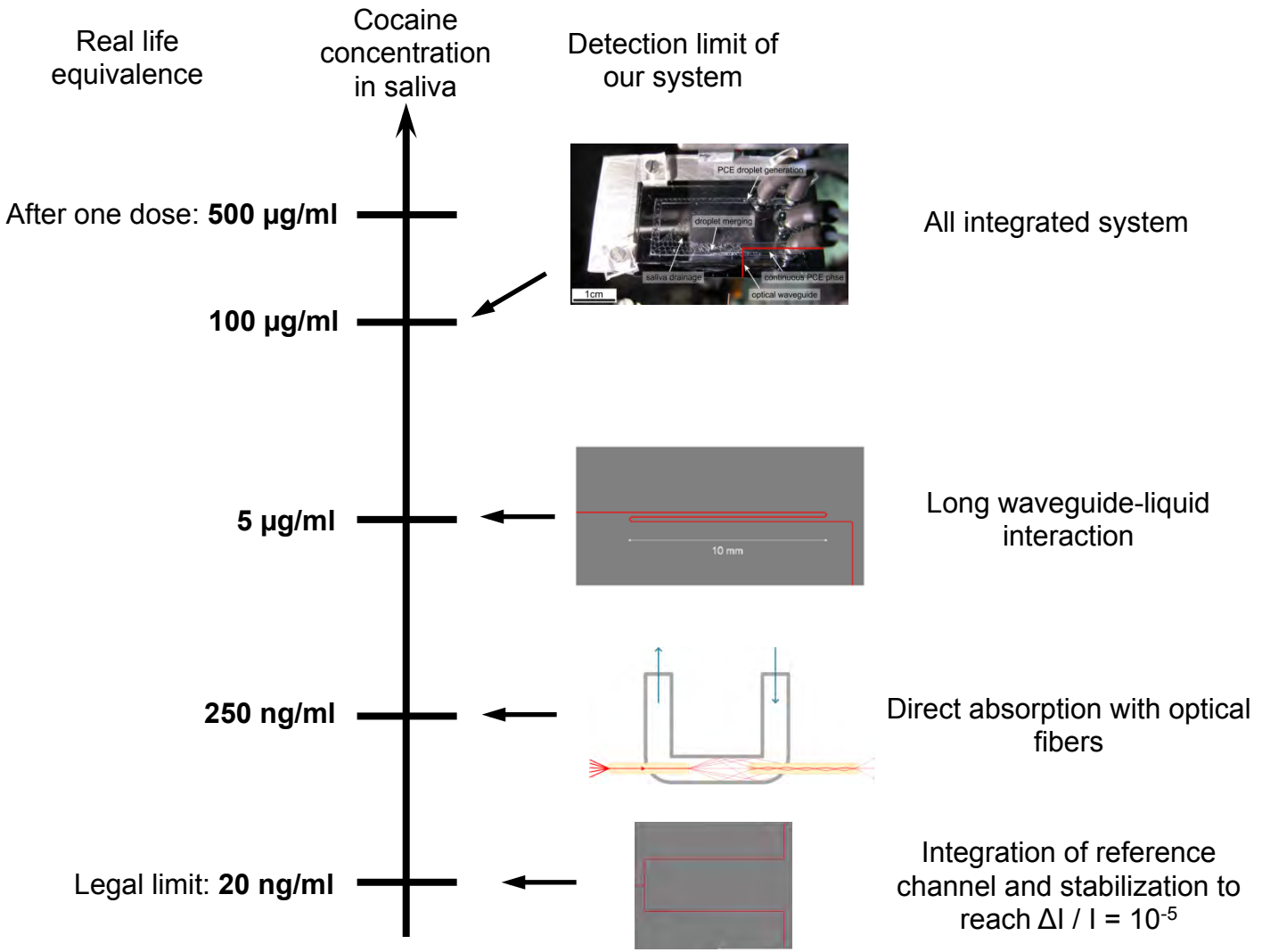


500 ng/mL

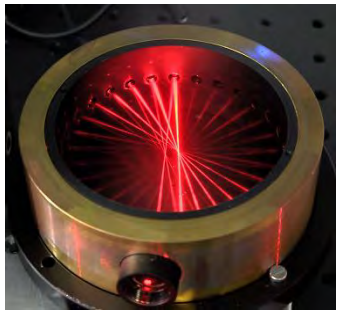


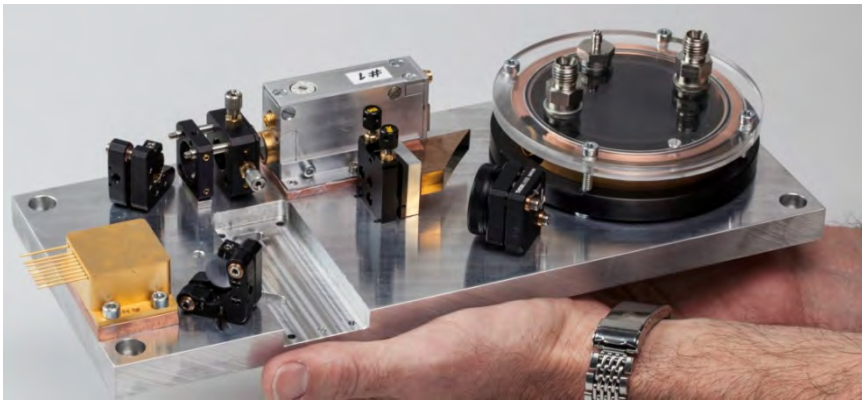
250 ng/mL

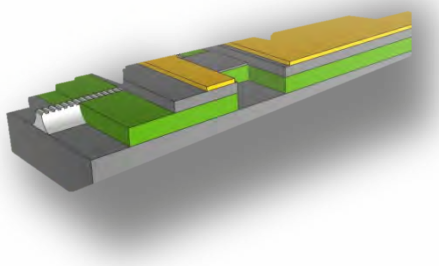
Measurements in liquids: status

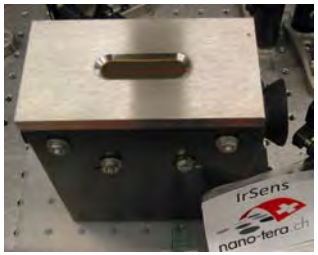


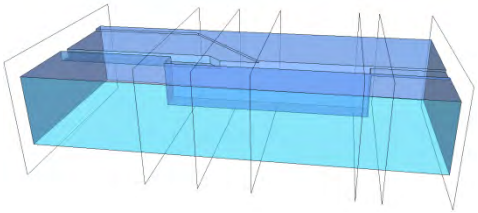
Conclusion

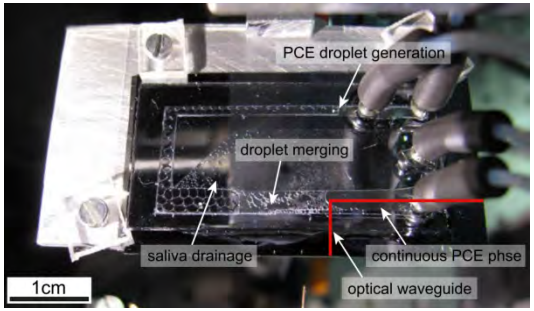


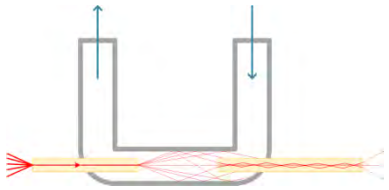












References:

- P. Jouy et al, "*Mid-infrared spectroscopy for gases and liquids based on quantum cascade technologies*", Analyst, in press (2014)
- www.qoe.ethz.ch

www.rsc.org/analyst **PAPER**

Mid-infrared spectroscopy for gases and liquids based on quantum cascade technologies

Pierre Jouy*[a], Markus Mangold[b], Béla Tuzson[b], Lukas Emmenegger[b], Yu-Chi Chang[c], Lubos Hvozdara[c], Hans Peter Herzig[c], Philip Wägli[d], Alexandra Homsy[d,e], Nico F. de Rooij[d] and Jerome Faist[a]

IrSens team

ETH Zurich:
Markus Sigrist
J. Faist

Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

UNINE
D. Hofstetter

FHNWS
H. Looser

Fachhochschule Nordwestschweiz

EPFL
E. Kapon
E. Charbon
A. Homsy, N. DeRooij,
H.P Herzig

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

EMPA
L. Emmenegger

Materials Science & Technology

Group in ETH

FIR team: G. Scalari, M. Geiser, C. Bonzon, D. Turcinkova, G. Cerullo, M. Roesch

Metamaterial C. Maissen, F. Valmorra,P. Liu

MIR team: B. Hinkov, S. Riedi, J. Wolf, G. Villares, A. Hugi

Growth Team: M. BeckV. Liverini, K Ohtani