SPIE. PHOTONICS WEST

Highly sensitive and rugged gas optical detection via interferometric cavity-assisted photothermal spectroscopy

31.01.2023

Davide Pinto
davide.pinto@tuwien.ac.at

OPTAPHI has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No. 860808

Outline

1. Motivation – Gas sensing
2. Laser spectroscopy for gas sensing: ICAPS
3. Experimental Setup & Results
4. Conclusion & Outlook

Outline

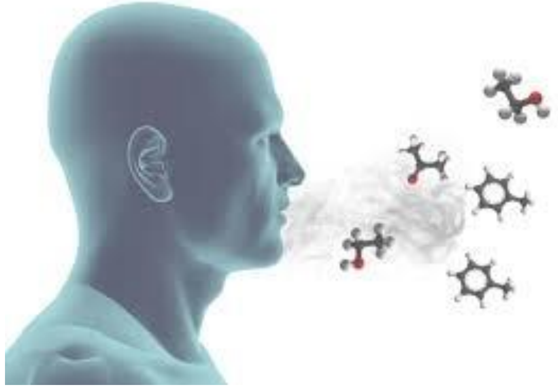
1. Motivation – Gas sensing
2. Laser spectroscopy for gas sensing: ICAPS
3. Experimental Setup & Results
4. Conclusion & Outlook

01 Motivation – Gas sensing

1. **Industrial Process Control**
   - Detection of leaks
   - In-line/on-line monitoring

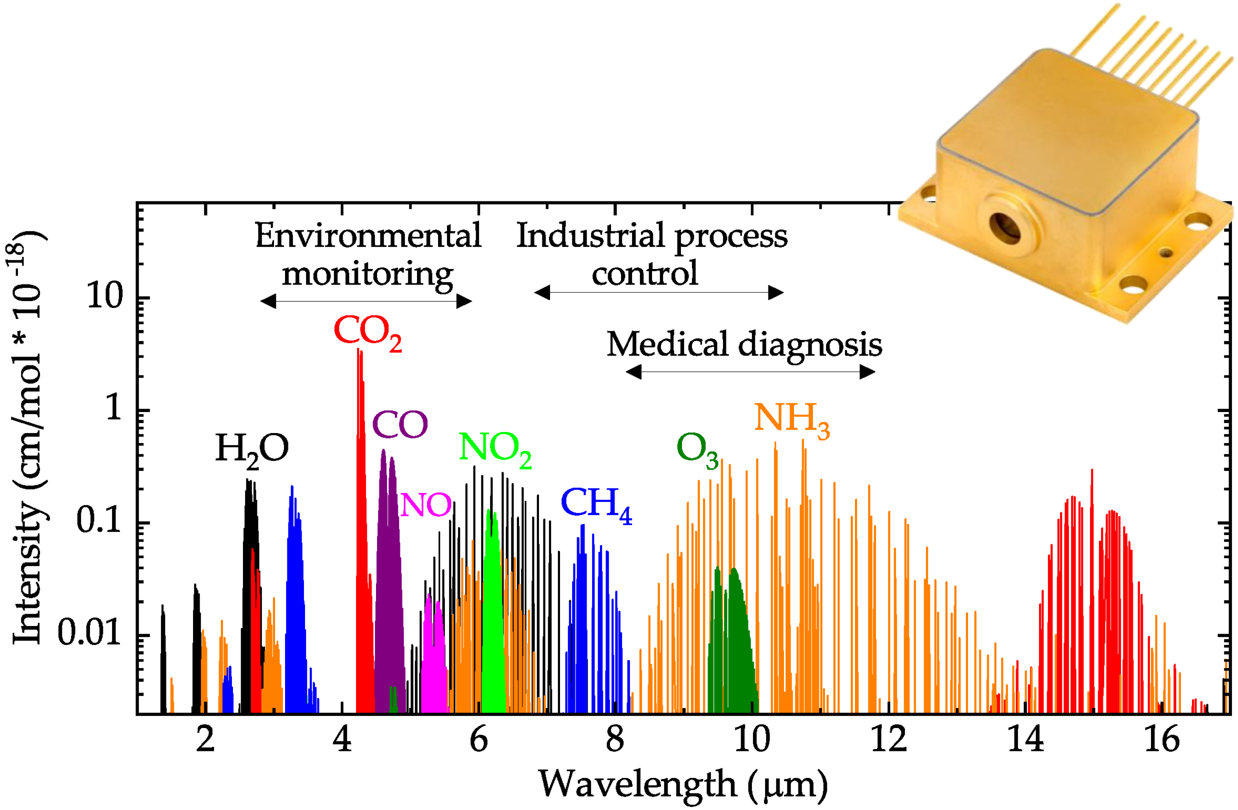
2. **Environmental Monitoring**
   - Greenhouse gases monitoring
   - Detection of toxic gases and pollutant

3. **Health and Life Science**
   - Breath analysis for early-stage disease detection



Why laser spectroscopy?

- High selectivity:
  roto-vibrational absorption lines can be targeted selectively to avoid cross-talking
- High sensitivity:
  many approaches are capable to achieve <u>sub-ppb</u> detection limits
- High speed measurement
- No sample treatment needed

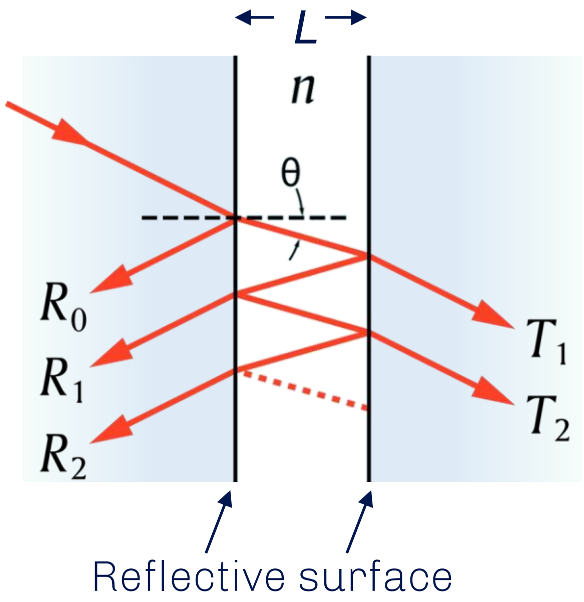


Outline

1. Motivation – Gas sensing
2. Laser spectroscopy for gas sensing: ICAPS
3. Experimental Setup & Results
4. Conclusion & Outlook

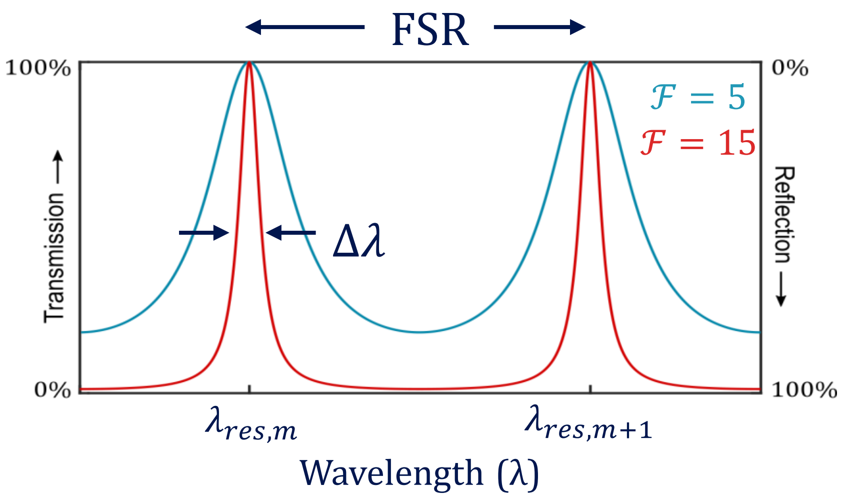
Direct absorption – TDLAS

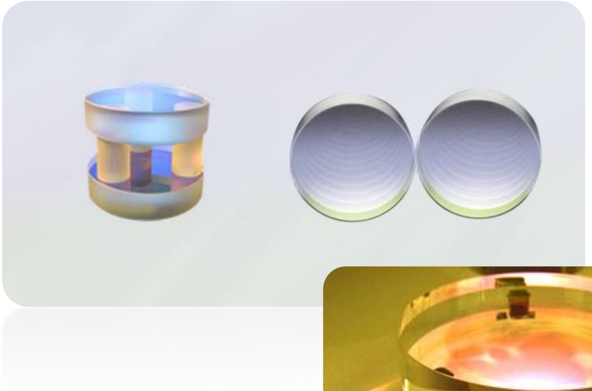
Indirect absorption – PAS, PTS

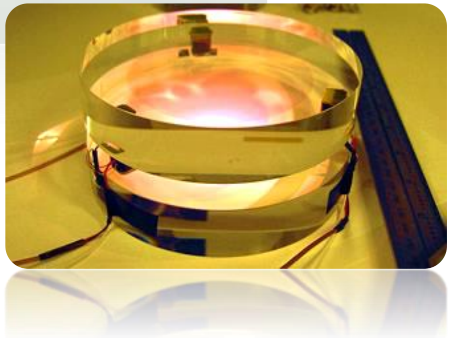


$$\mathcal{F} := \frac{\text{FSR}}{\Delta\lambda} = \frac{\pi\sqrt{R}}{1-R}$$

Interferometer Transfer Function







Reflected intensity:

$$I_R = I_0 \frac{4R\sin^2(\varphi)}{(1-R)^2 + 4R\sin^2(\varphi)}$$

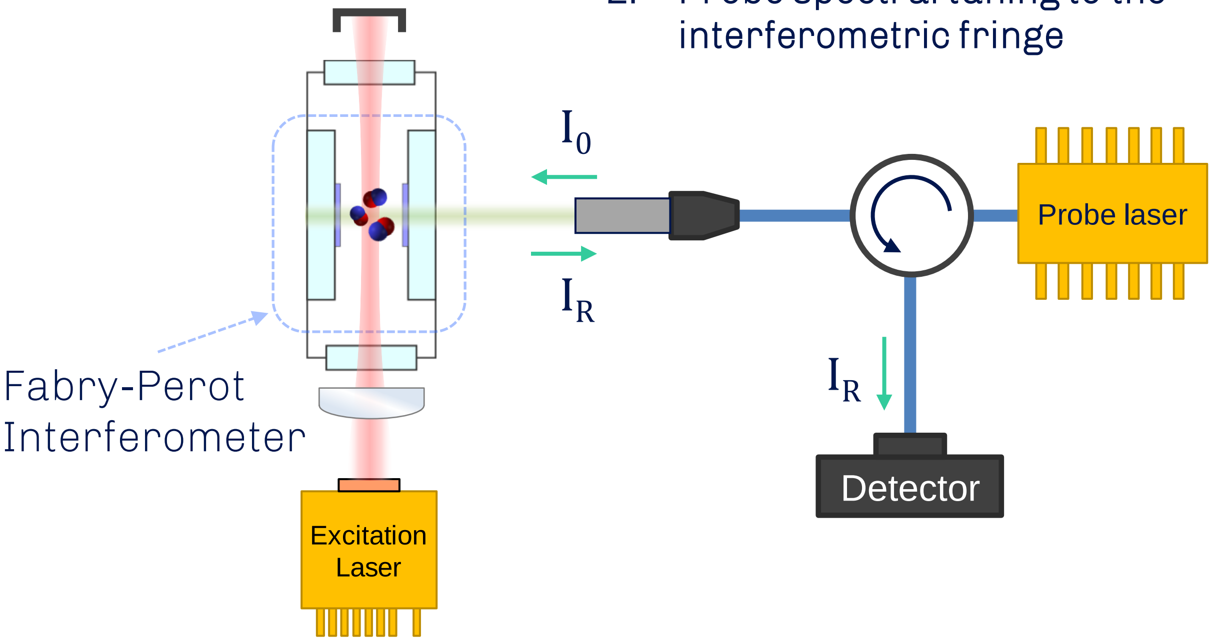
$$m\lambda_{res,m} = 2\boldsymbol{n}L\cos\theta$$

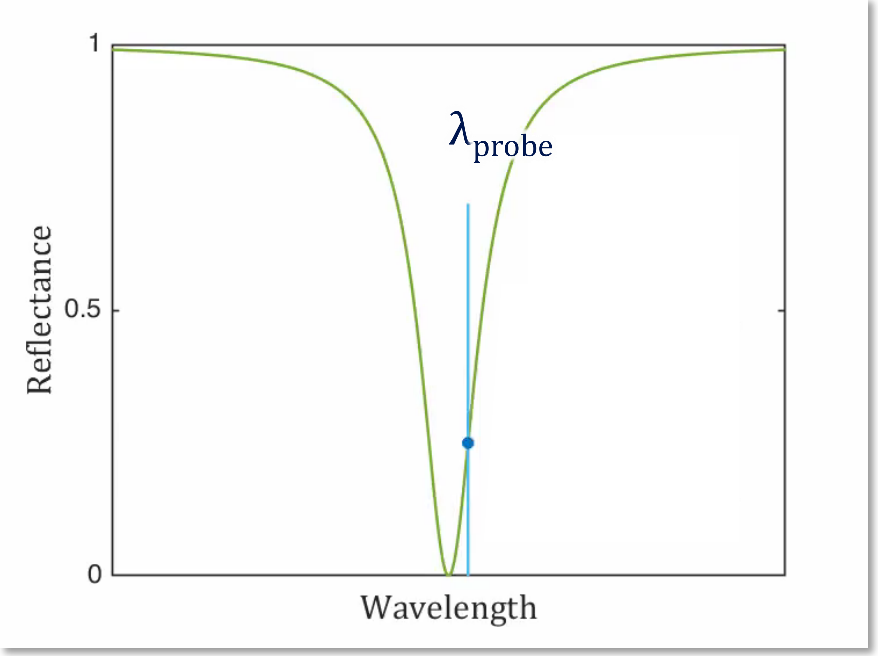
I_R	Reflected intensity
I_0	Incident intensity
R	Mirror reflectivity
λ_{res}	Resonance wavelength
$\boldsymbol{n}$	Medium refractive index
m	Integer number

ICAPS principle

Fundamental conditions:

1. Spatial overlap of probe and excitation beams
2. Probe spectral tuning to the interferometric fringe





On the side-fringe (inflection point):

1. δn Transduced linearly as δI_R

2. The higher the Finesse, the higher will be the sensitivity towards photothermal effect

Clausius-Mossotti approximation: $\delta n = -\frac{n_0 - 1}{T_{abs}} \delta T$

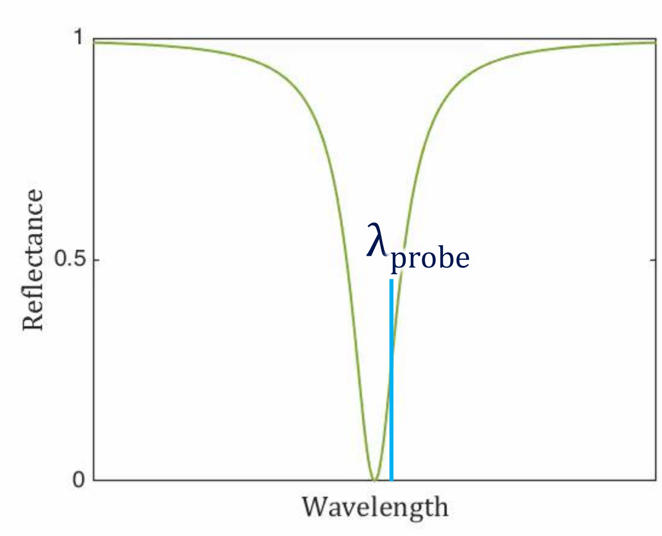
[1] D. Pinto, J.P. Waclawek, S. Lindner, H. Moser, G. Ricchiuti, B. Lendl, Wavelength modulated diode probe laser for an interferometric cavity-assisted photothermal spectroscopy gas sensor, Sensors and Actuators B: Chemical. 377 (2023) 133061. doi:10.1016/j.snb.2022.133061.

Interferometer stability

- In real-case scenarios, many parameters affect the **interferometer stability**:

- Temperature
- Pressure
- Gas composition

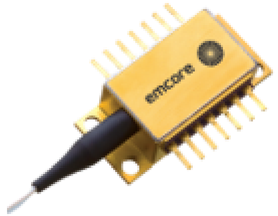
→ Affect the refractive index

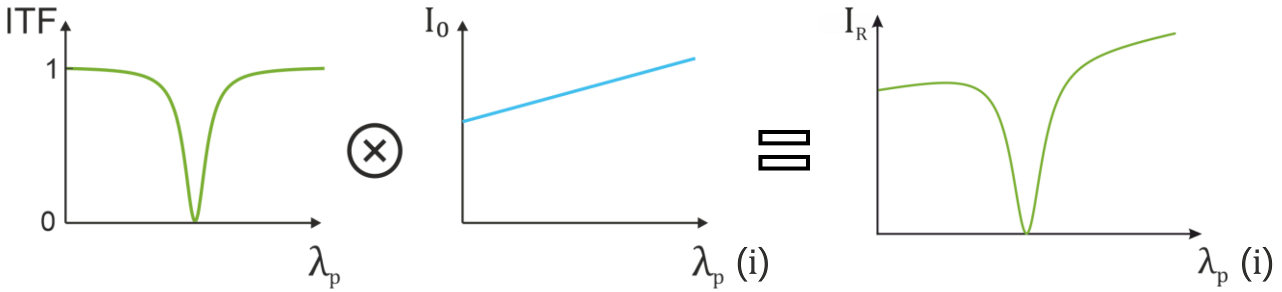


!

- **Probe laser** must be locked to the inflection point to compensate for drifts

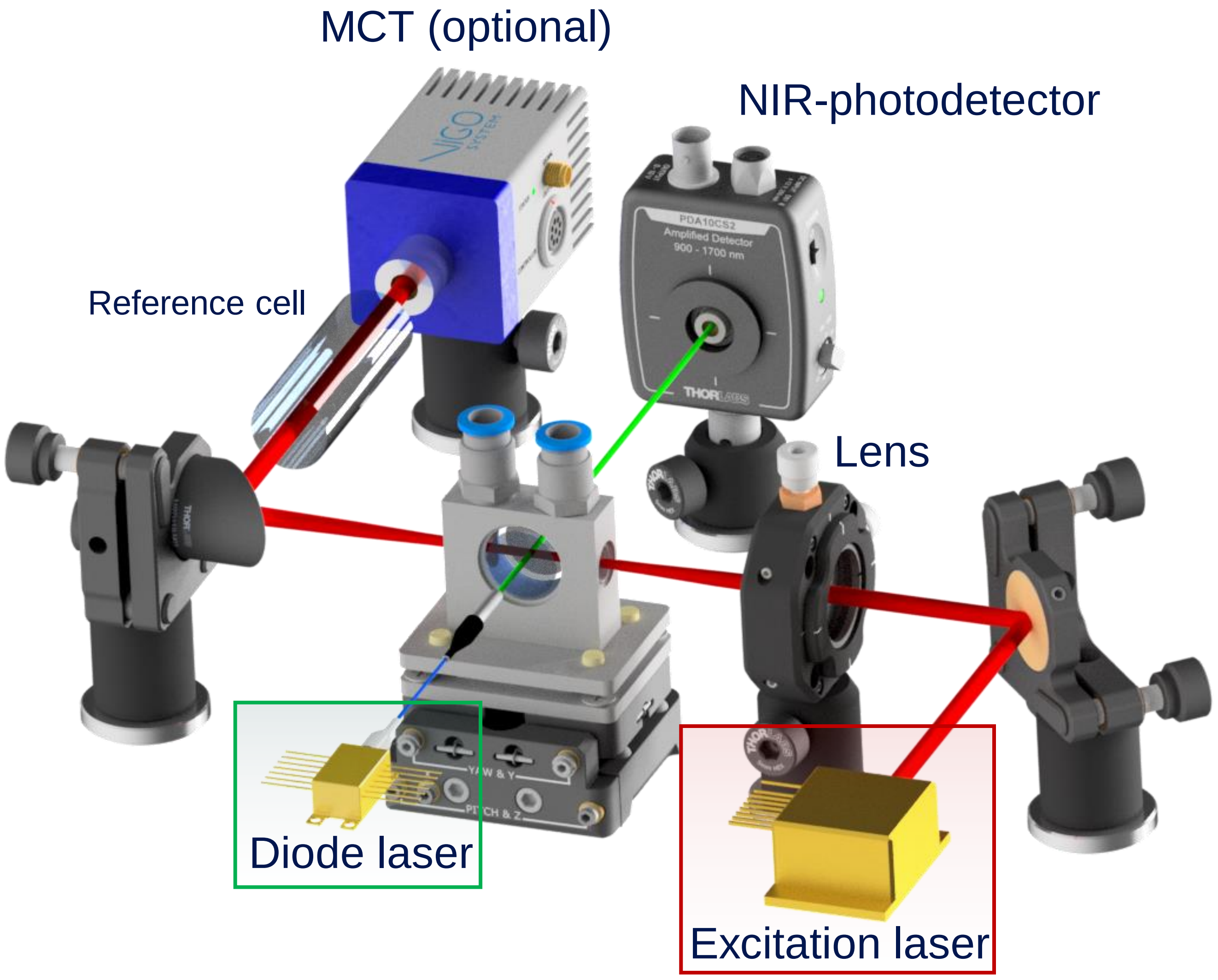
- **Diode lasers** are capable of fast **wavelength tuning** by acting on the bias current. However, also the **emitted optical intensity** (I_0) changes as a **function of the current**!

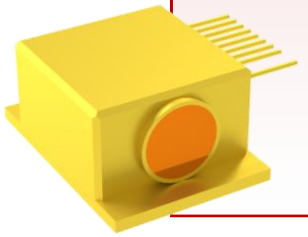




Outline

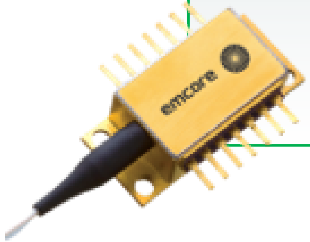
1. Motivation – Gas sensing
2. Laser spectroscopy for gas sensing: ICAPS
3. Experimental Setup & Results
4. Conclusion & Outlook





Excitation laser:

- CW-DFB-QCL @ 5.26 μm ($1900\ cm^{-1}$)
- Optical Power $30\ mW$



Probe diode laser:

- CW-DFB-DL telecom @ 1552 nm

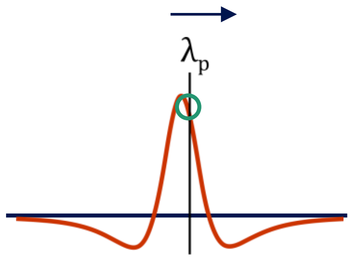
NIR detector

Shift in detection from **MID-IR** to **NIR**, where photodetectors are cheaper and perform better.

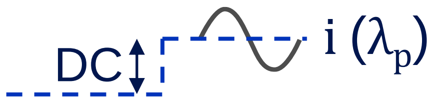
2f zero-crossing locking

Current dithering of probe

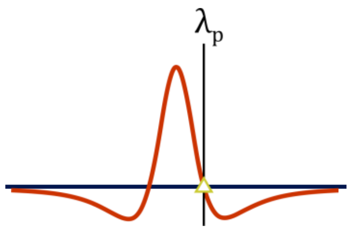
2nd harmonic signal used as error signal

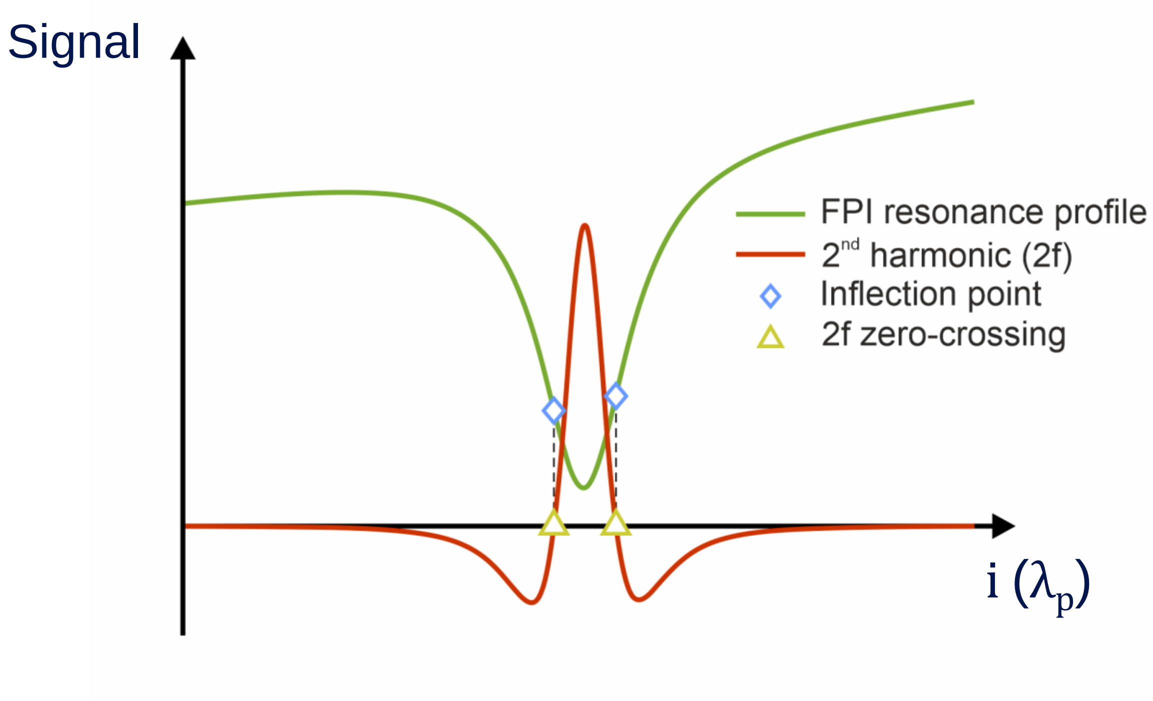


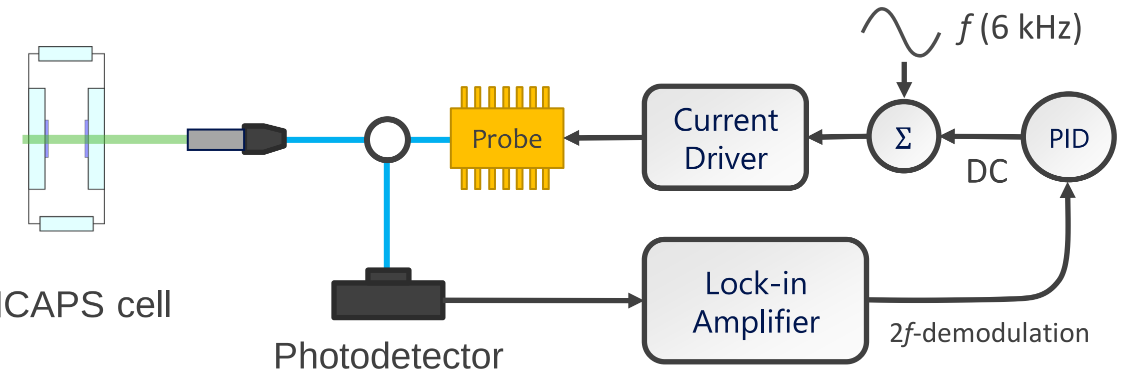
PID controller acts on probe DC current



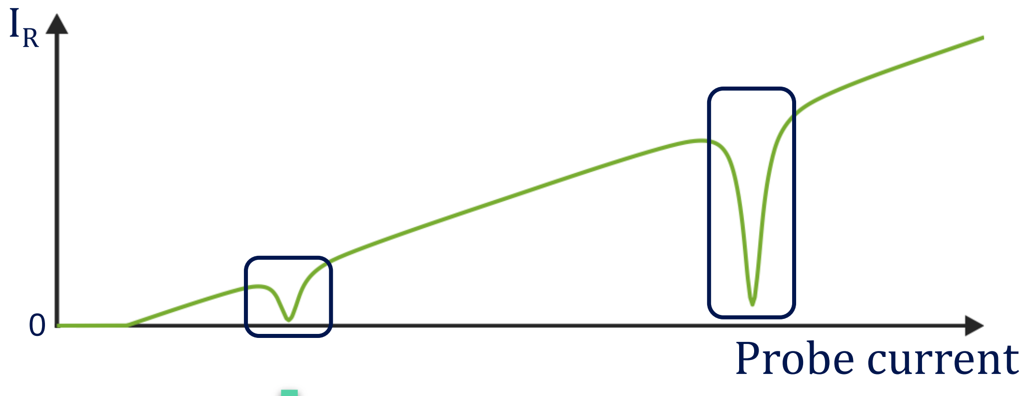
2nd harmonic signal kept to zero-crossing



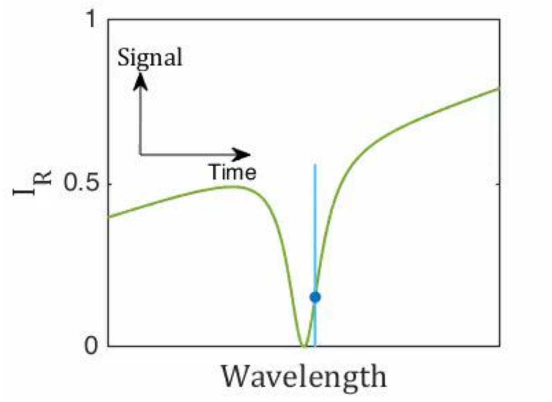




Normalization scheme



! **Probe wavelength is modulated for locking purposes**

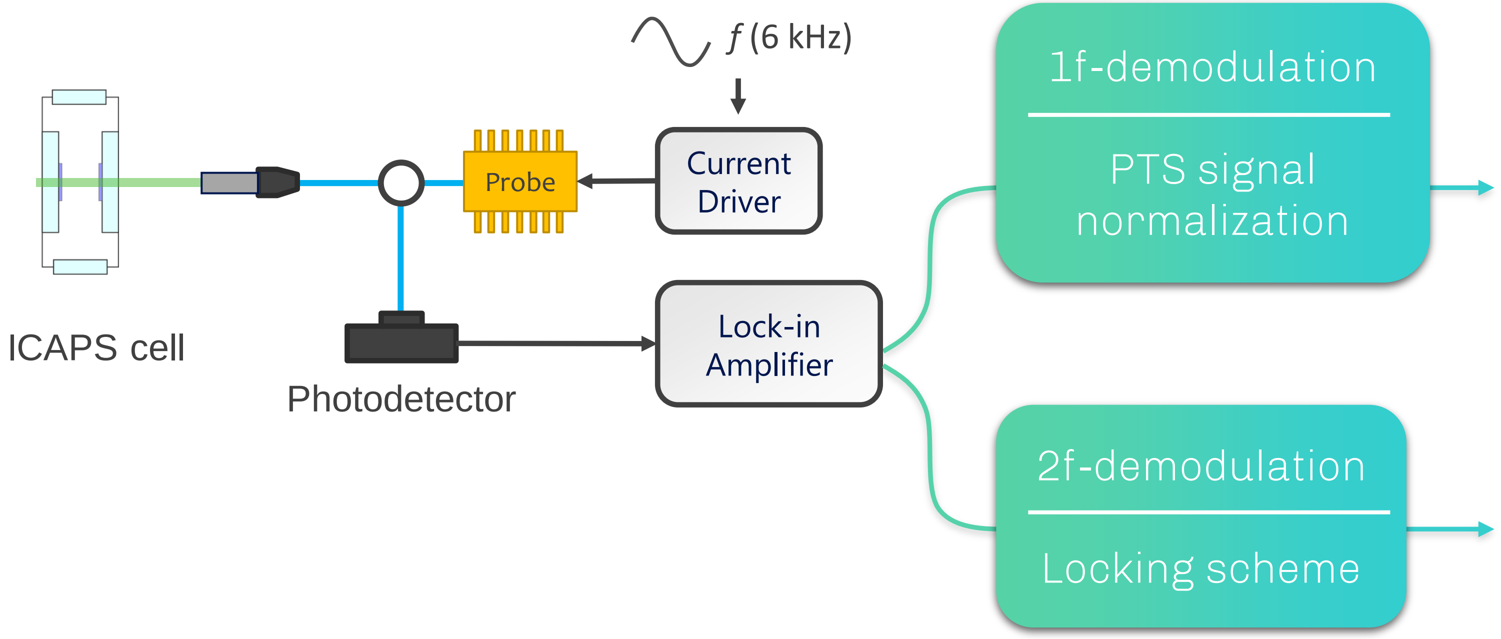


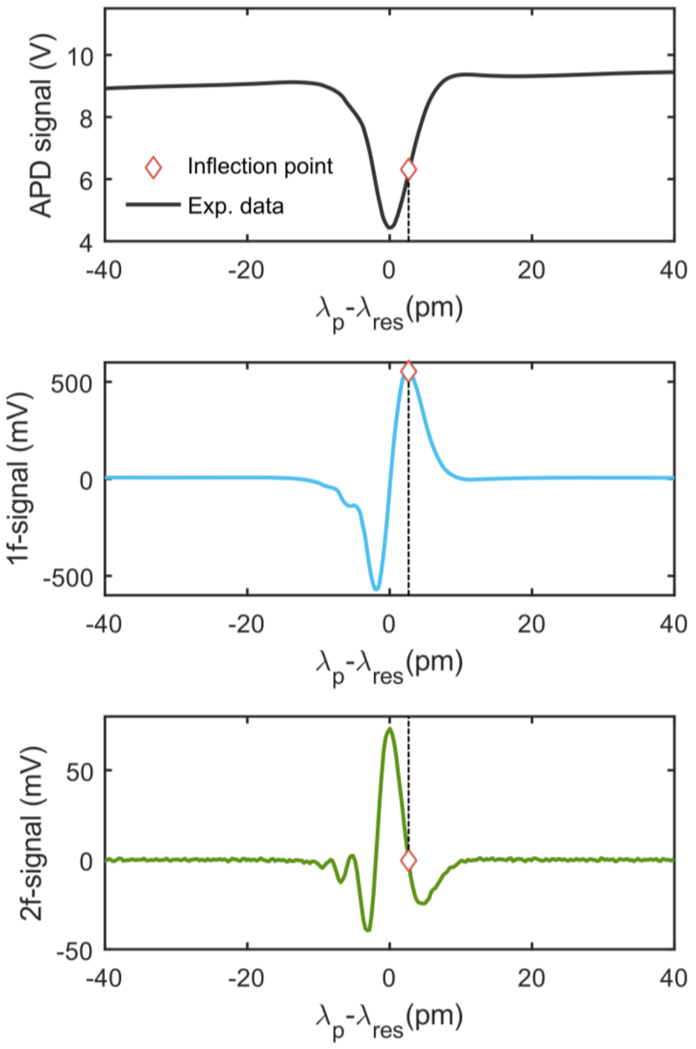
Real-time investigation of the interferometer

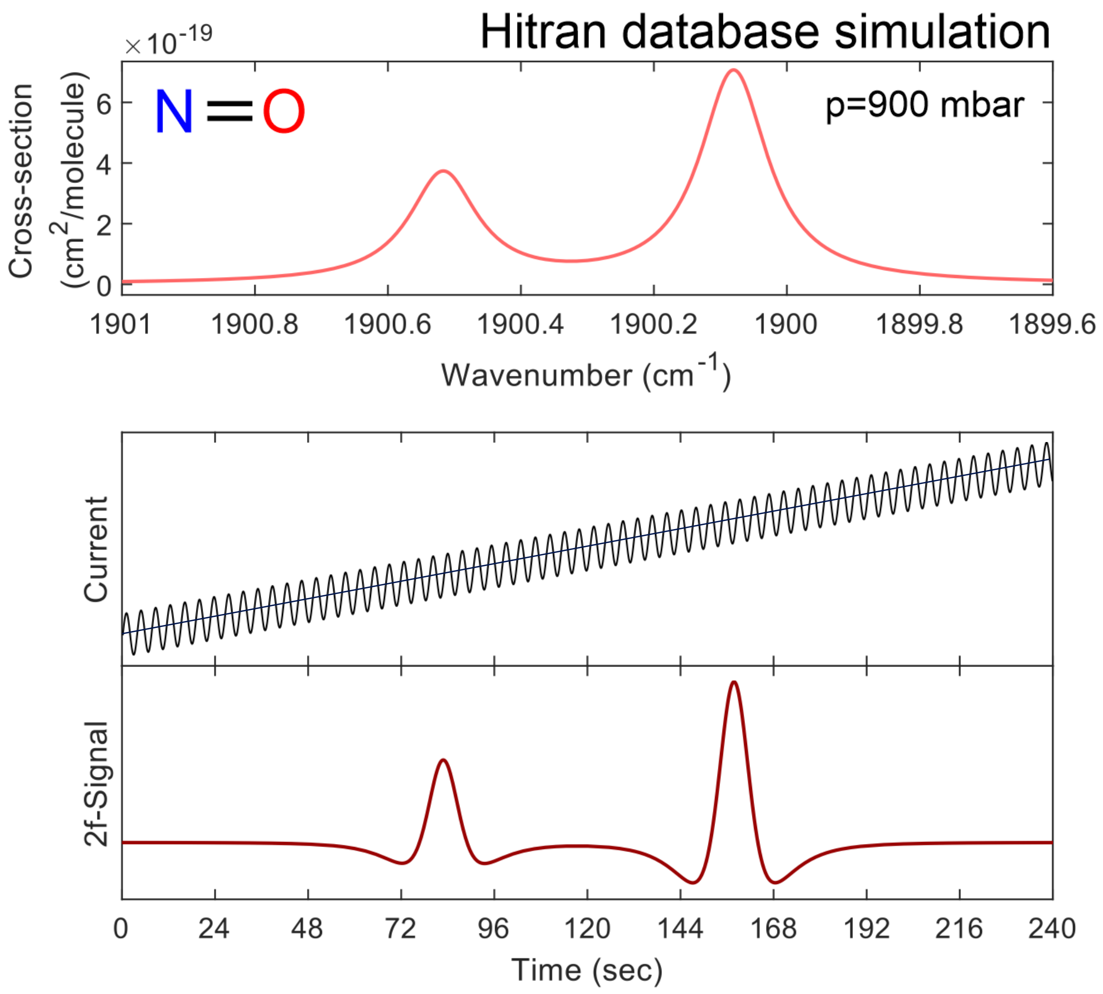
System sensitivity depends upon:

1. incident intensity
2. interferometric fringe quality

Summary of the probe line







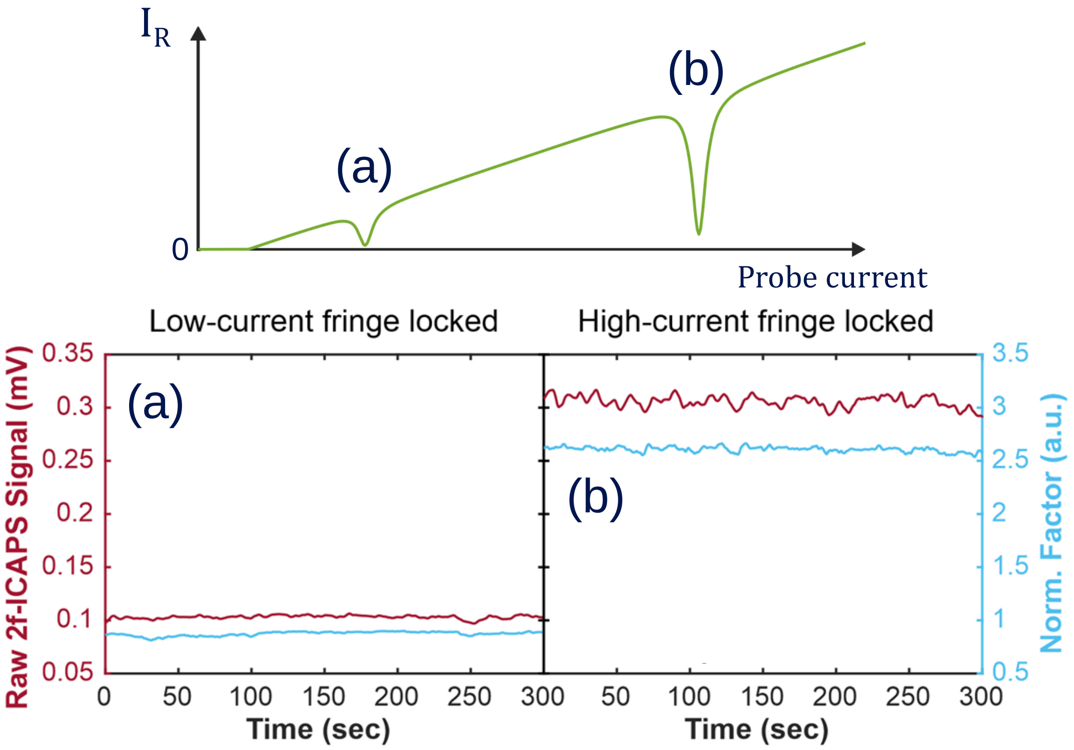
QCL current is modulated with a sine wave (f_{exc}) and scanned across the analyte absorption line

The signal is demodulated at the 2nd harmonic ($2f_{exc}$)

- ✓ Background free technique
- ✓ Peak value stores the analytical information

Proof of normalization

1. A constant PTS signal was generated (97.5 ppm of NO/N_2)
2. The PTS signal was transduced at low-current and high-current fringes
3. The PTS signal is normalized to the probe 1f-demodulated signal (ratio of red and blue curves)
4. Normalized signal doesn't depend upon:
   - Interferometer quality (aging)
   - Varying optical intensity

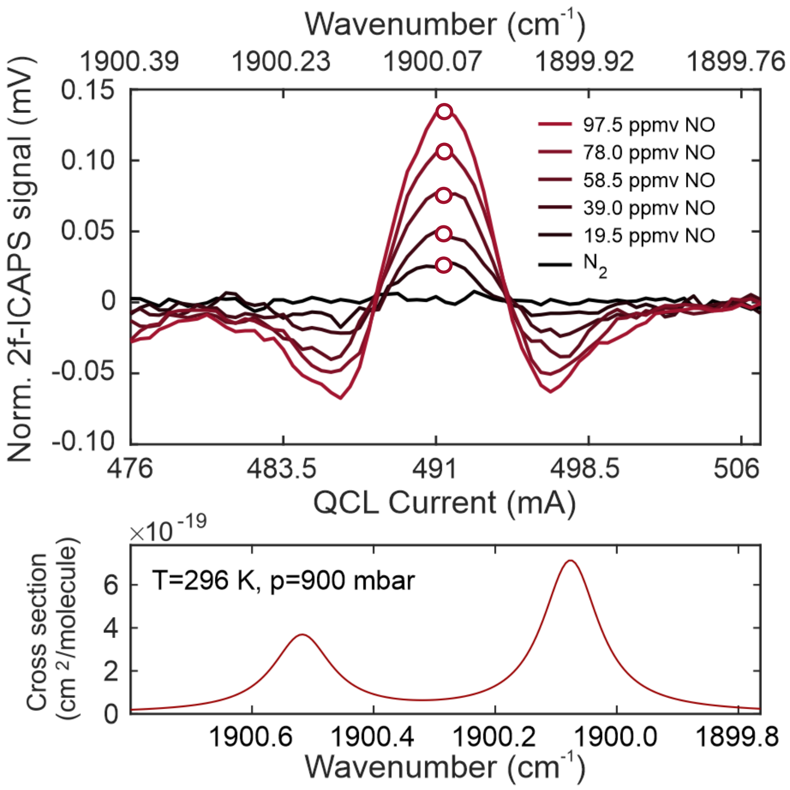


Photothermal signal

Normalization factor

Ratio only depends upon gas concentration

Spectral Scan

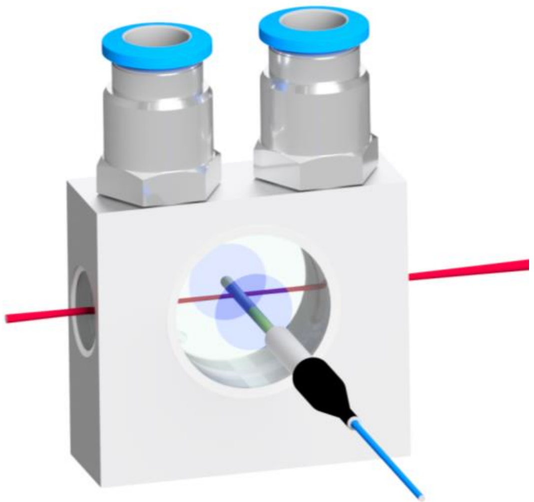


- ✓ Excellent linearity ($R^2 = 0.999$) in the whole concentration range
- ✓ $NEC = \frac{1\sigma_{noise}}{\text{sensitivity}} \approx 2\ \text{ppm}$
- ✓ $NNEA = \frac{P\alpha_{min}}{\sqrt{\Delta f}} \sim 3 \cdot 10^{-6}\ \text{W cm}^{-1}\text{Hz}^{-\frac{1}{2}}$

$(\alpha_{min} \approx 3 \cdot 10^{-5}\ \text{cm}^{-1})$

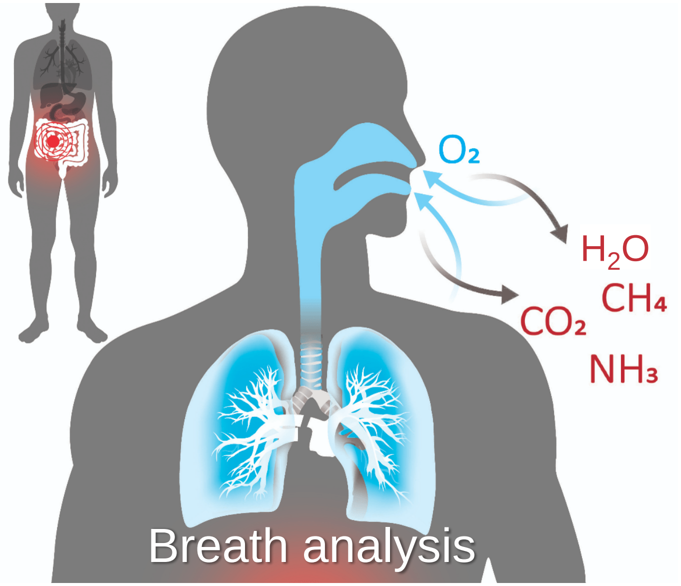
Outline

1. Motivation – Gas sensing
2. Laser spectroscopy for gas sensing: ICAPS
3. Experimental Setup & Results
4. Conclusion & Outlook



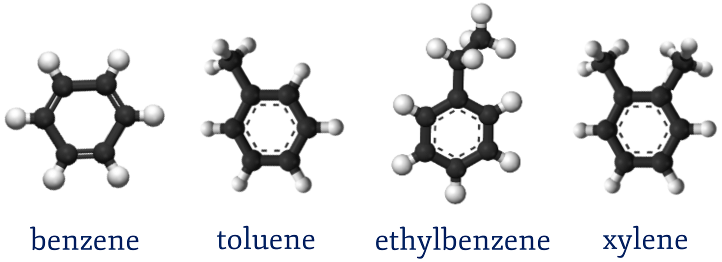
Advantages over other techniques

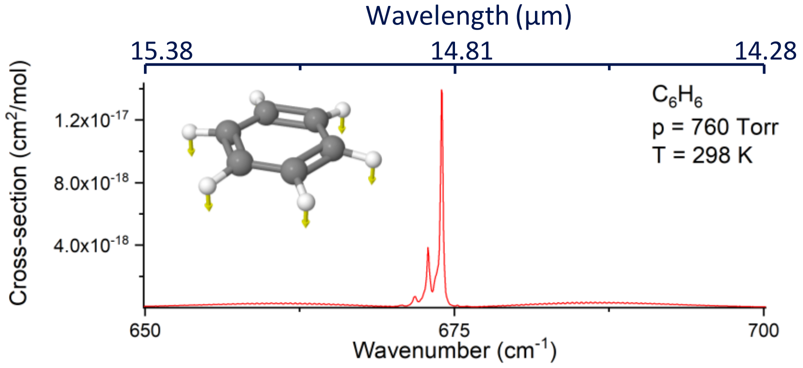
- ✓ Reduced sensing volume: design of portable and rugged sensors
- ✓ Modulation frequency can be freely tuned: fundamental for slow relaxing gases
- ✓ Open for many applications!



04 Outlooks

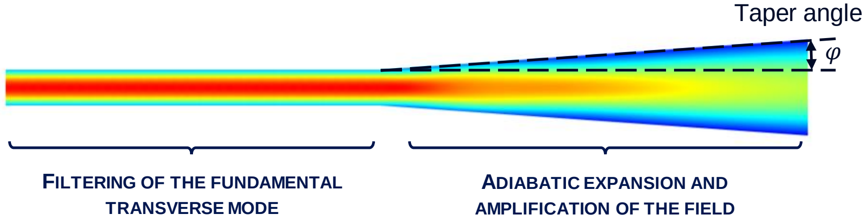
- Long-wavelength QCLs for BTEX detection

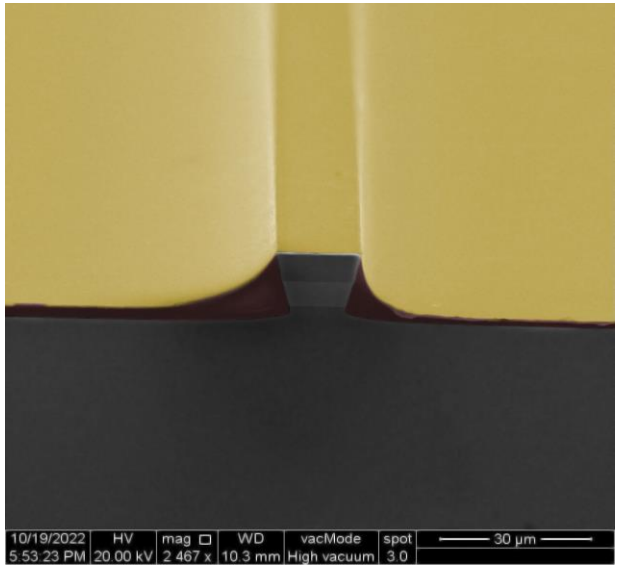


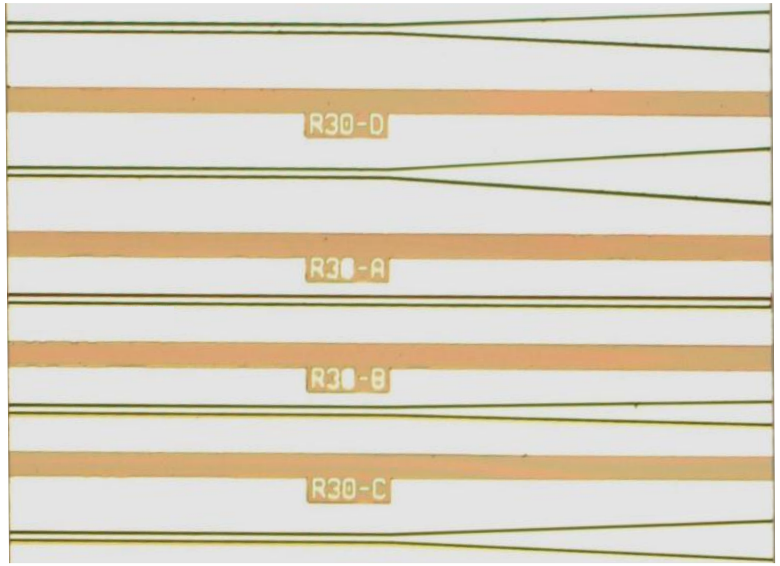


- Tapered QCLs for improved optical power output

$$PTS\ signal \propto \frac{P_{exc}\alpha}{fV}$$







POSTER 12430-90

Tapered quantum cascade lasers in the long-wavelength mid-infrared region

Mercoledì, Febbraio 1 • 18:00 - 20:00
Moscone Center, Level 2 West

Thank you for your attention

Special thanks to the ones contributing to this work:

- Paul Waclawek
- Harald Moser
- Stefan Lindner
- Giovanna Ricchiuti
- Bernhard Lendl

And the CAVS and Nanomir Groups

This project has received fundings from the European Union's Horizon 2020 research and innovation programme under the Marie Curie Grant Agreement n° 860808