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OUTLINE

Trace gas sensing applications of quantum cascade lasers

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- Background and motivation
- Specific issues related to pulsed QC-DFB lasers
- Spectroscopic gas sensing with pulsed QC-DFB lasers
- CRDS with a CW QC-DFB laser
- Summary and future developments

Wide range of gas sensor applications

- Urban and Industrial Emission Measurements
  - Industrial Plants – Fence-line perimeter monitoring
  - Combustion Diagnostics
  - Automobile
- Rural Emission Measurements
  - Agriculture
- Environmental Monitoring
  - Atmospheric Chemistry
  - Volcanic Emissions
- Spacecraft and Planetary Surface Monitoring
  - Crew Health Maintenance & Life Support
- Diagnostic and Industrial Process Control
  - Petrochemical and Semiconductor Industry
- Medical Diagnostics
- Fundamental Science-Kinetics and Photochemistry

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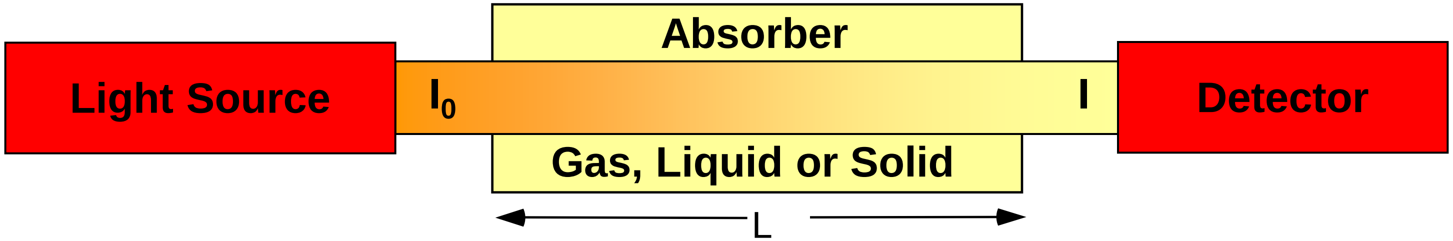
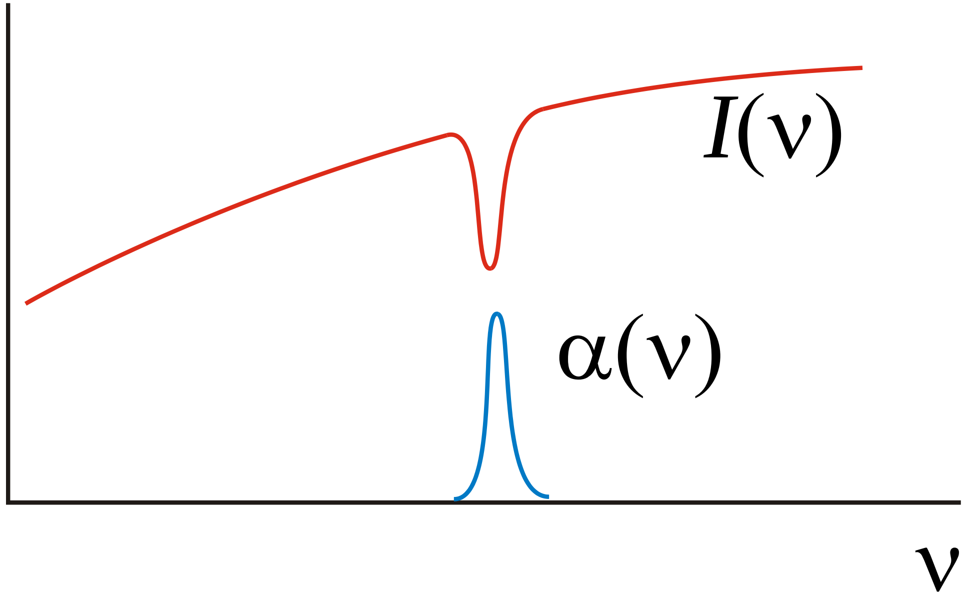
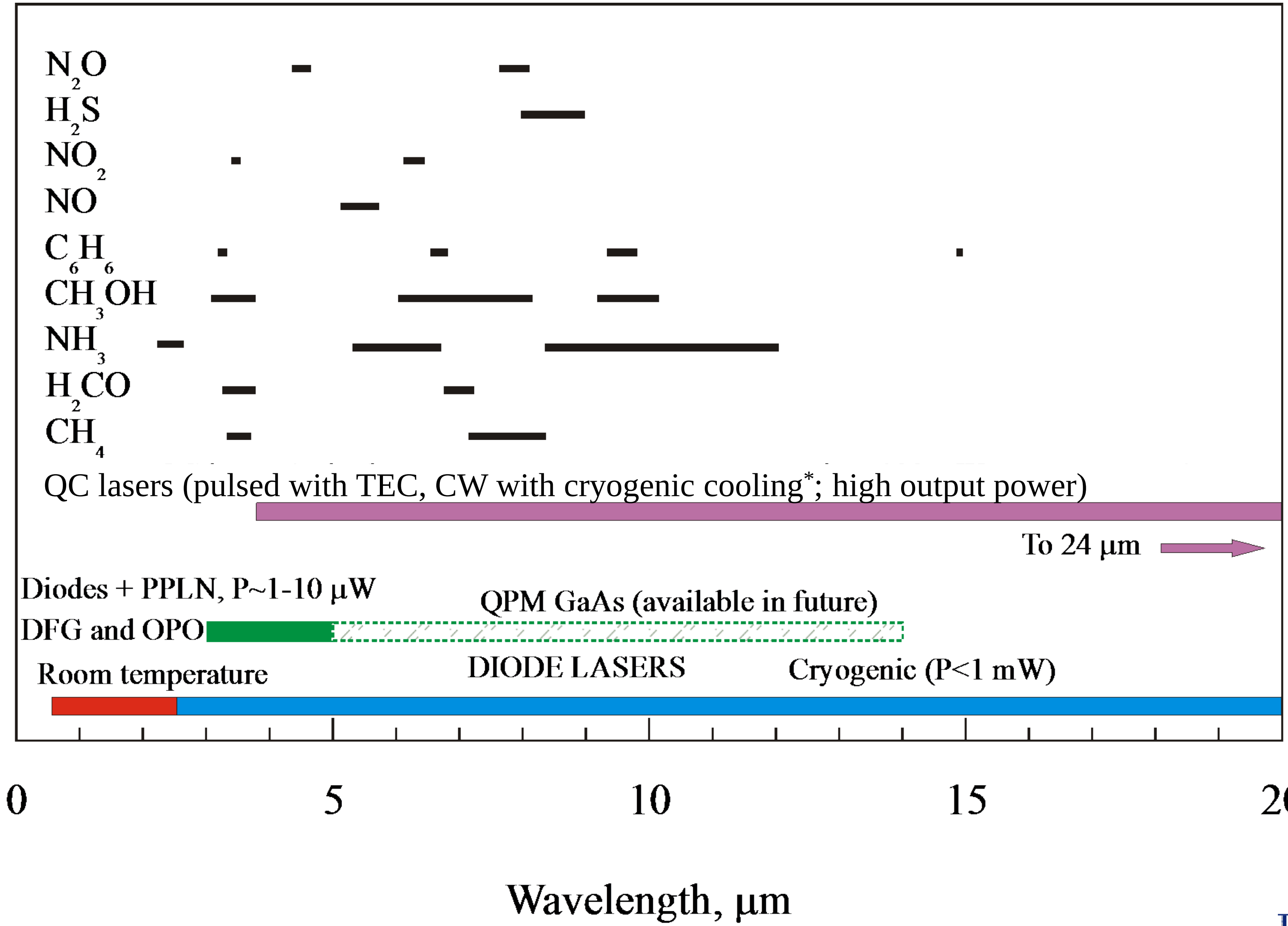
Absorption spectroscopy





$$I(\nu) = I_0(\nu)\times\exp\left[-\alpha(\nu)\cdot nL\right] \quad \Rightarrow n = -\ln\left(\frac{I(\nu)}{I_0(\nu)}\right)\cdot\frac{1}{\alpha(\nu)L}$$

Molecular absorption and laser sourses



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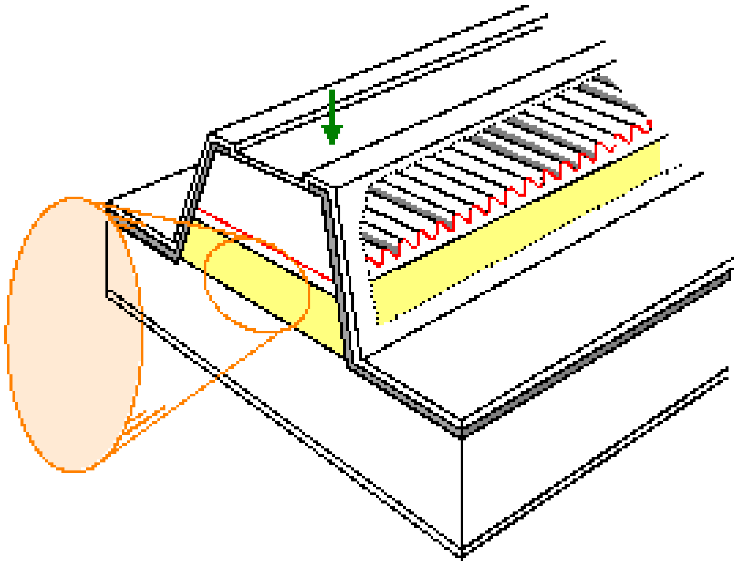
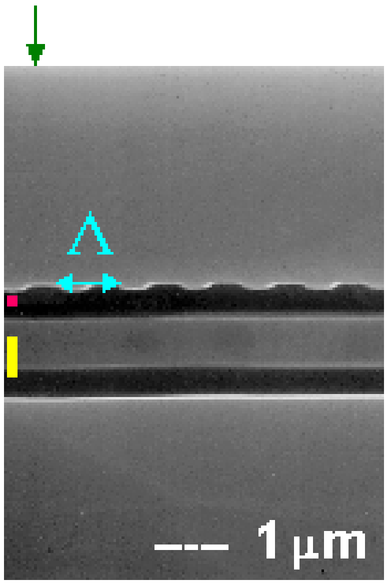
QC laser with distributed feedback (QC-DFB)



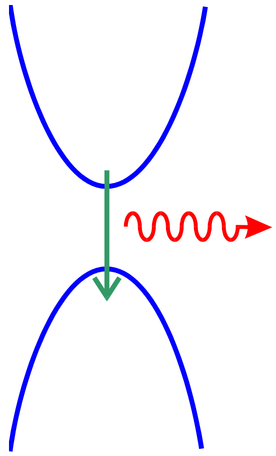
schematic

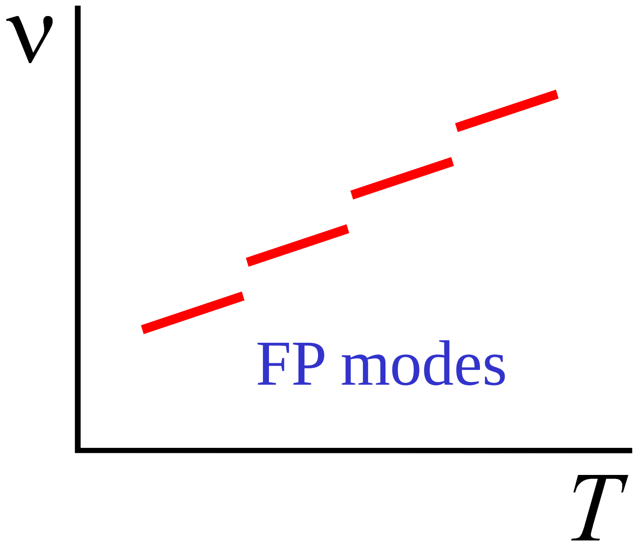


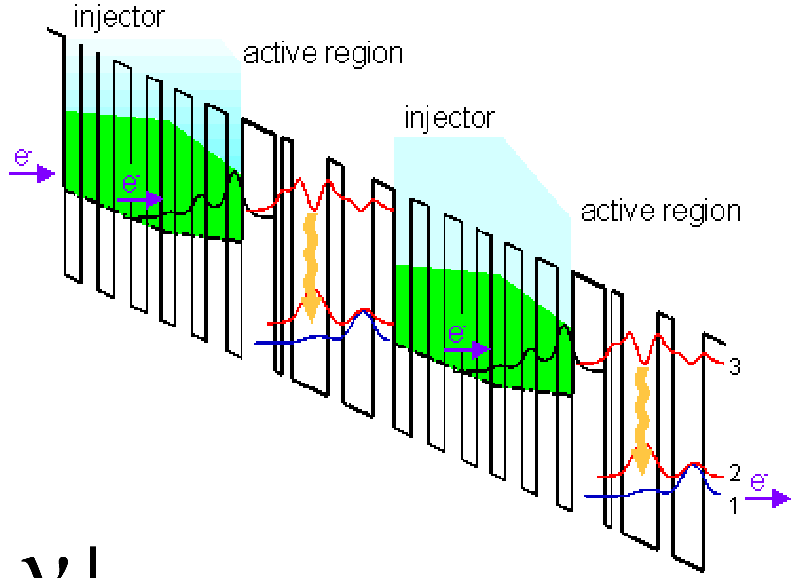
cross-section micrograph

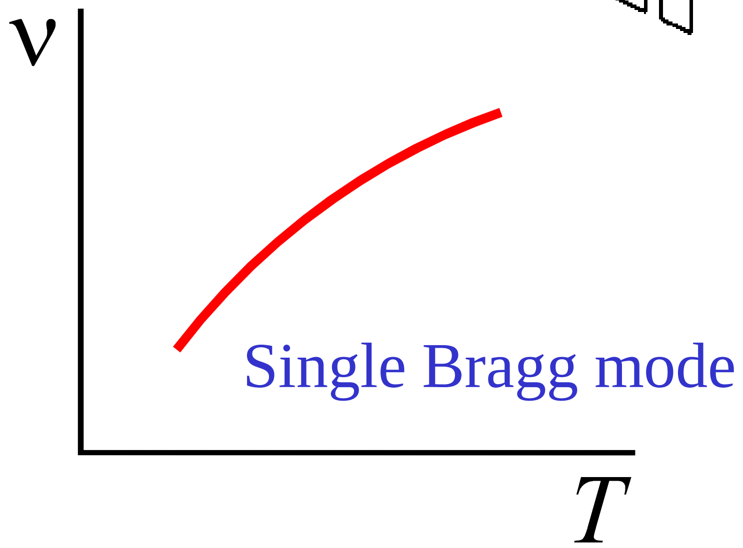
- Grating selects well defined single wavelength
- Tunable with temperature

QC-DFB compared to FP diode laser









Pulsed QC-DFB lasers

- Advantages:
  - Wider availability – full wavelength coverage
  - Thermoelectric cooling
  - Lower power consumption

Problem	**Solution**
Wide laser emission line	?
Low average power	Fast detectors and gated signal detection
Pulse-to-pulse energy fluctuations	Reference channel and normalization

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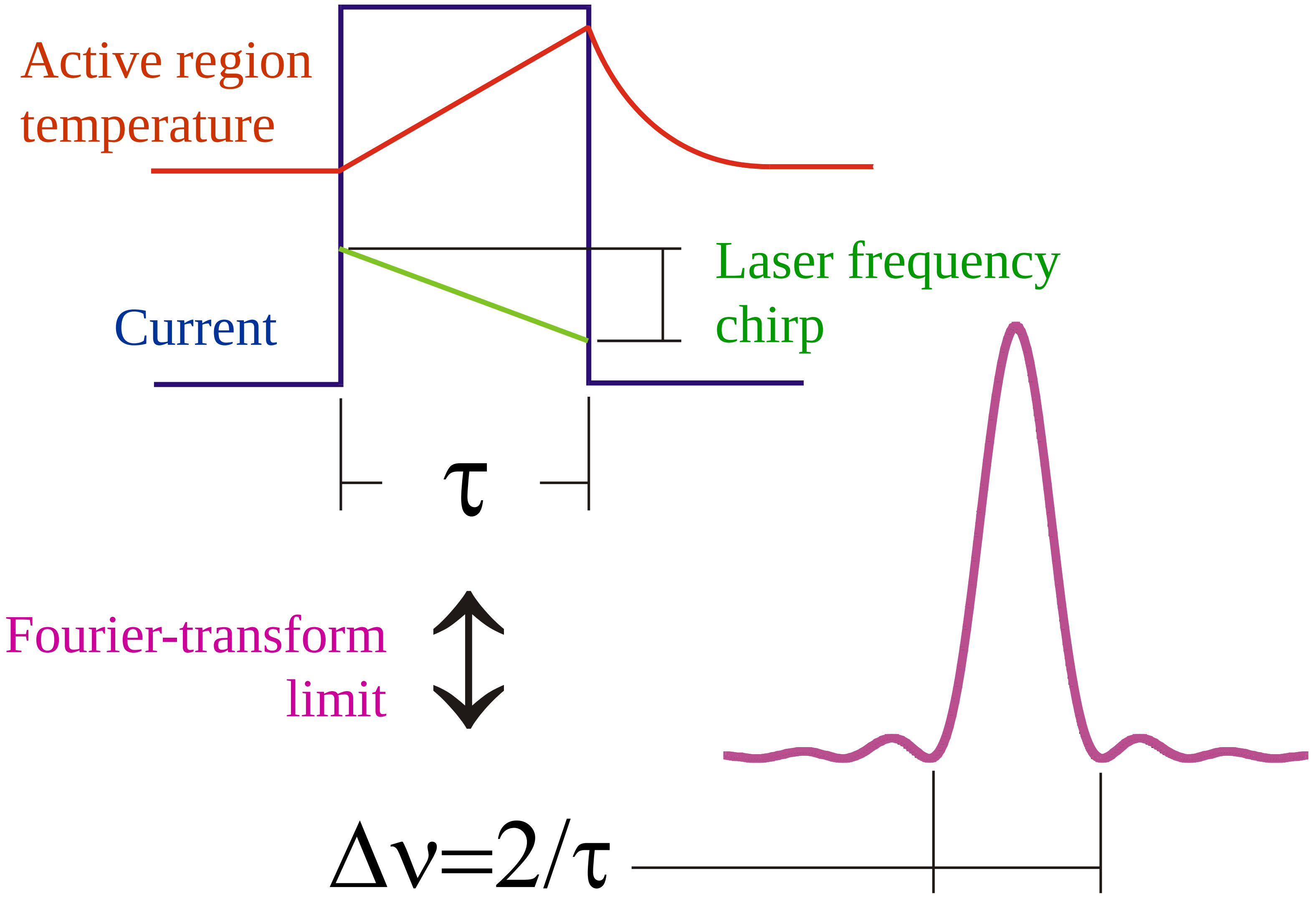
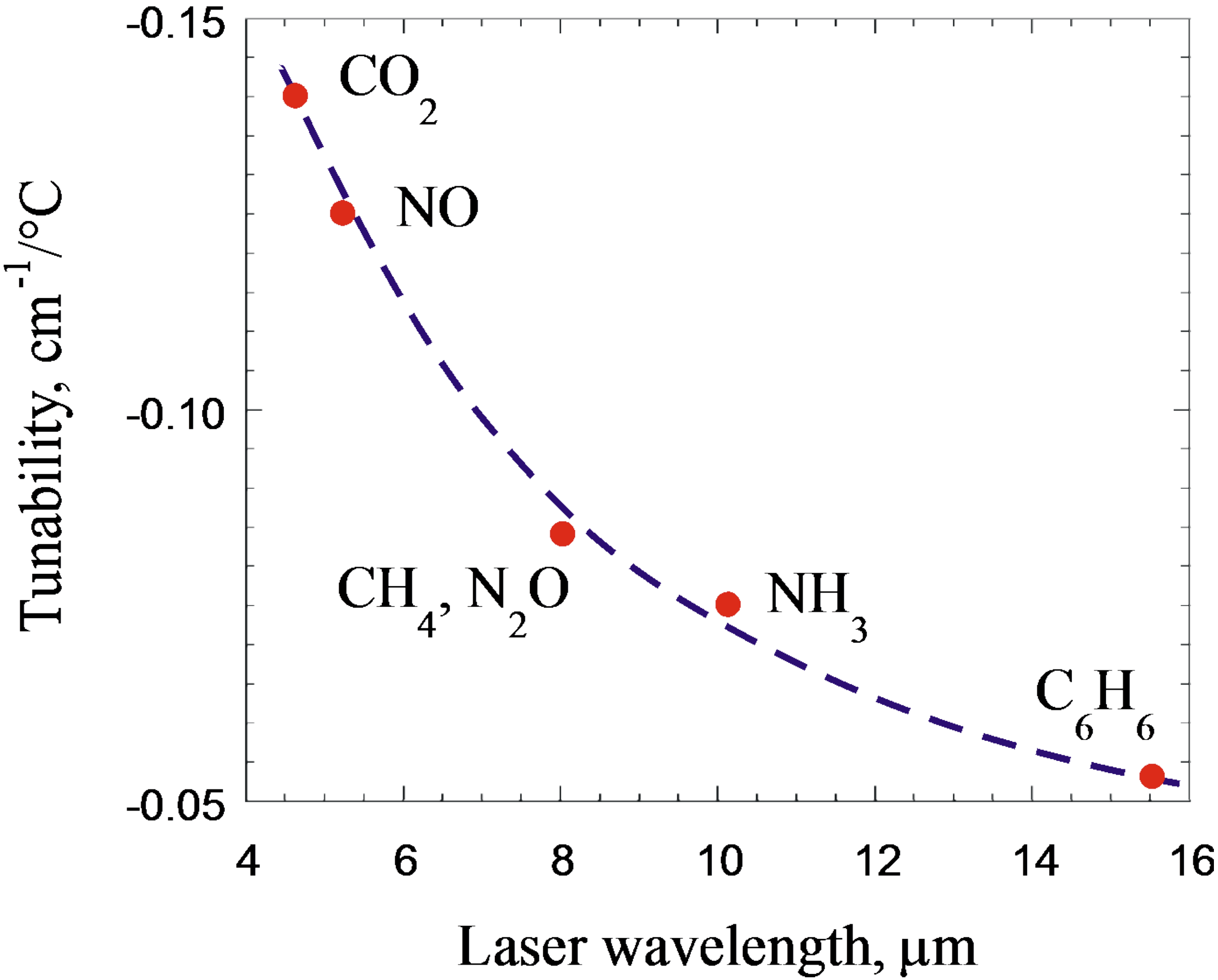
QC-DFB laser line broadening mechanisms



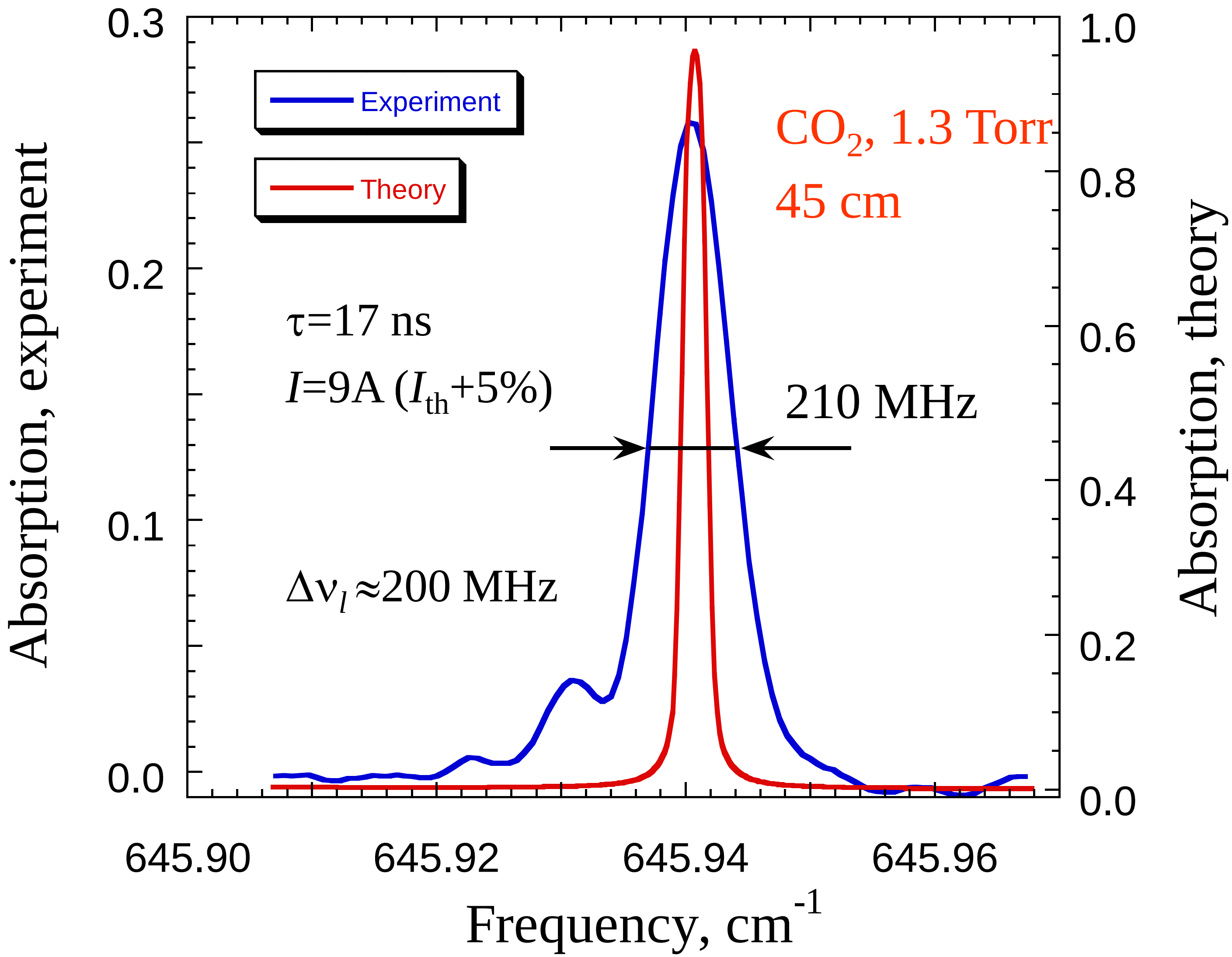
Pulsed QC-DFB lasers

Problem	Solution
Wide laser emission line	Optimized current pulse width
Low average power	Fast detectors and gated signal detection
Pulse-to-pulse energy fluctuations	Reference channel and normalization

QC-DFB laser tunability vs. wavelength



Record narrow linewidth of pulsed QC Laser



A. Kosterev et al, Applied Physics B (2002)
DOI: 10.1007/s00340-002-0963-z

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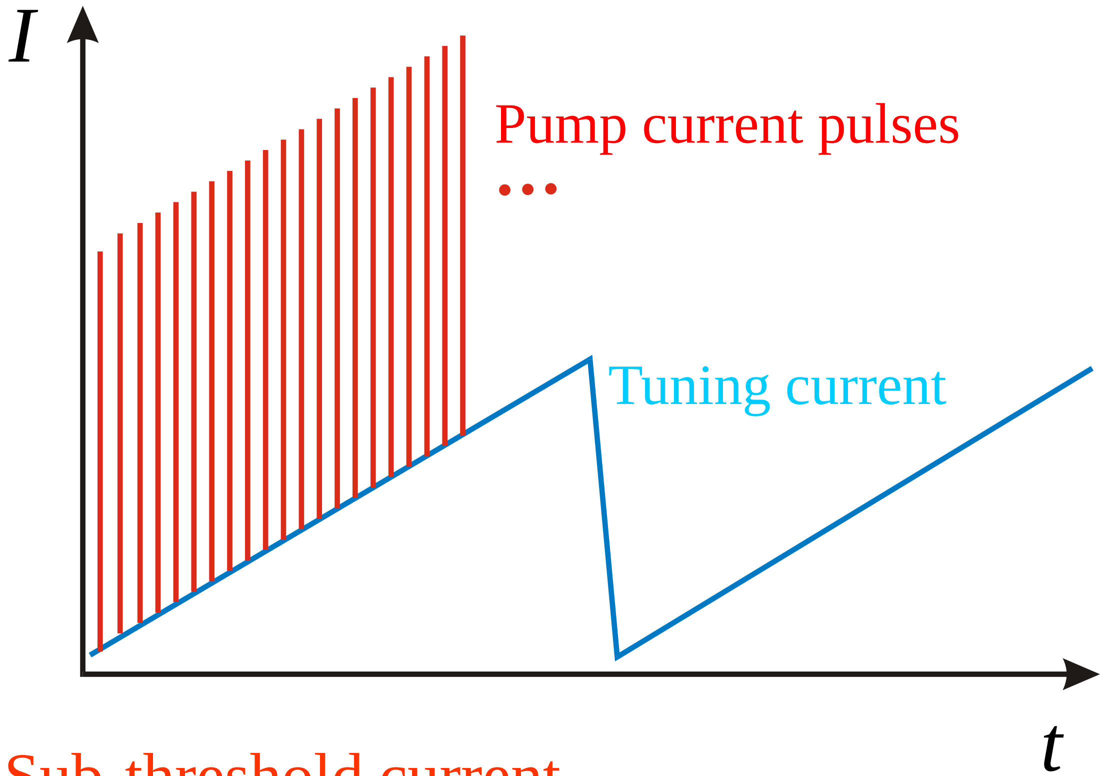
Pulsed QC laser wavelength scanning



Solution: Sub-threshold current

K. Namjou, S. Cai, E.A. Whittaker, J. Faist, C. Gmachl, F. Capasso, D.L. Sivco, and A.Y. Cho, "Sensitive absorption spectroscopy with a room-temperature distributed-feedback quantum-cascade laser", *Opt. Lett.* **23**, 219-221 (1998)

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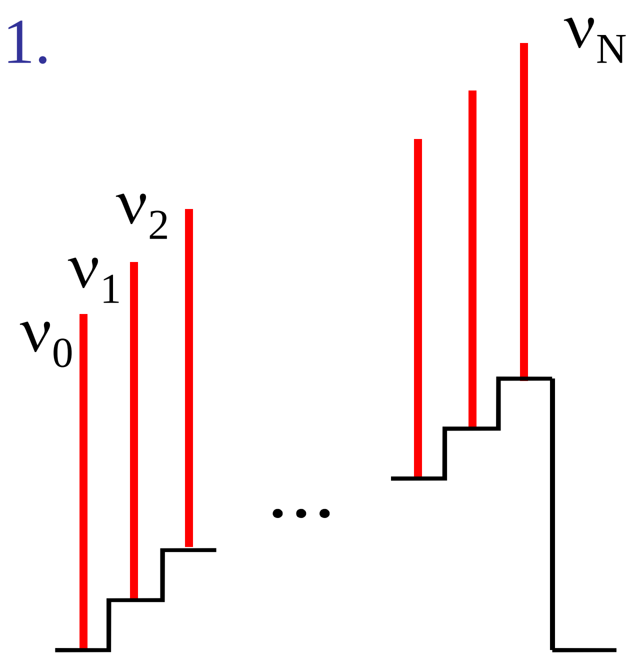
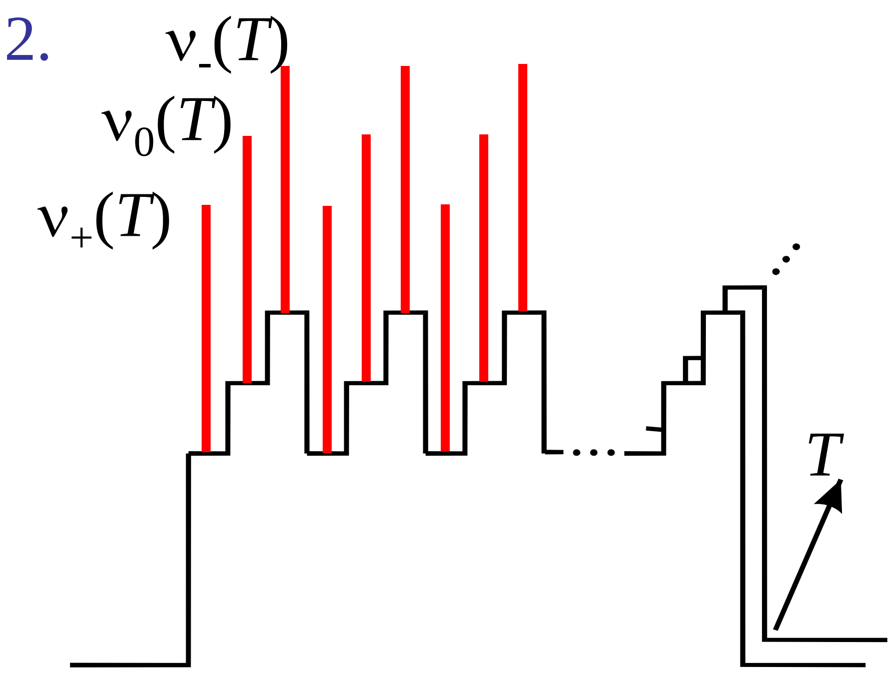
Synchronous frequency manipulation



Synchronous digitally synthesized steps of tuning current (enables linearization of scan)



Fast cycling of the laser frequency with a subthreshold current and slow scanning with temperature (wavelength modulation)

A. A. Kosterev, F. K. Tittel, C. Gmachl, F. Capasso, D. L. Sivco, J. N. Baillargeon, A. L. Hutchinson, and A. Y. Cho, “Trace-gas detection in ambient air with a thermoelectrically cooled, pulsed quantum-cascade distributed feedback laser”, *Appl. Opt.* **39**, 6866-6872 (2000)

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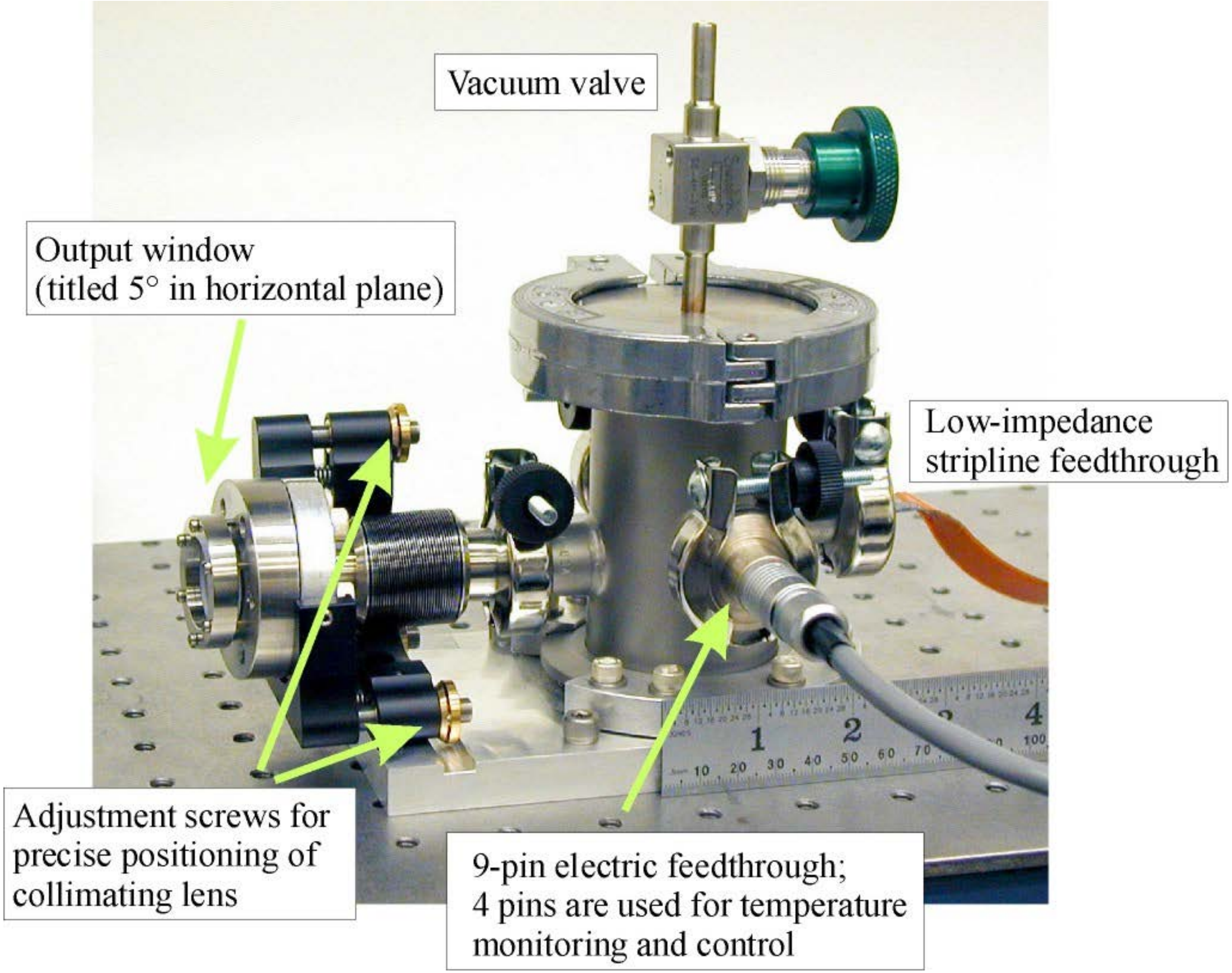
Pulsed QC laser housing



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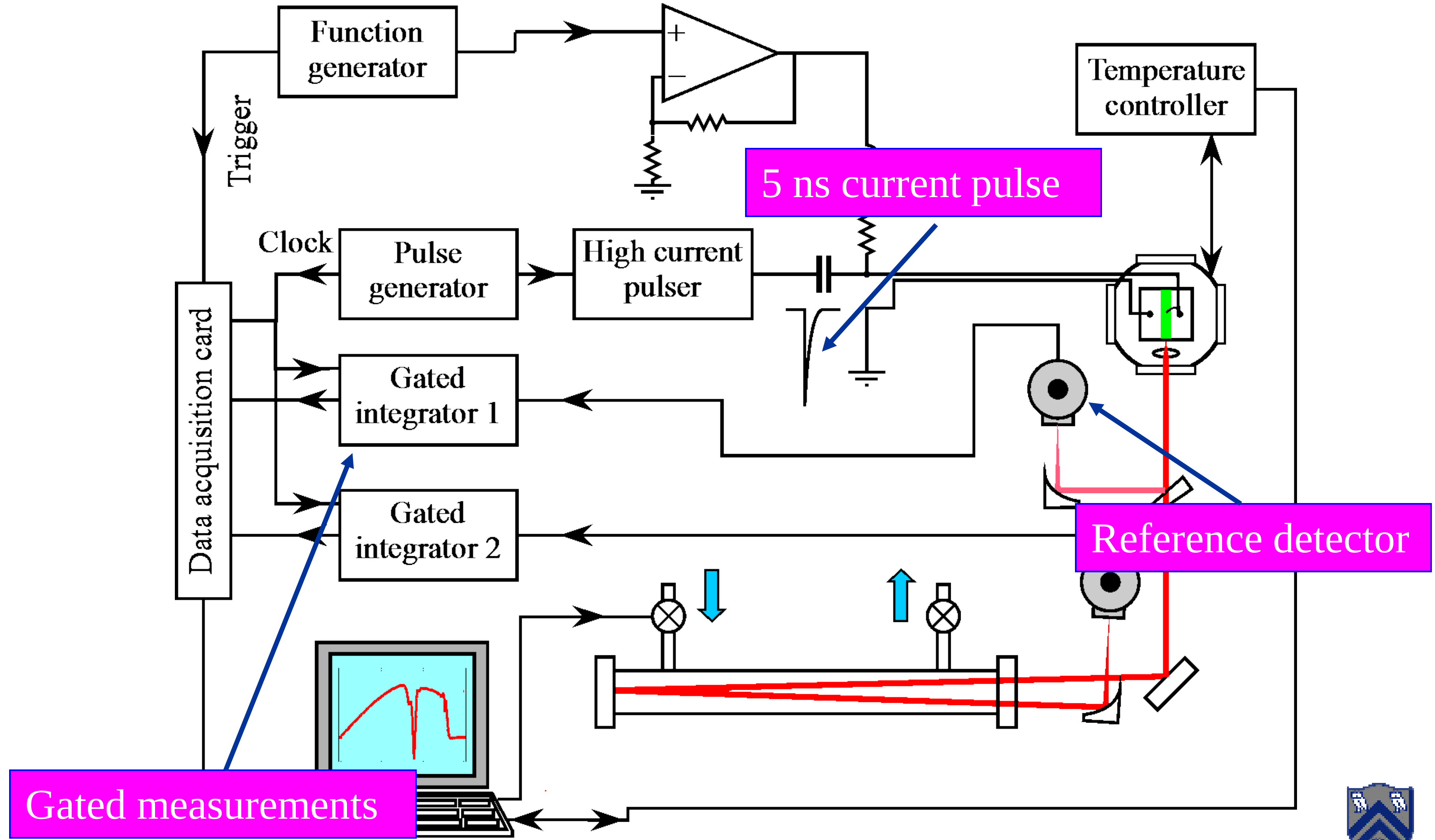
Two-channel data acquisition



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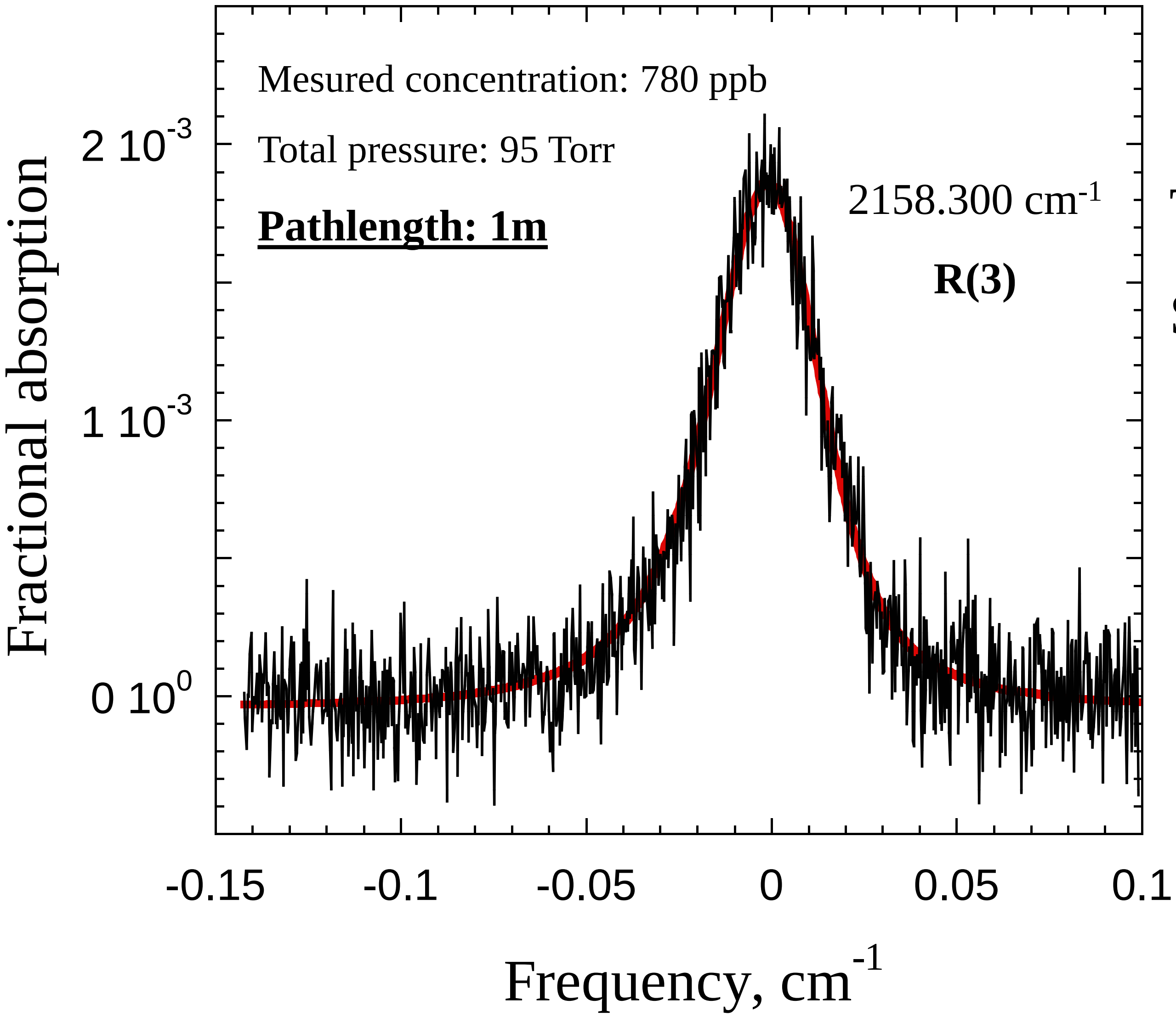
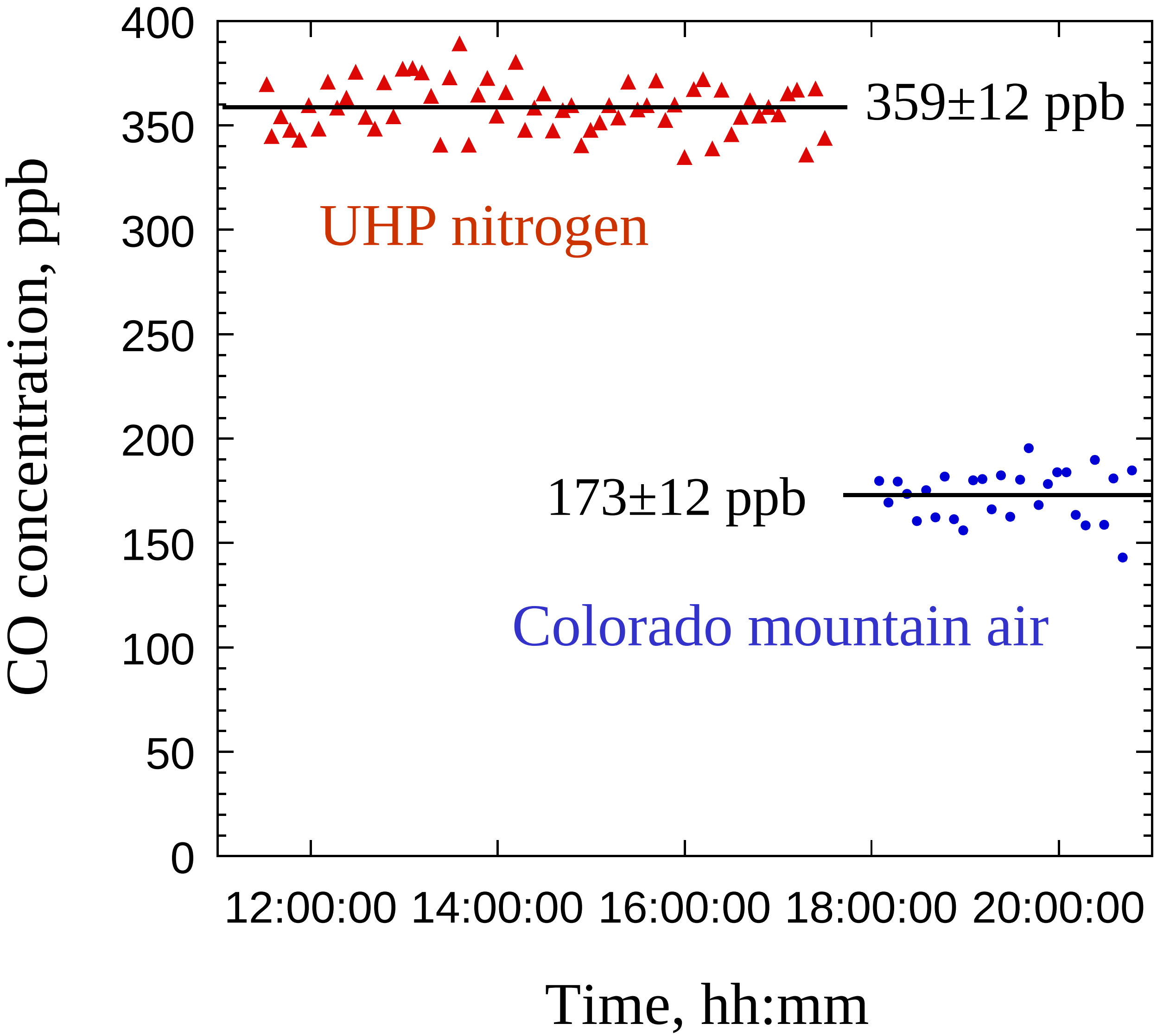
CO absorption: ambient air sample



Two IR detectors

Sensitivity ~10 ppb

CO concentration in two gas cylinders



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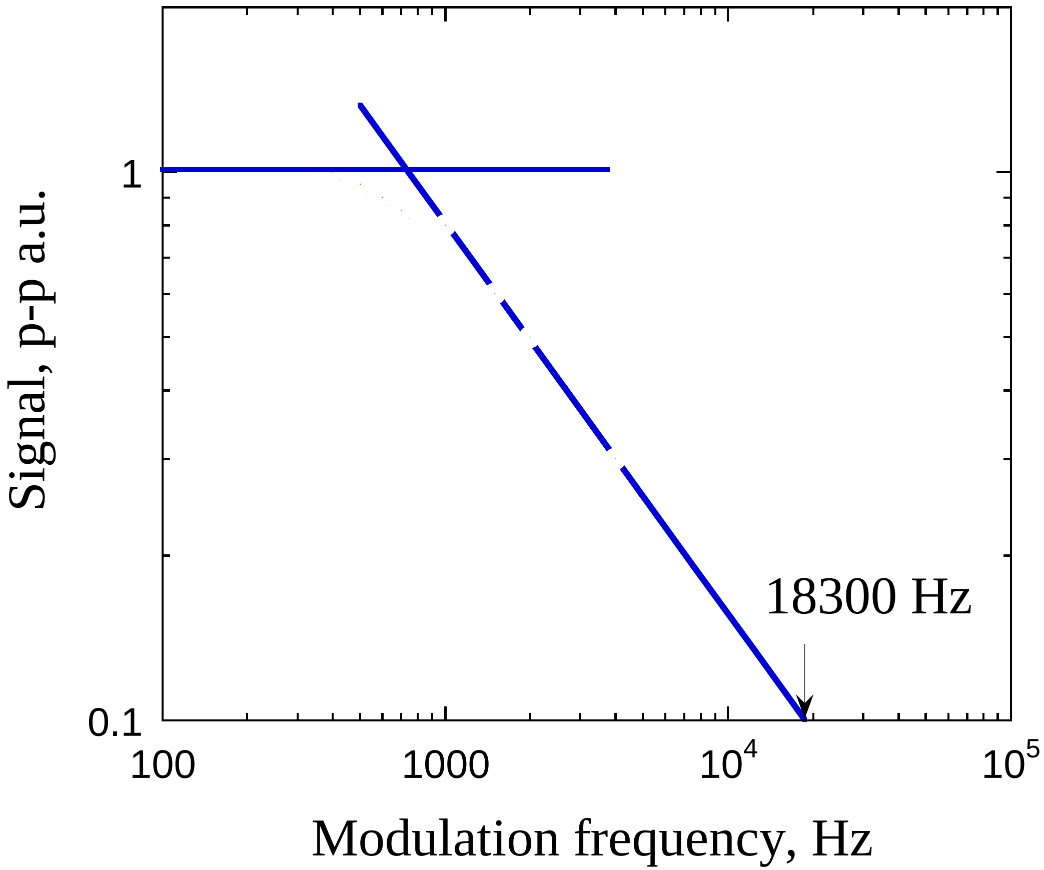
Longer wavelength: QC-DFB laser at λ=15.5 μm

- Fast sensitive detectors are not available
- Quantum detectors are expensive and LN2 cooled

  ! What about a thermal detector?

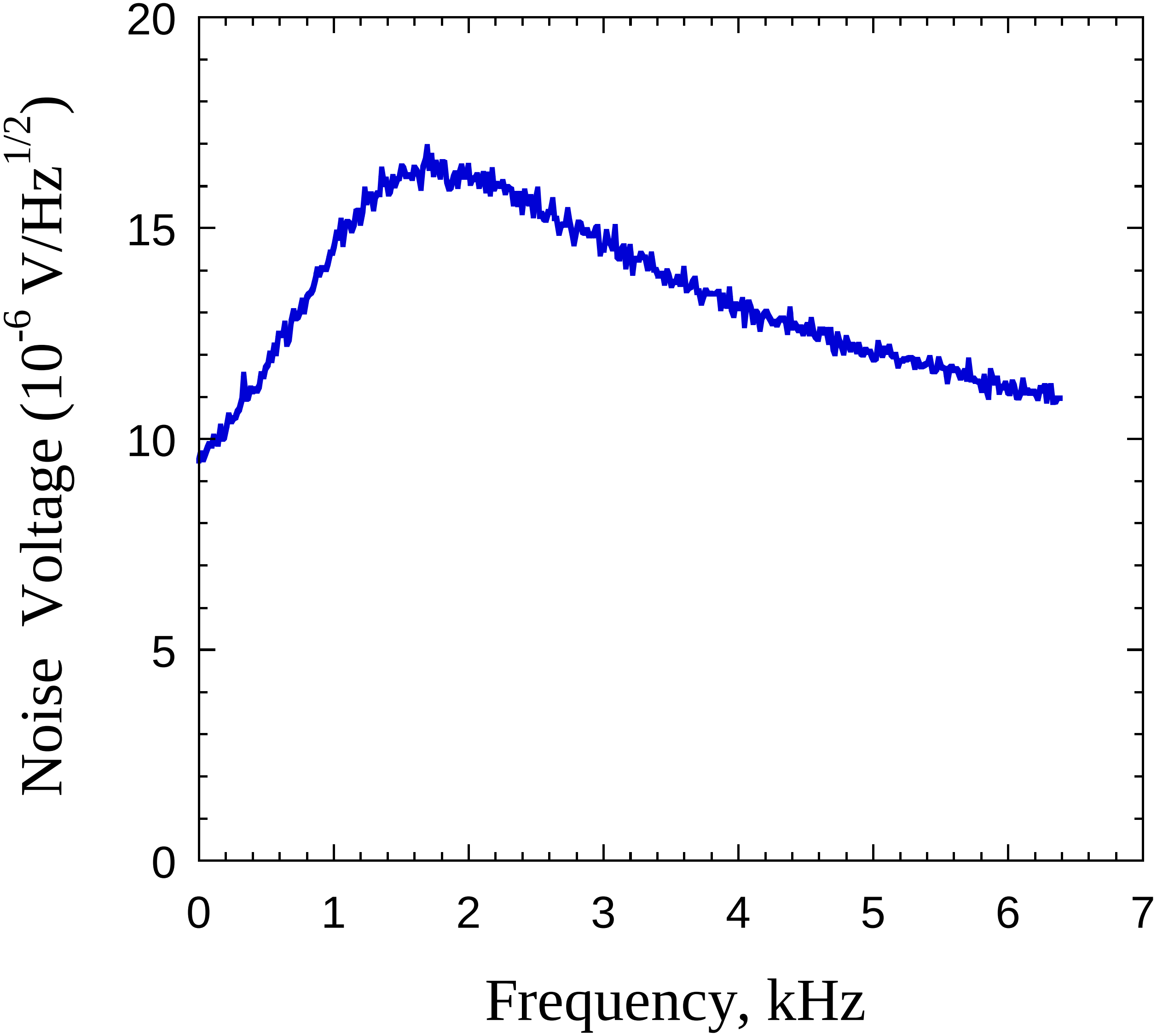
Pyroelectric detector and preamplifier



Detector/preamplifier band: 8 to 1150 Hz

Sensitivity: 3.84 V/mW

Pyroelectric detector noise and detectivity



IF:

f=200 Hz
Δf=1 Hz
W=100 μW

THEN:

SNR=38,000
Detectable absorption
$<3\times10^{-5}$

Longer wavelength: QC-DFB laser at λ=15.5 μm

- Operation current ~10A, peak thermal dissipation ~300W
  - Average dissipation >5W at 1 MHz repetition rate
- Low thermal tunability coefficient

! Alternative tuning method required

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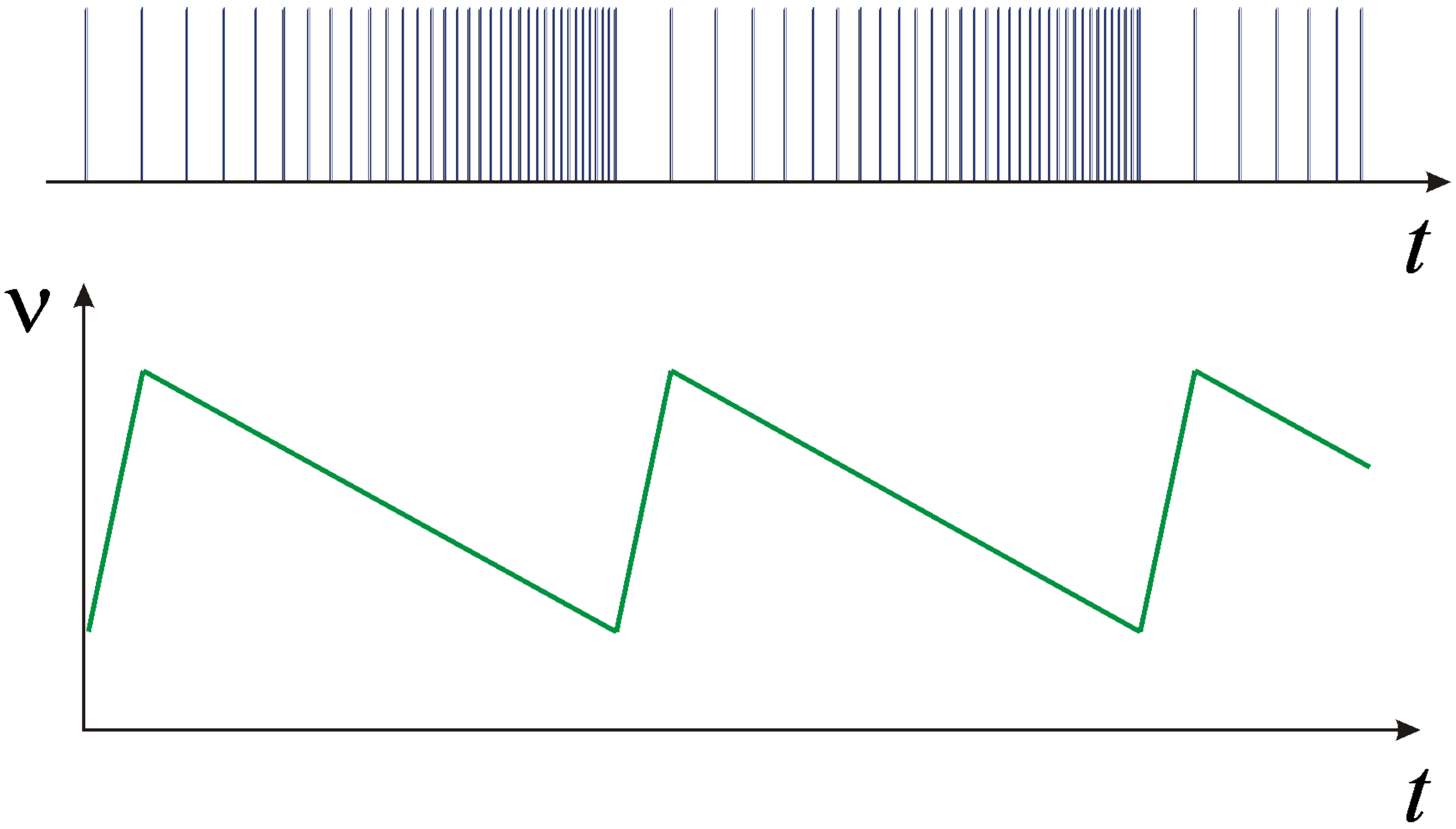
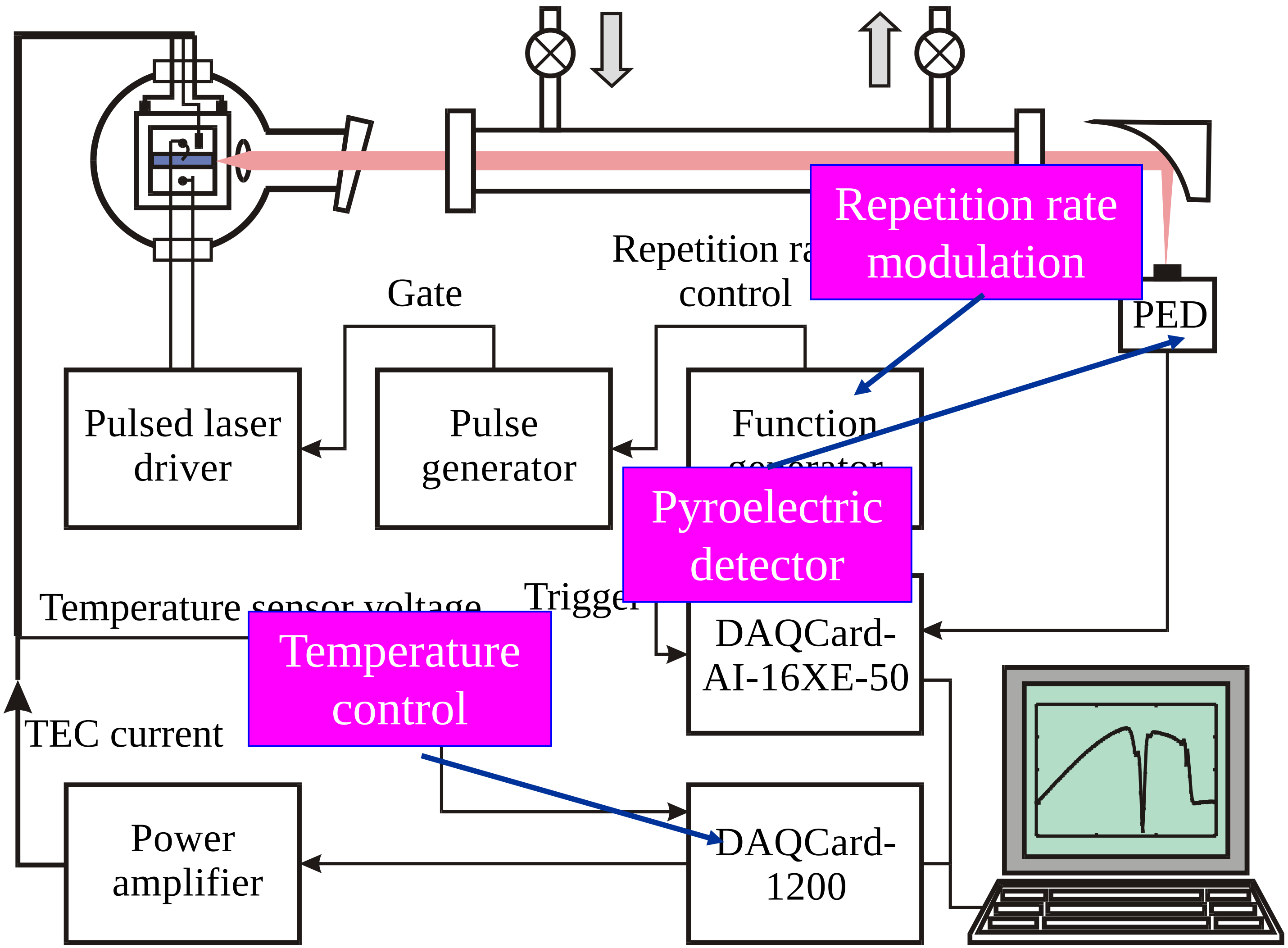
Frequency tuning of pulsed QC laser by using repetition rate modulation



16 μm QC laser based gas sensor



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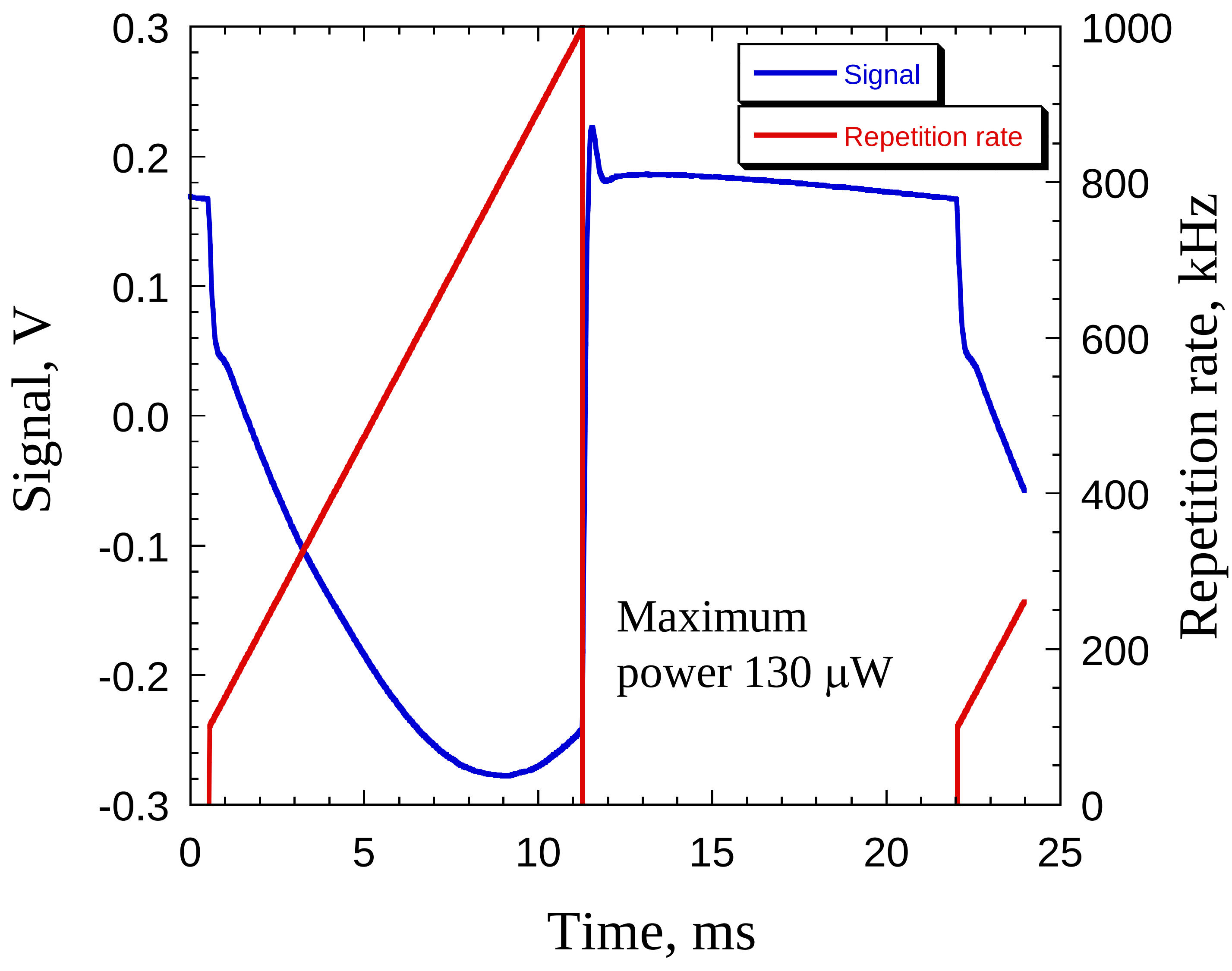
Fast wavelength scan by repetition rate modulation



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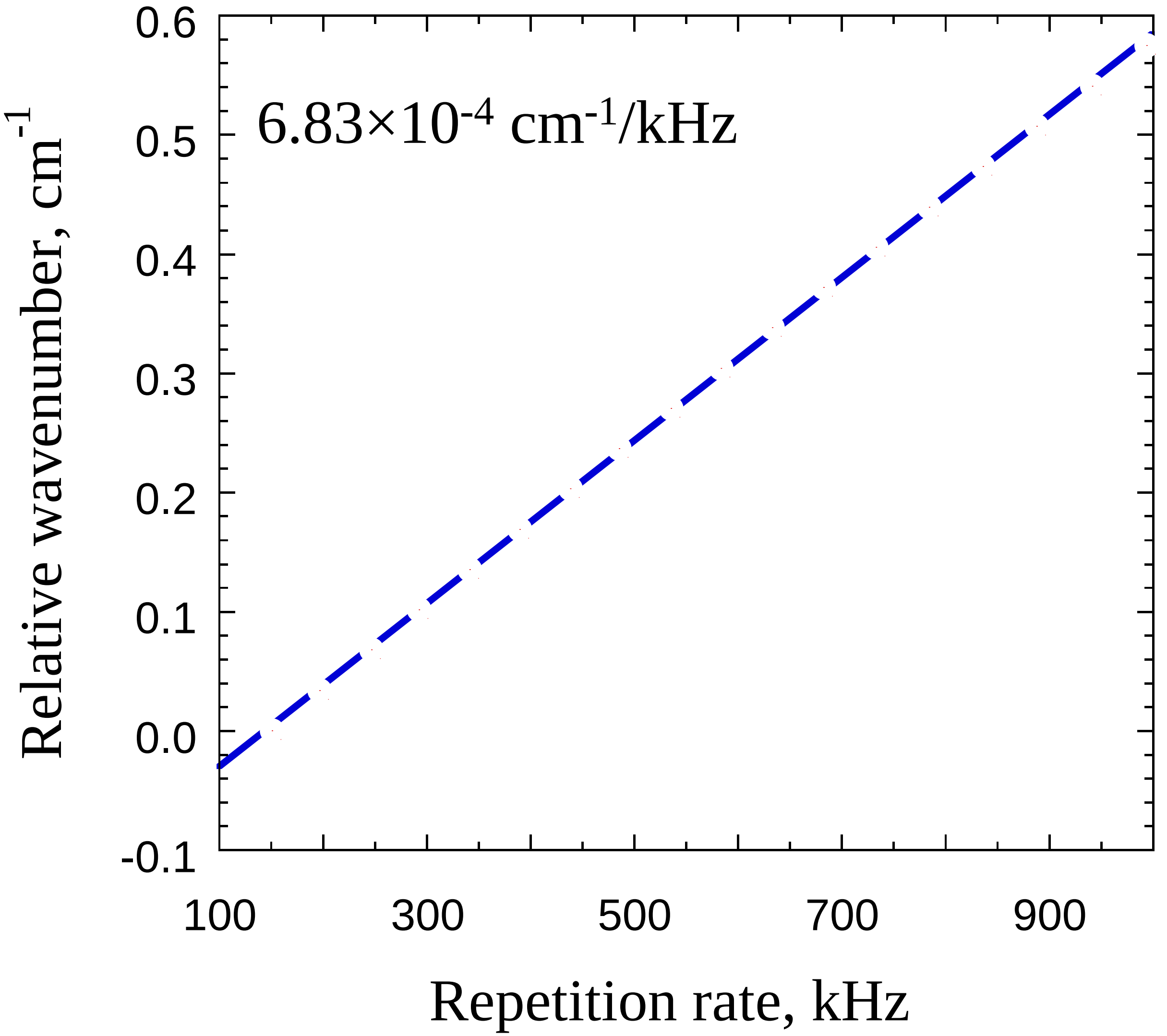
Calibration of fast wavelength scan



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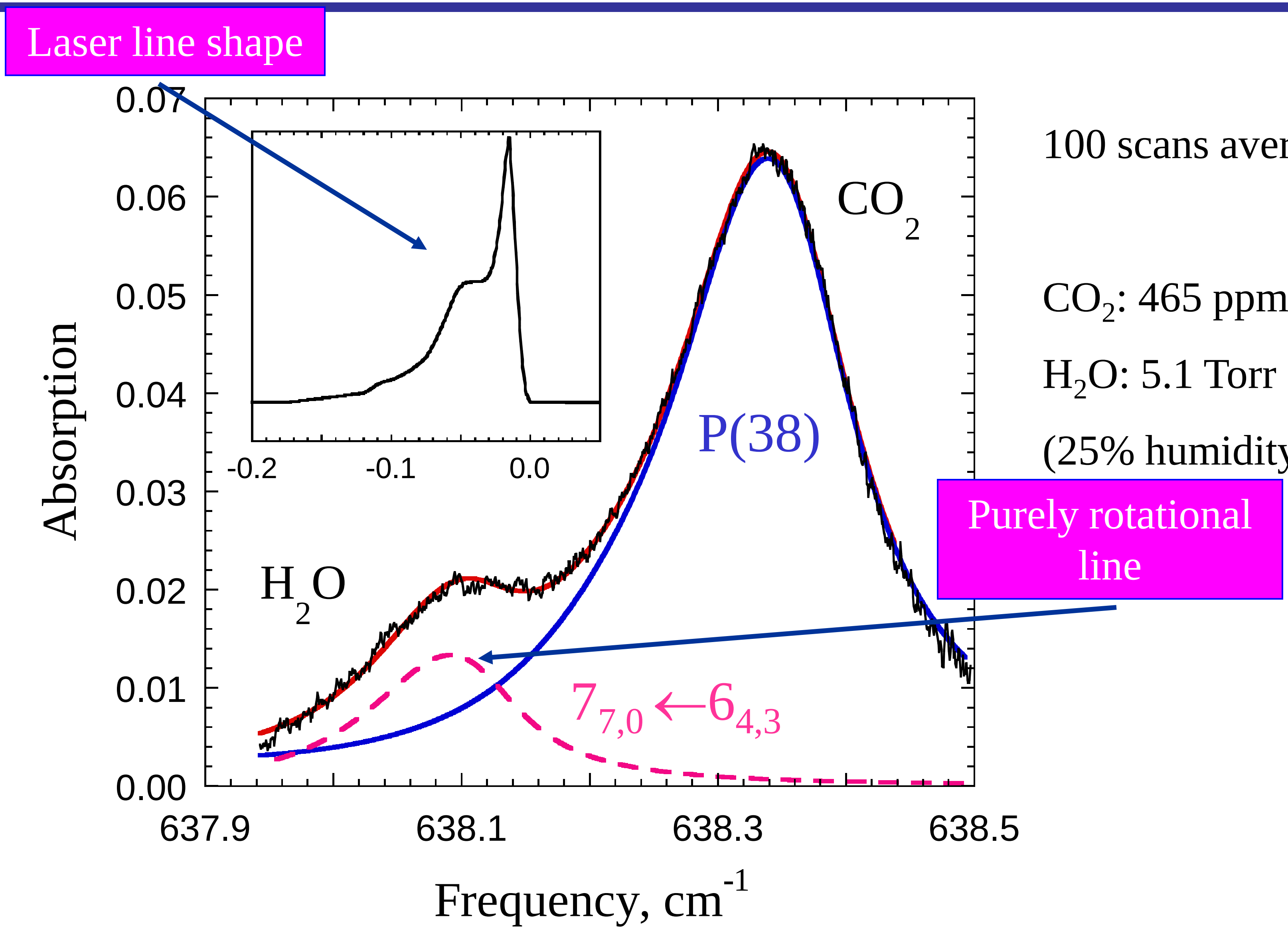
Ambient air absorption – 45 cm path, 1 atm



100 scans averaged

CO_2: 465 ppmv

H_2O: 5.1 Torr

(25% humidity - **???**)

Are CW QC lasers better?

Of course they are!

- Narrow linewidth without effort
- High average power

Can be used for such techniques as:

- Cavity ring-down spectroscopy
- Nonlinear (saturation) spectroscopy
- Photoacoustic spectroscopy

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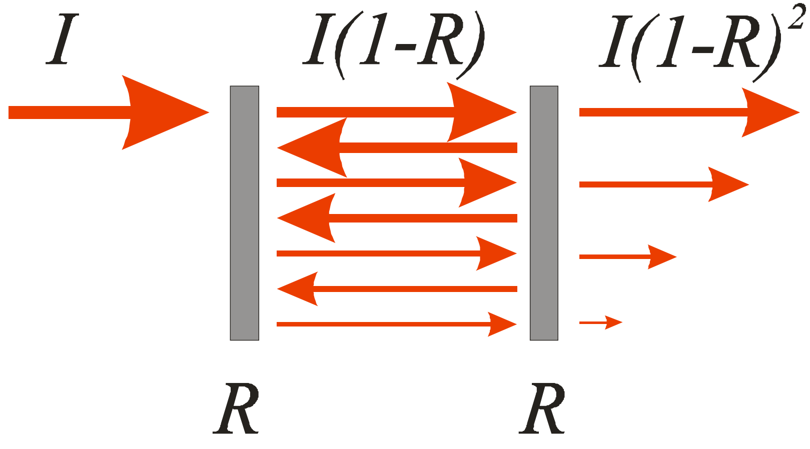
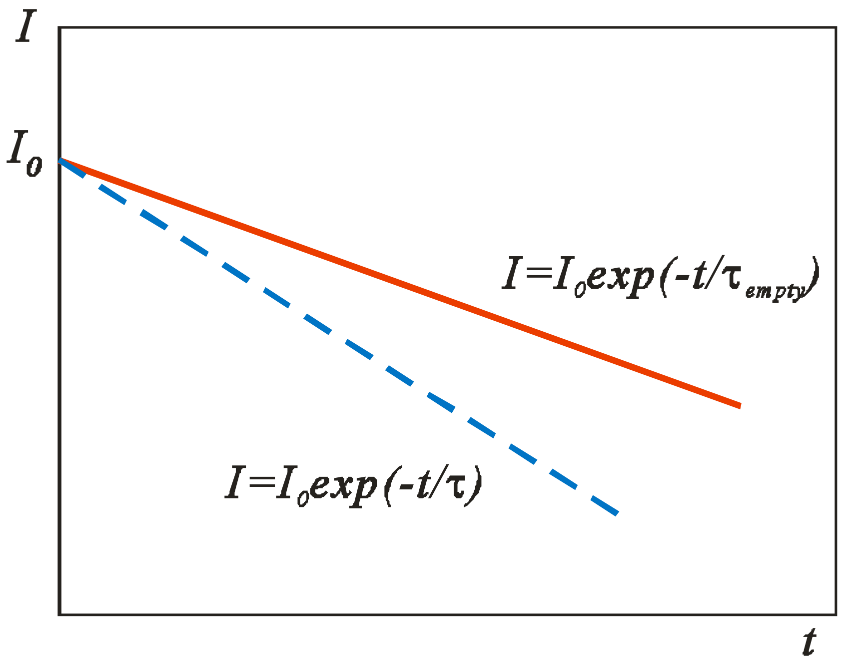
Cavity ring-down spectroscopy



$R>0.999...$

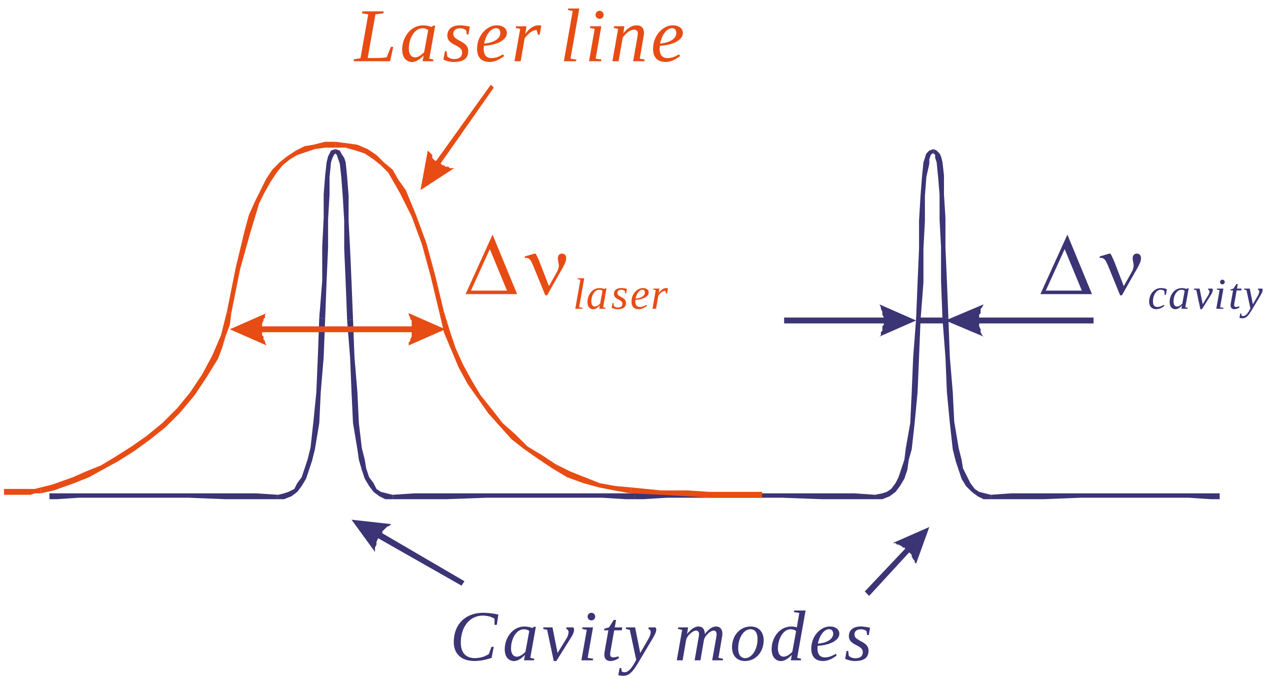


$$I = I_0 \exp\left(-\frac{t}{\tau}\right)$$

$$\tau = \frac{\boldsymbol{l}}{\boldsymbol{c}} \cdot \frac{1}{\alpha \boldsymbol{l} - \ln\sqrt{\boldsymbol{R}_1 \boldsymbol{R}_2}}$$

$$\alpha = \frac{1}{c}\left(\frac{1}{\tau} - \frac{1}{\tau_{empty}}\right)$$

Optical Cavity Transmission



$$T \approx \frac{\Delta\nu_{cavity}}{\Delta\nu_{laser}} \qquad \Delta\nu_{cavity} = \frac{c(1-R)}{2\pi d} = \frac{1}{2\pi\tau}$$

$$\tau = 3.5\mu s \quad \Rightarrow \quad \Delta\nu_{cavity} = 45\,\text{kHz};\ T = \frac{45\,\text{kHz}}{3\,\text{MHz}} = 1.5\%$$

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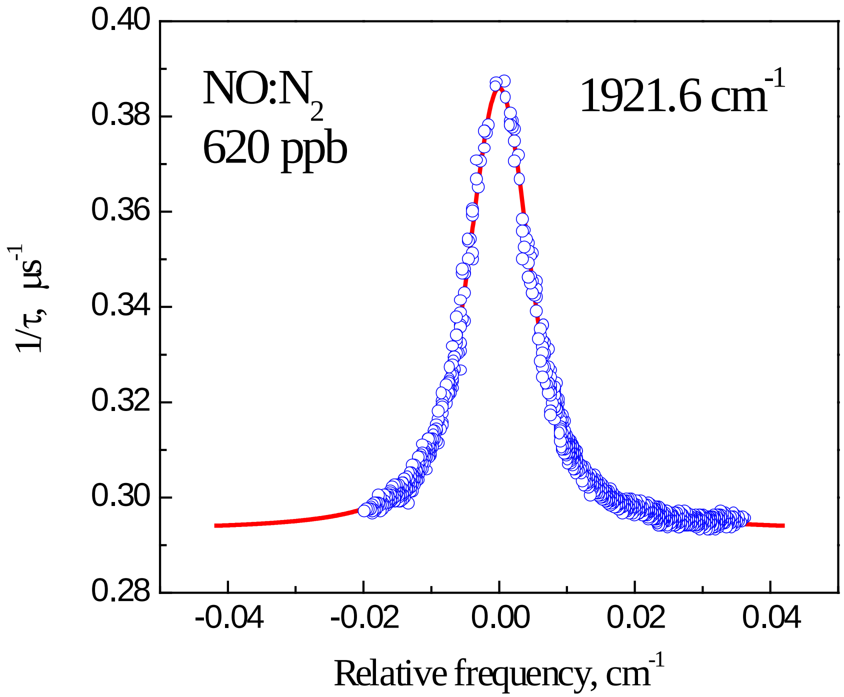
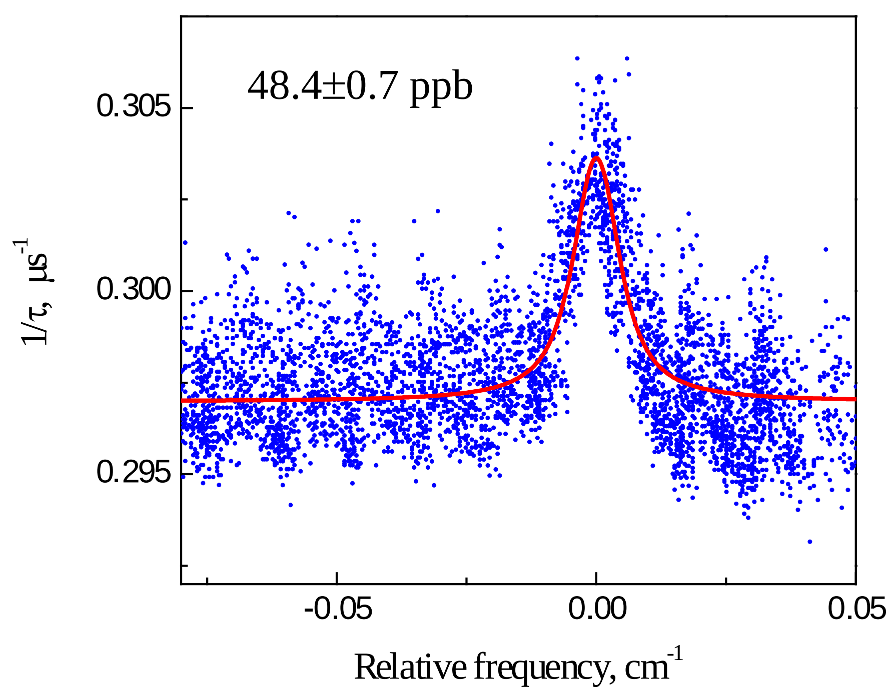
NO absorption, 60 Torr total pressure





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Summary

- QC-DFB lasers are powerful and robust sources for spectroscopic chemical detectors
- To date, commercially offered QC-DFB lasers are designed for pulsed operation mode with thermoelectric cooling
- Pulsed operation imposes specific limitations to the laser linewidth, noise, and power, which can be addressed by proper sensor design.
- CW QC-DFB lasers have better performance characteristics and allow the use of a wider range of high-sensitivity spectroscopic methods. However, most SW QC lasers require cryogenic cooling, and their availability is presently limited.

TE cooled CW QC-DFBs are coming!!!

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