The state-of-the-art and grand challenges of mid-infrared technology and applications

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OUTLINE

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Institute of Physics PAS, Warsaw, Poland

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- New Laser Based Trace Gas Sensor Technology
  - Novel Multipass Absorption Cell & Electronics
  - Quartz Enhanced Photoacoustic Spectroscopy
- Examples of Mid-Infrared Sensor Architectures
  - C_2H_6, NH_3, NO, CO, SO_2, CH_4 & N_2O
  - Future Directions of Laser Based Gas Sensor Technology and Conclusions

Research support by NSF ERC MIRTHE, NSF-ANR NexCILAS, the Robert Welch Foundation, Scinovation, Inc. and Sentinel Photonics Inc. via an EPA Phase 1 SBIR sub-award is acknowledged

Wide Range of Trace Gas Sensing Applications

- **Urban and Industrial Emission Measurements**
  - Industrial Plants
  - Combustion Sources and Processes (e.g. fire detection)
  - Automobile, Truck, Aircraft and Marine Emissions
- **Rural Emission Measurements**
  - Agriculture & Forestry, Livestock
- **Environmental Monitoring**
  - Atmospheric Chemistry (e.g. isotopic signatures)
  - Volcanic Emissions
- **Chemical Analysis and Industrial Process Control**
  - Petrochemical, Semiconductor, Nuclear Safeguards, Pharmaceutical, Metals Processing, Food & Beverage Industries
- **Spacecraft and Planetary Surface Monitoring**
  - Crew Health Maintenance & Life Support
- **Applications in Medical Diagnostics and the Life Sciences**
- **Technologies for Law Enforcement, Defense and Security**
- **Fundamental Science and Photochemistry**

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Laser based Trace Gas Sensing Techniques

- **Optimum Molecular Absorbing Transition**
  - Overtone or Combination Bands (NIR)
  - Fundamental Absorption Bands (MID-IR)
- **Long Optical Pathlength**
  - Multipass Absorption Cell (White, Herriot (Aerodyne), Chernin and Sentinel Photonics, Inc)
  - Cavity Enhanced and Cavity Ringdown Spectroscopy
  - Open Path Monitoring (with retro-reflector): Standoff and Remote Detection
  - Fiberoptic Evanescent Wave Spectroscopy
- **Spectroscopic Detection Schemes**
  - Frequency or Wavelength Modulation
  - Balanced Detection
  - Zero-air Subtraction
  - Photoacoustic & Quartz Enhanced Photoacoustic Spectroscopy (QEPAS)

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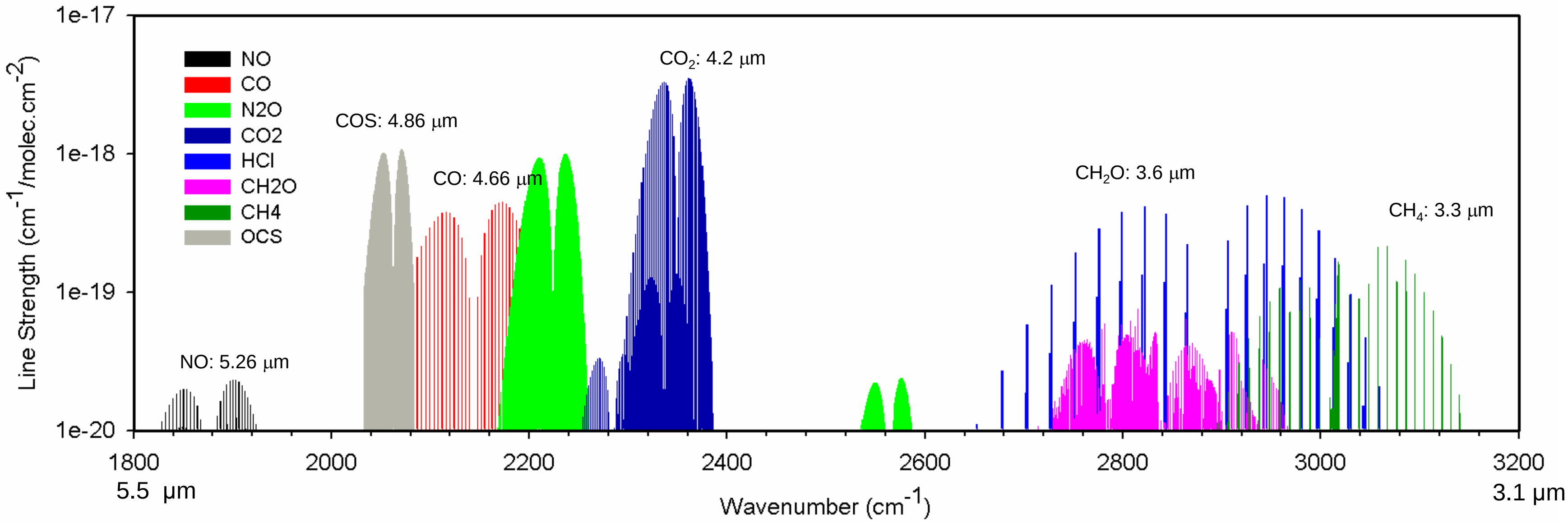
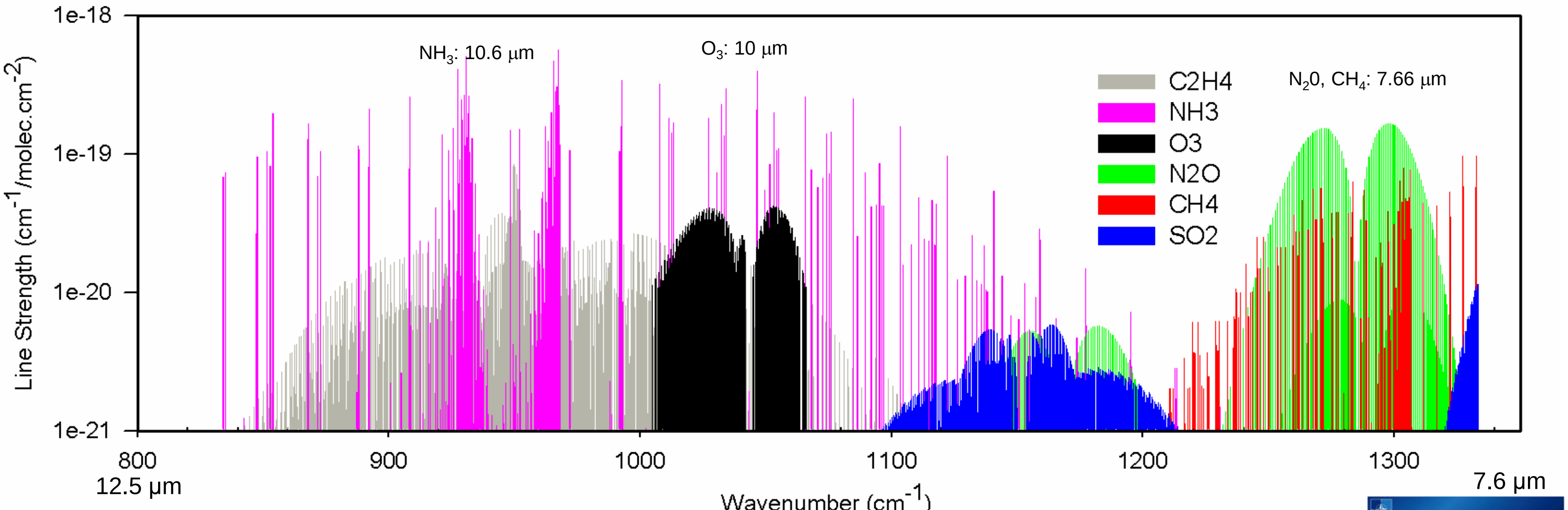
Other Spectroscopic Trace Gas Sensing Techniques

- Faraday Rotation Spectroscopy (limited to paramagnetic chemical species)
- Noise Immune Cavity Enhanced-Optical Heterodyne Molecular Spectroscopy (NICE-OHMS)
- Frequency Comb Spectroscopy
- Laser Induced Breakdown Spectroscopy (LIBS)

HITRAN Simulated Mid-Infrared Molecular Absorption Spectra





Source: HITRAN 2000 database

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Mid-IR Source Requirements for Laser Spectroscopy

REQUIREMENTS	**IR LASER SOURCE**
Sensitivity (% to ppt)	**Optimum Wavelength, Power**
Selectivity (Spectral Resolution)	**Stable Single Mode Operation and Narrow Linewidth**
Multi-gas Components, Multiple Absorption Lines and Broadband Absorbers	**Mode Hop-free Wavelength Tunability**
Directionality or Cavity Mode Matching	**Beam Quality**
Rapid Data Acquisition	**Fast Time Response**
Room Temperature Operation	**High wall plug efficiency, no cryogenics or cooling water**
Field deployable in harsh environments	**Compact, Robust, Packaging, Low Noise**

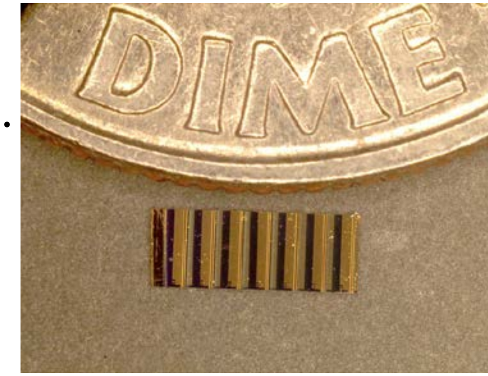
Key Characteristics of Mid-IR QCL& ICL Sources – Feb 2013

- **Band – structure engineered devices**
  Emission wavelength is determined by layer thickness – MBE or MOCVD; Type I QCLs operate in the 3 to 24 µm spectral region; Type II and GaSb based ICLs can cover the 3 to 6 µm spectral range.
  - Compact, reliable, stable, long lifetime, and commercial availability
  - Fabry-Perot (FP), single mode (DFB) and multi-wavelength devices

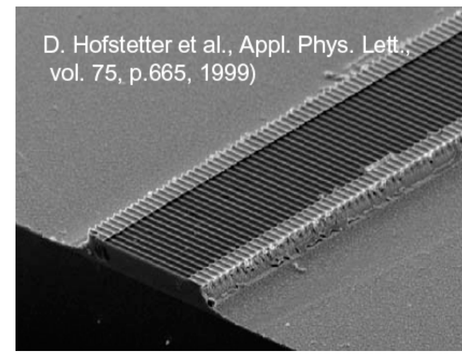
- **Wide spectral tuning ranges in the mid-IR**
  - 1.5 cm^{-1} using injection current control for DFB devices
  - 10-20 cm^{-1} using temperature control for DFB devices
  - ~ 525 cm^{-1} (22% of c.w.) using an external grating element and FP chips with heterogeneous cascade active region design; also QCL DFB Array

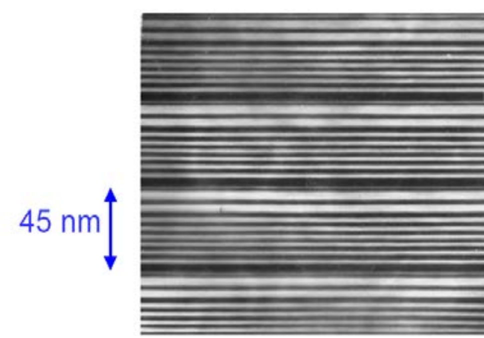
- **Narrow spectral linewidths**
  - CW: 0.1 - 3 MHz & <10kHz with frequency stabilization (0.0004 cm^{-1})
  - Pulsed: ~ 300 MHz

- **High pulsed and CW powers of QCLs at TEC/RT temperatures**
  - Room temperature pulsed power of > 30 W with 27% wall plug efficiency and CW powers of ~ 5 W with 21% wall plug efficiency
  - > 1 W, TEC CW DFB @ 4.6 µm
  - > 600 mW (CW FP) @ RT; wall plug efficiency of ~17 % at 4.6 µm;



4 mm





Recent Improvements and New Capabilities of QCLs and ICLs

- **Optimum wavelength** (> 3 to < 20 µm) and **power** (>10 mw to < 1 W) at room temperature (> 15 ºC and < 30 ºC) with state-of-the-art fabrication/processing methods based on MBE and MOCVD, **good wall plug efficiency** and **lifetime** (> 20,000 hours) for **detection sensitivities from % to pptv** with **low electrical power budget**
- **Stable single $\mathbf{TEM_{00}}$ transverse and axial mode, CW and pulsed operation of mid-infrared laser sources** (narrow linewidth of ~ 300 MHz to < 10kHz)
- **Mode hop-free ultra-broad wavelength tunability for detection of broad band absorbers and multiple absorption lines** based on external cavity or mid-infrared semiconductor arrays
- **Good beam quality for directionality**_and/or cavity mode matching. Implementation of **innovative collimation concepts.**
- Rapid data acquisition based on **fast time response.**
- **Compact, robust, readily commercially available** and **affordable** in order to be field deployable in harsh operating environments (low and high temperature, pressure, etc…)

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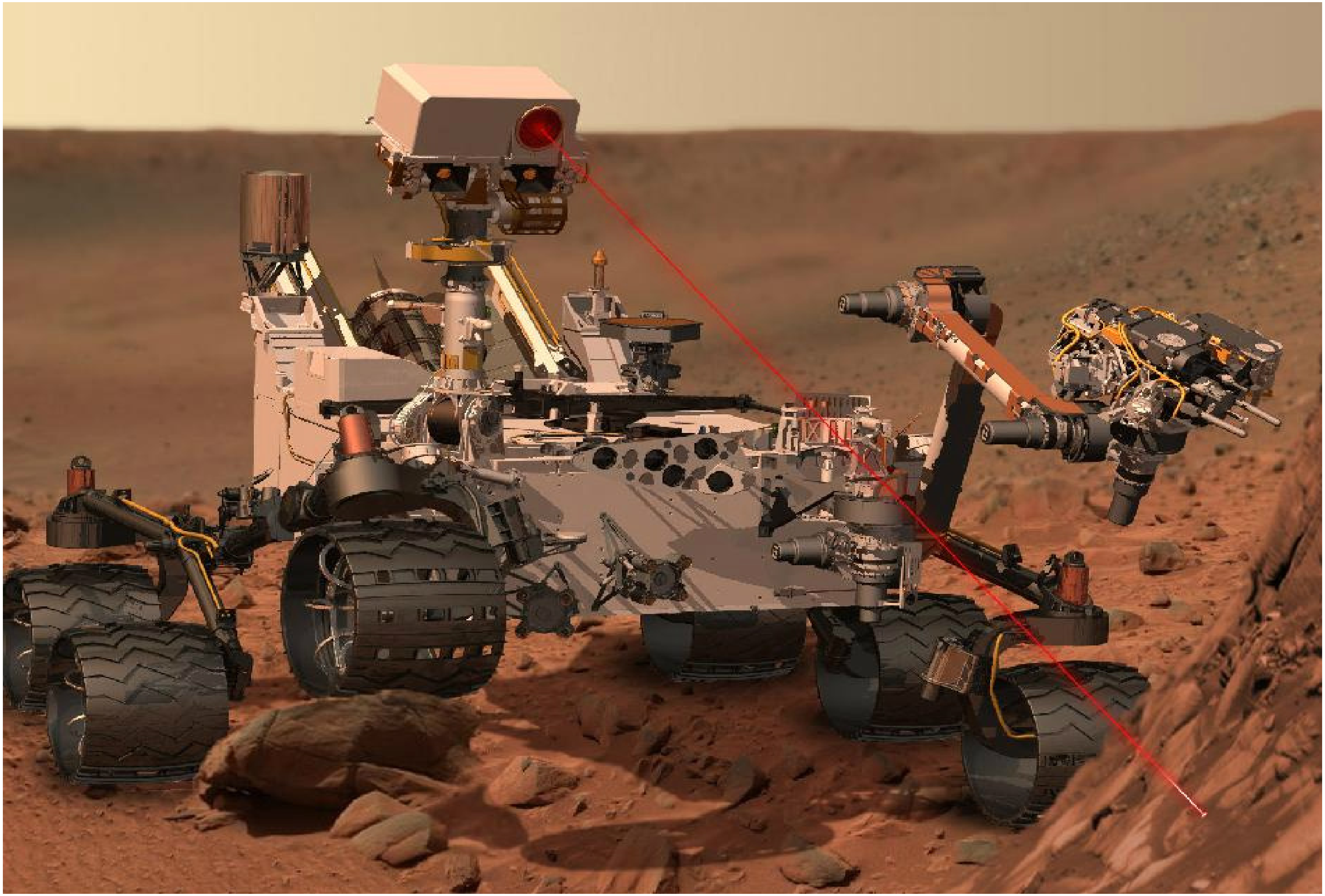
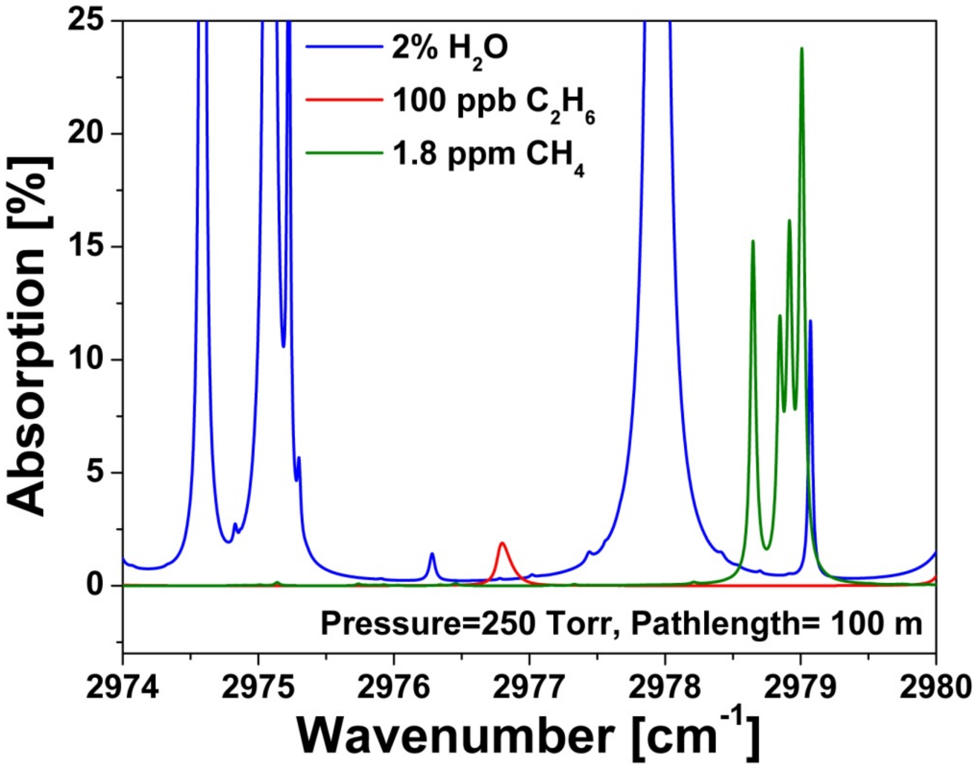
“Curiosity” landed on Mars on August 6, 2012



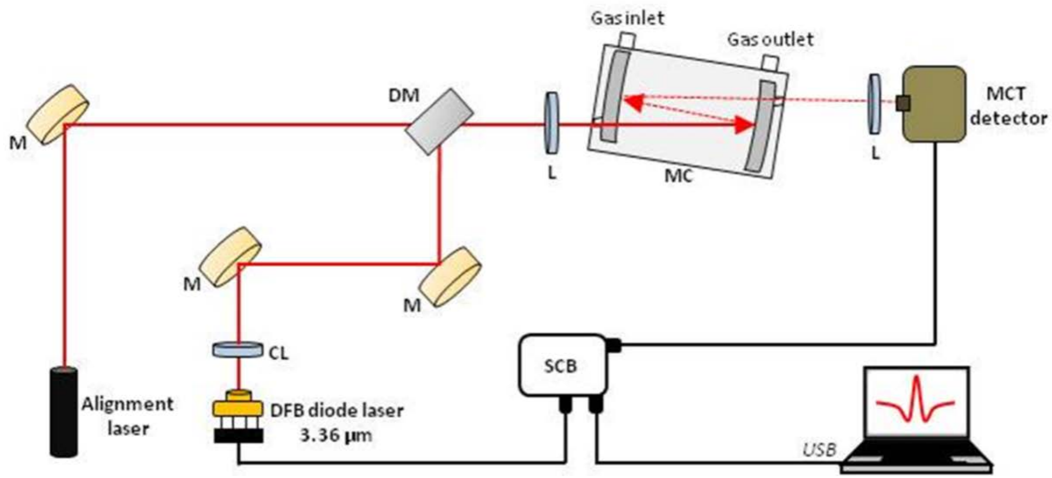
Motivation for Mid-infrared C_2H_6 Detection

- Atmospheric chemistry and climate
  - Fossil fuel and biofuel consumption,
  - Biomass burning,
  - Vegetation/soil,
  - Natural gas loss
- Oil and gas prospecting
- Application in medical breath analysis (a non-invasive method to identify and monitor different diseases):
  - Asthma,
  - Schizophremia,
  - Lung cancer,
  - Vitamin E deficiency.

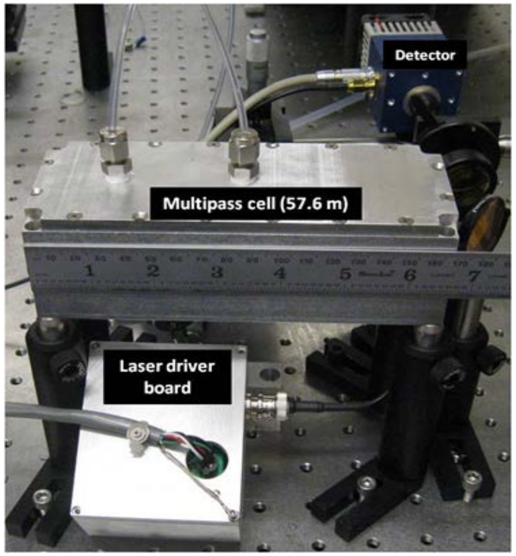


HITRAN absorption spectra of C_2H_6, CH_4, and H_2O

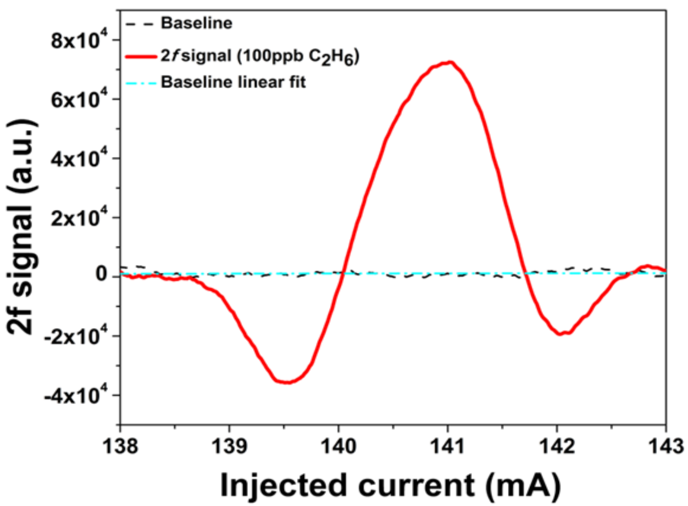
C_2H_6 Detection with a 3.36 µm DFB LD using a Novel Compact Multipass Absorption Cell and Control Electronics



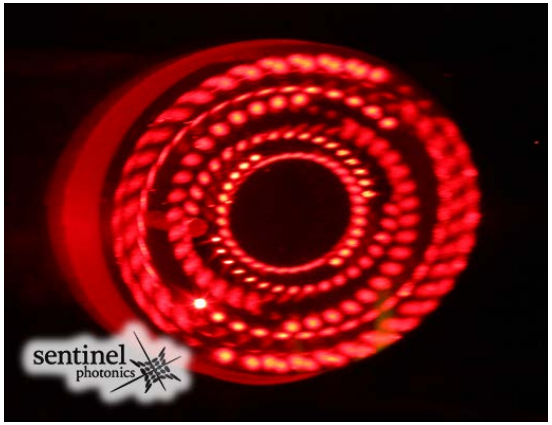
Schematic of a C_2H_6 gas sensor using a Nanoplus 3.36 µm DFB laser diode as an excitation source. M – mirror, CL – collimating lens, DM – dichroic mirror, MC – multipass cell, L – lens, SCB – sensor control board.



Innovative long path, small volume multipass gas cell:57.6m with 459 passes



2f WMS signal for a C_2H_6 line at 2976.8 cm^{-1} at a pressure of 200 Torr



Minimum detectable C_2H_6 concentration is:

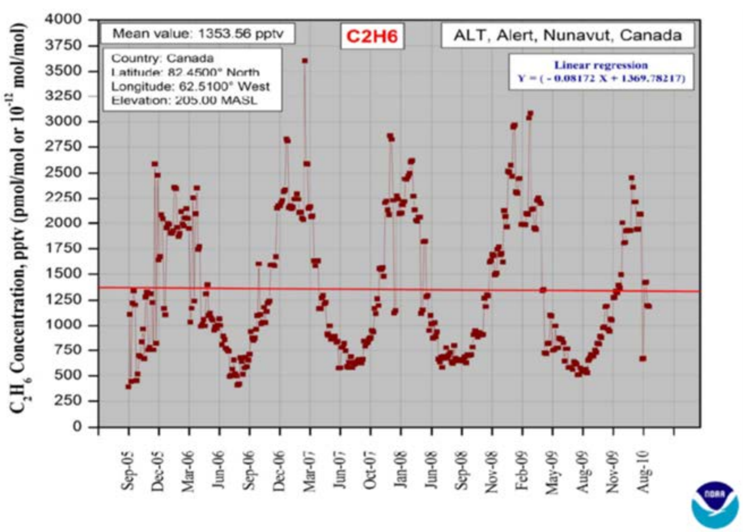
~ 130 pptv (1σ; 1 s time resolution)

MC dimensions: **17** x **6.5** x **5.5** (cm)

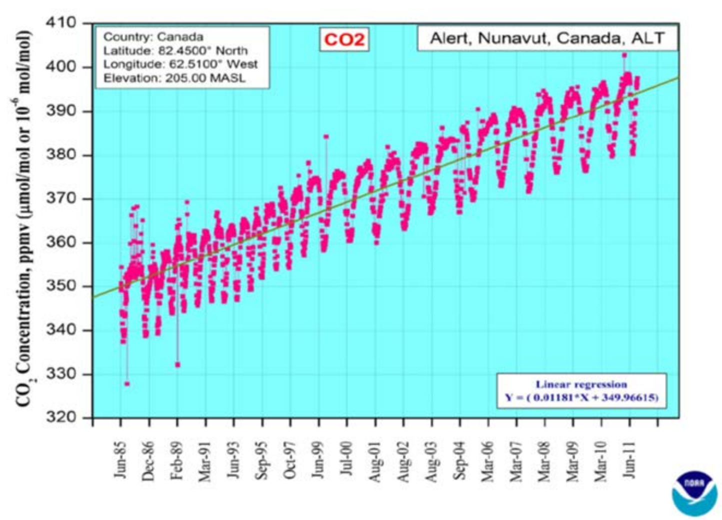
Distance between the MGC mirrors: 12.5 cm

NOAA Monitoring and Sampling Location: Alert (ALT), Nunavut, Canada

General view on Alert NOAA Facility



Ethane Concentration Measurements at ALT



CO_2 Concentration Measurements at ALT

Motivation for NH_3 Detection

- Detection of ammonium-nitrate explosives
- Spacecraft related gas monitoring
- Monitoring NH_3 concentrations in the exhaust stream of NO_x removal systems based on selective catalytic reduction techniques
- Semiconductor process monitoring & control
- Monitoring of industrial refrigeration facilities
- Pollutant gas monitoring
- Atmospheric chemistry
- Medical diagnostics (kidney & liver diseases)

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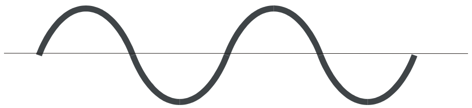
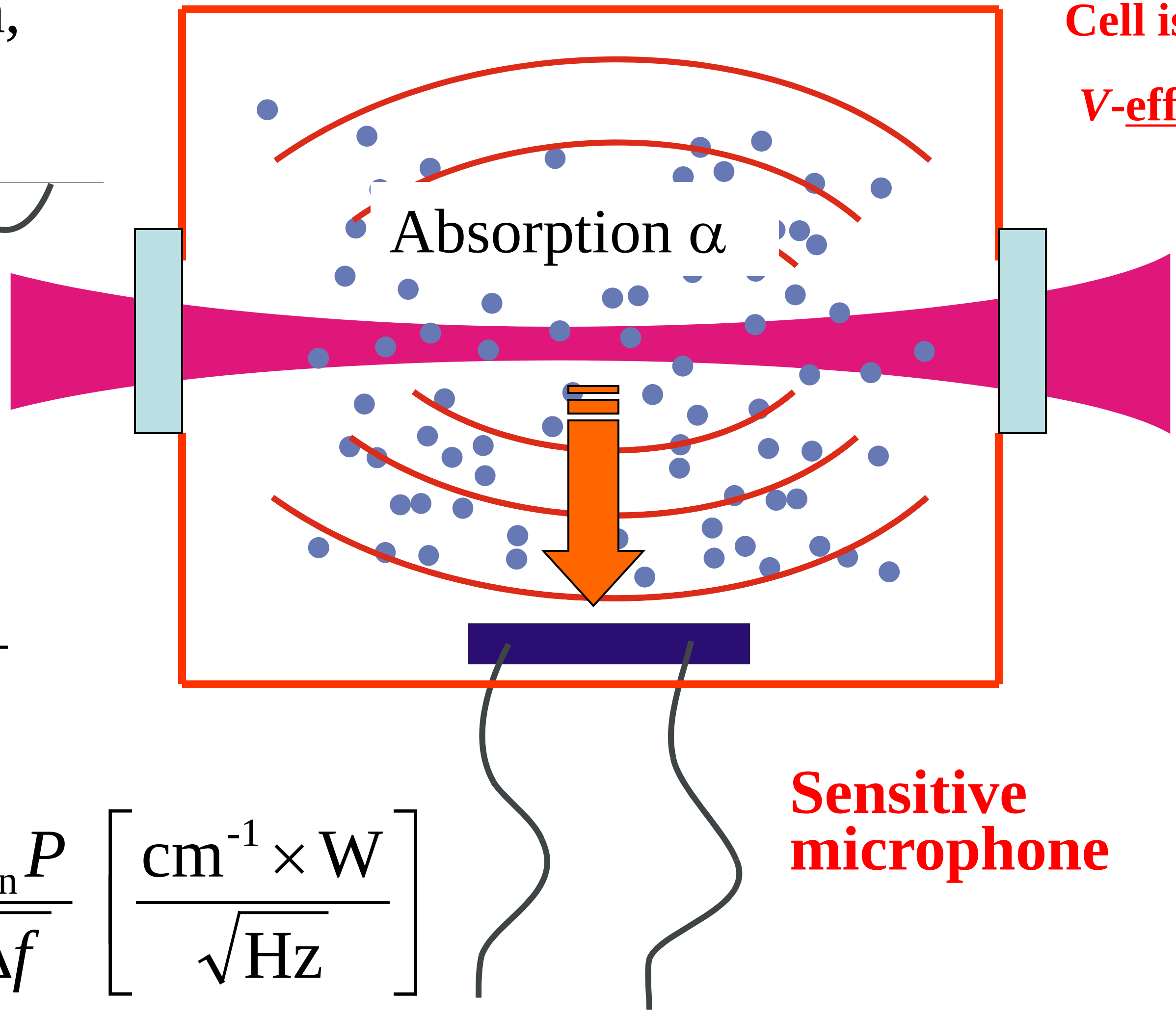
Conventional PAS

Laser beam, power P



Modulated (P or λ) at f or $f/2$



Q>>1000

Cell is OPTIONAL!

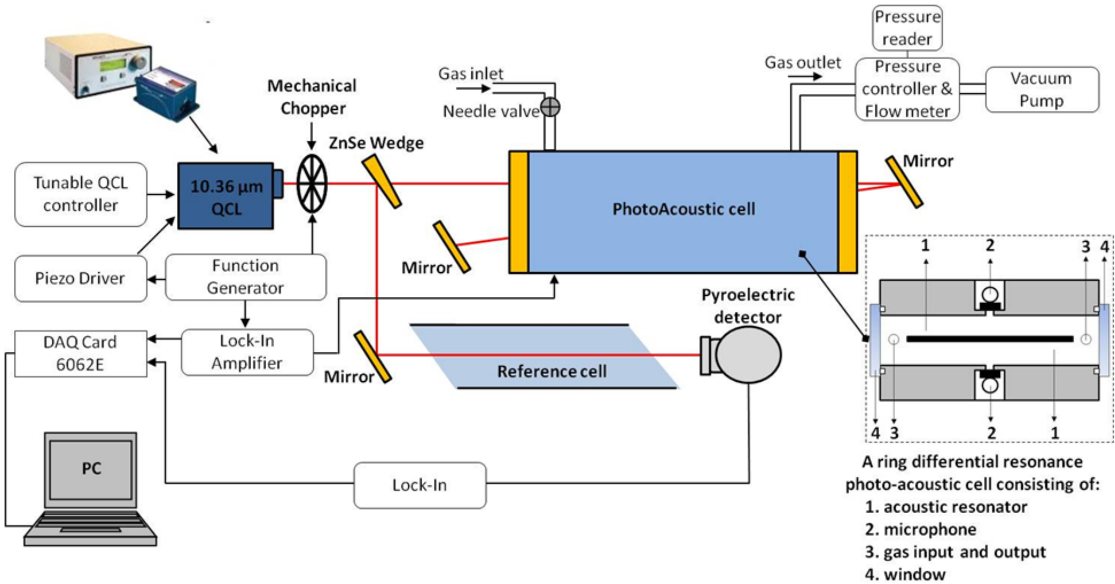
V-effective volume

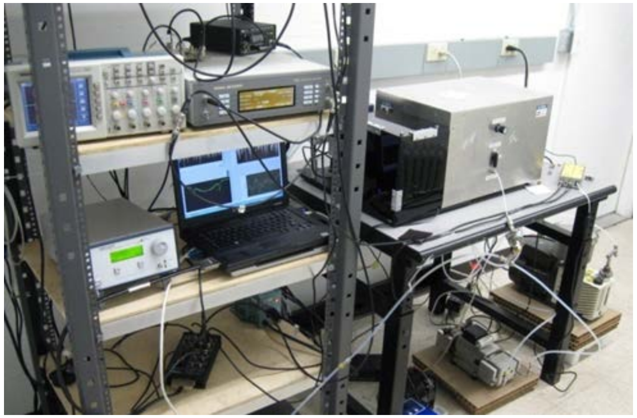
Sensitive microphone

$$S \sim \frac{Q\,\alpha\,P}{f\,V}$$

$$NNEA = \frac{\alpha_{min} P}{\sqrt{\Delta f}} \left[\frac{\mathrm{cm}^{-1} \times \mathrm{W}}{\sqrt{\mathrm{Hz}}} \right]$$

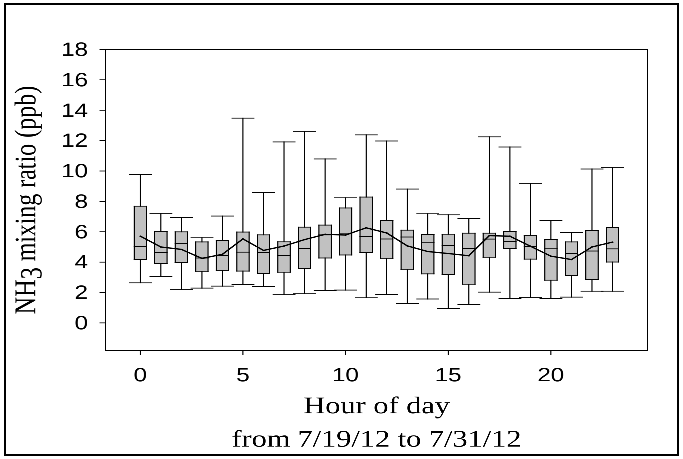
Atmospheric NH_3 Measurements using a CW EC-QCL PAS Sensor



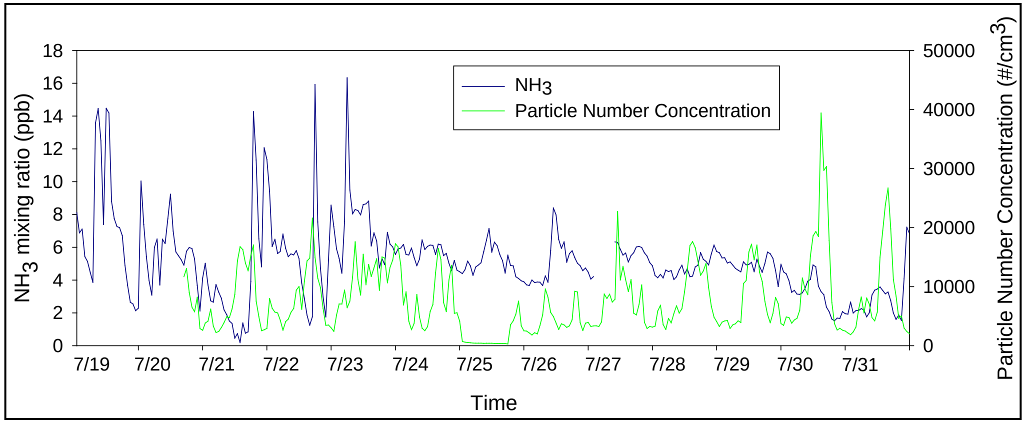


NH_3 sensor deployed at the UH Moody Tower rooftop monitoring site.

Schematic of a Daylight Solutions 10.36 µm CW TEC EC-QCL based PAS NH_3 Sensor.

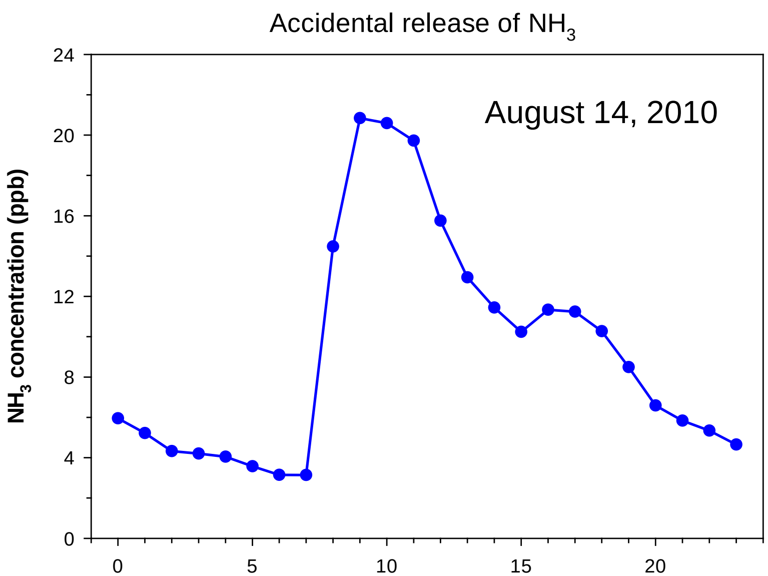


Diurnal profile of atmospheric NH_3 levels in Houston, TX.

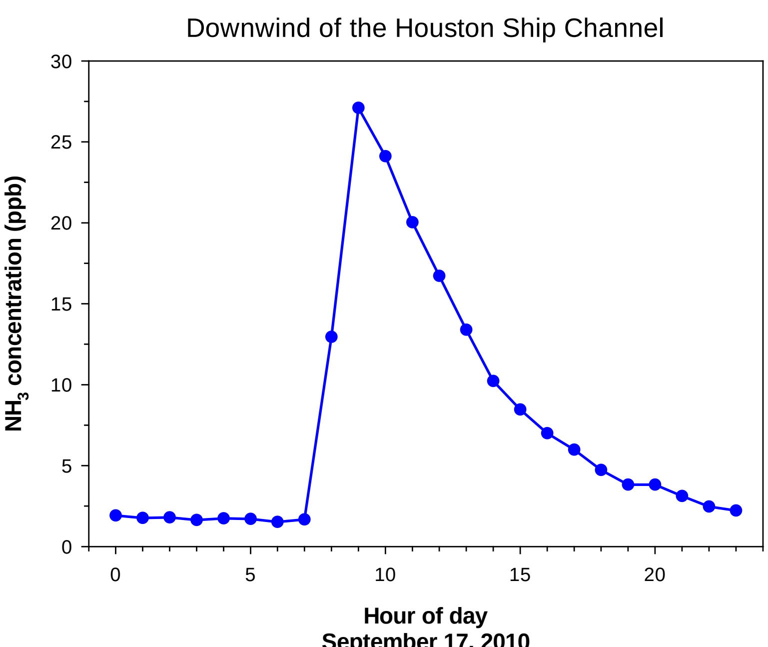


Comparison between NH_3 and particle number concentration time series from July 19 to July 31 2012.

NH_3 Detection due to a Fire resulting from a two Truck Collision



A chemical incident occurred at ~ 6 a.m. after two trucks collided on I-59. Both trucks caught fire. [www.chron.com]



Estimated hourly NH_3 emission from the Houston Ship Channel area is about 0.25 ton. Mellqvist et al., (2007) Final Report, HARC Project H-53.

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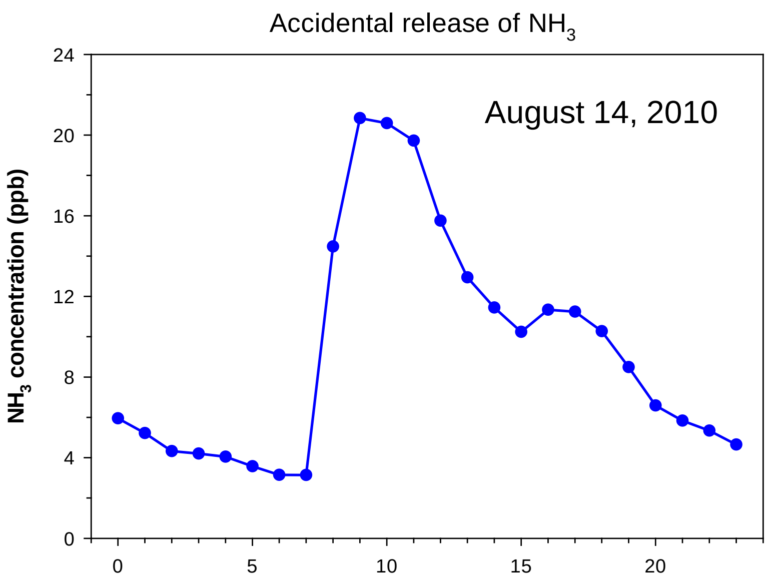

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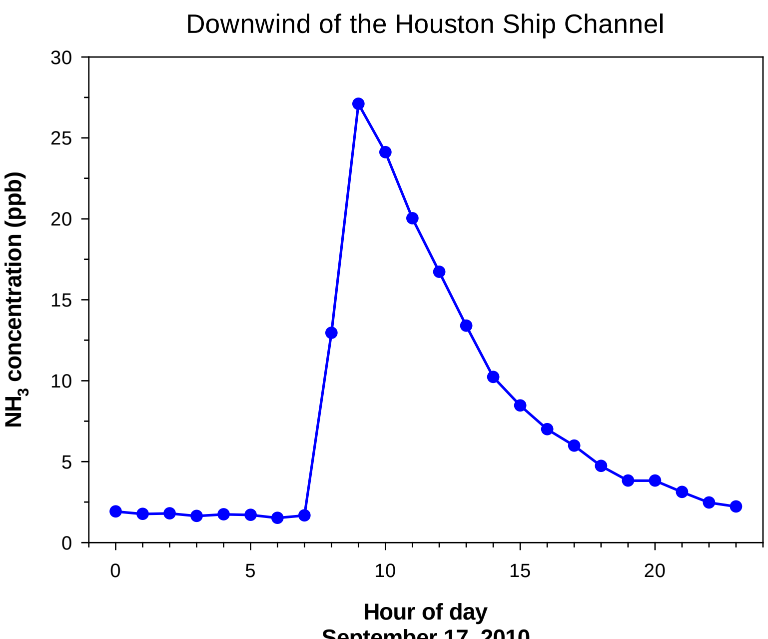

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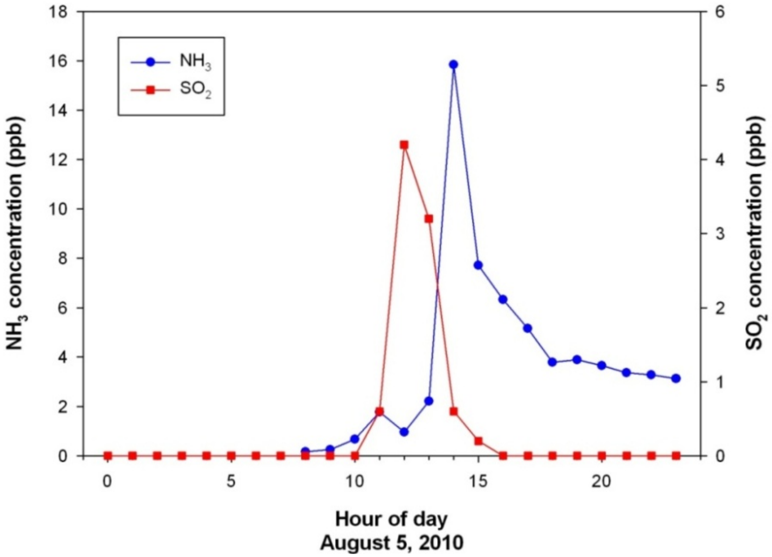
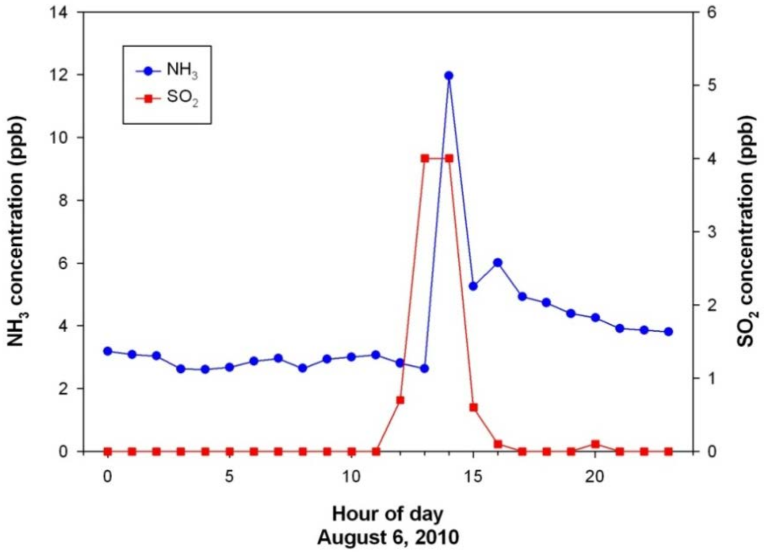
Sporadic increased NH_3 Concentration Levels related to Emissions by the Parish Electric Power Plant, TX





The Parish electric power plant,is located near the Brazos River in Fort Bend County, Texas (~27 miles SW of downtown Houston)

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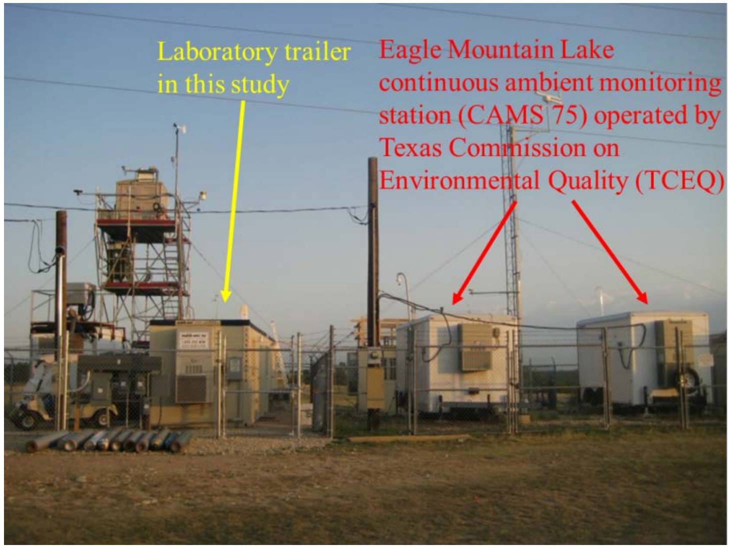
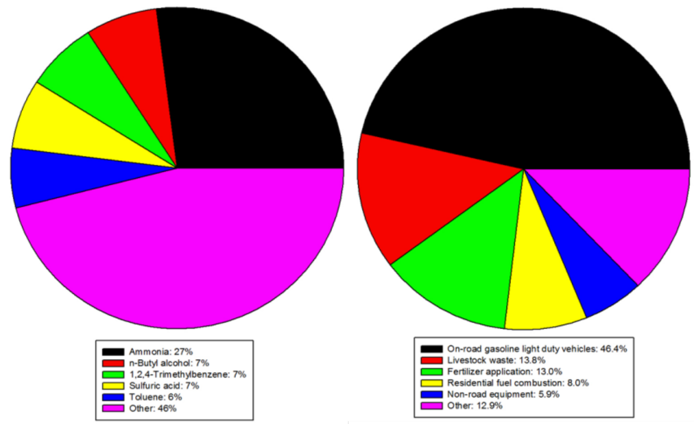
Atmospheric NH_3 Measurements and Implications for PM Formation near Fort Worth

- Four specific aims are being pursued:
  - Investigation of the NH_3 dynamics (e.g., temporal variations);
  - Identification of NH_3 sources using auxiliary data for CO and NO_x;
  - Performing NH_3 source apportionment using the EPA Positive Matrix Factorization 3.0 model including VOC_s data;
  - Evaluation of NH_3 effects on local and regional air quality with respect to PM formation using aerosol/PM data collected by an Aerodyne High Resolution Time-of-Flight Mass Spectrometer, a Scanning Electrical Mobility Spectrometer, and a Mist Chamber-Ion Chromatography system.





(a) (b)

(a) Annual total air releases by species in the DFW area (U.S. EPA TRI, 2010); (b) Annual NH_3 emissions by source categories in Tarrant County, Texas (U.S. EPA NEI, 2008)

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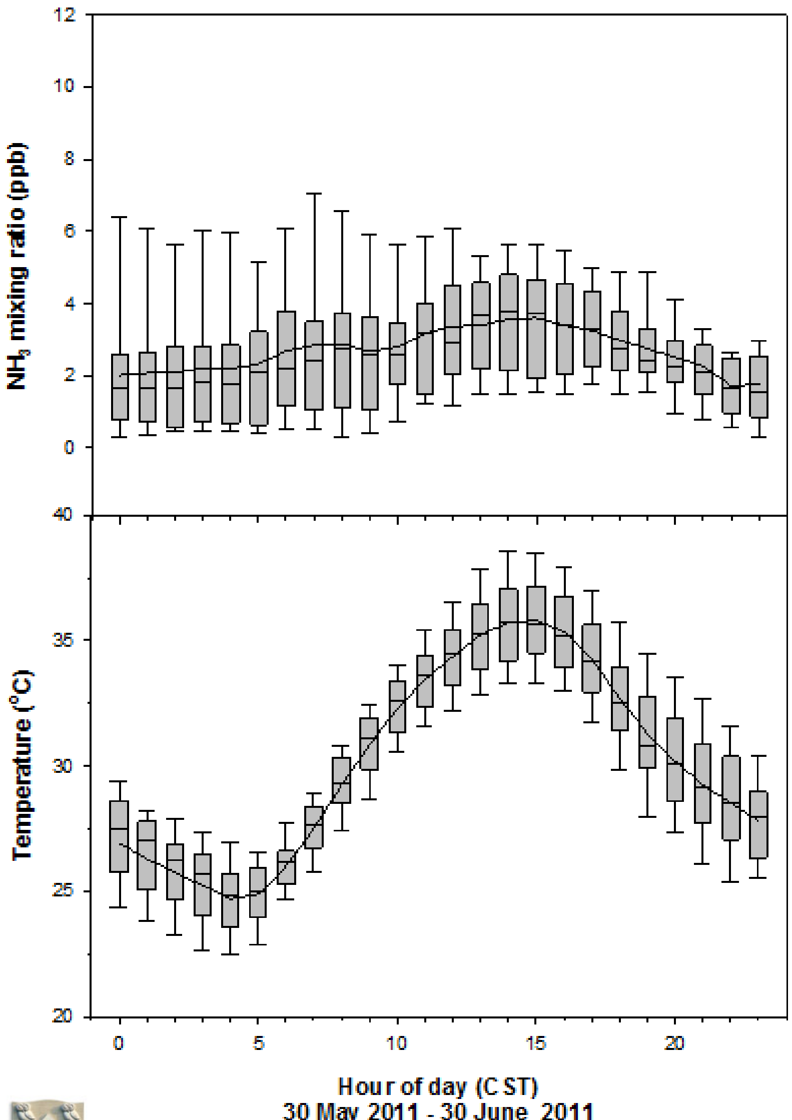
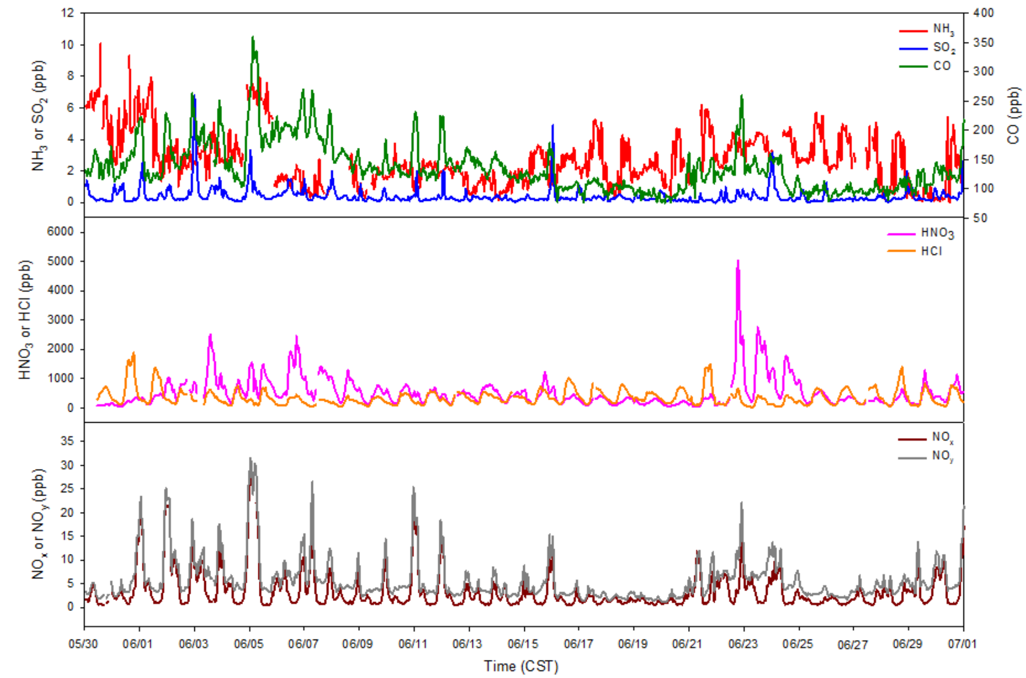
NH_3 vs. Temperature data & Time series of NH_3, SO_2, CO





- Emission events from specified point sources (i.e., industrial facilities)
- Estimated NH_3 emissions from cows (1.3 tons/day)
- Estimated NH_3 emissions from soil and vegetation (0.15 tons/day)
- EPA PMF (biogenic: 74.1%; light duty vehicles: 12.1%; natural gas/industry: 9.4%; and heavy duty vehicles: 4.4%)
- Livestock might account for approximately 66.4% of total NH_3 emissions
- Increased contribution from industry (→ 18.9%)

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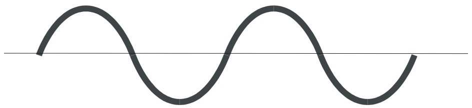
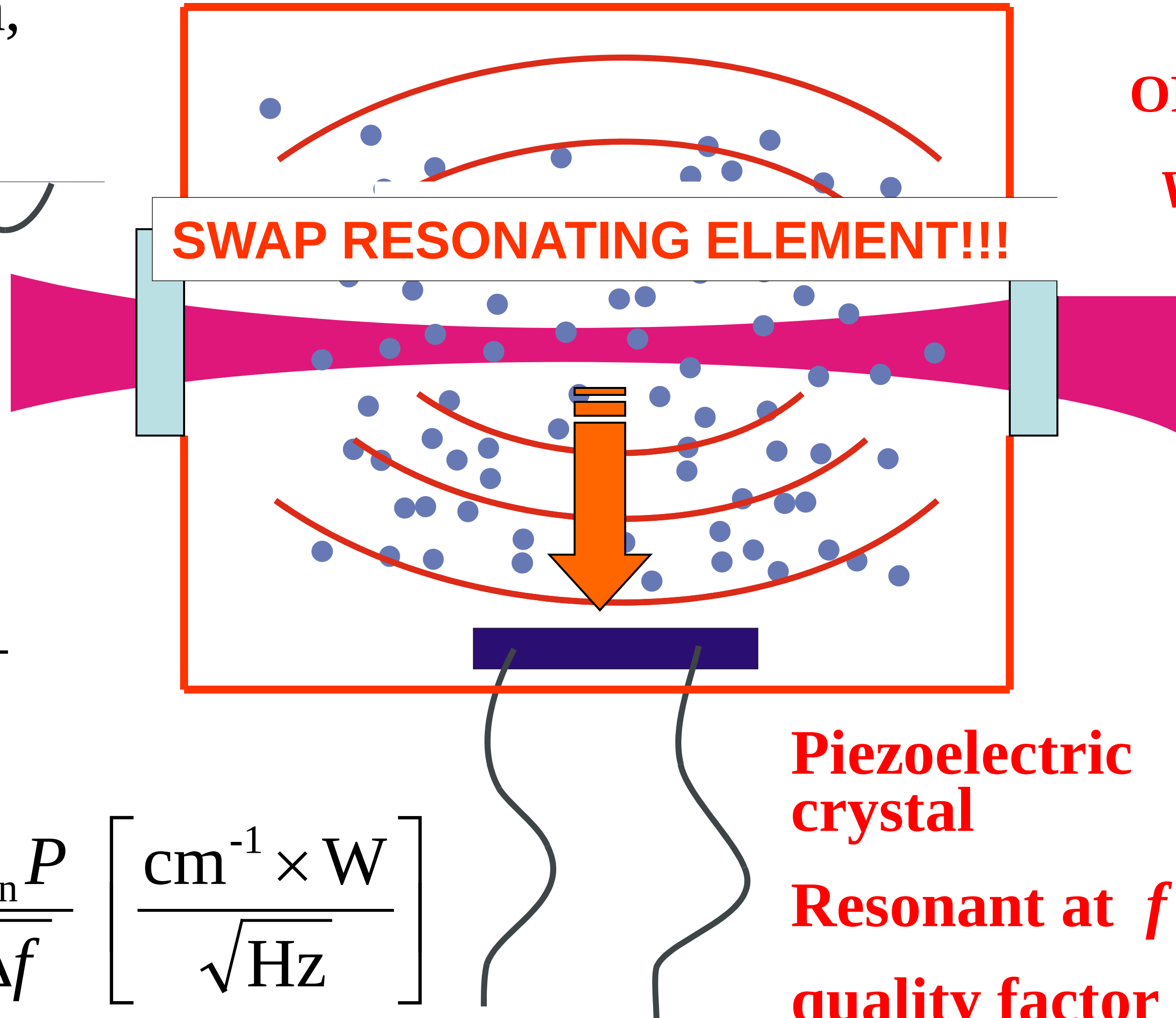
From Conventional PAS to QEPAS

Laser beam, power P



Modulated (P or λ) at f or $f/2$

$$S \sim \frac{Q\,\alpha\,P}{f\,V}$$



Q>>1000

Cell is OPTIONAL!

V-effective volume

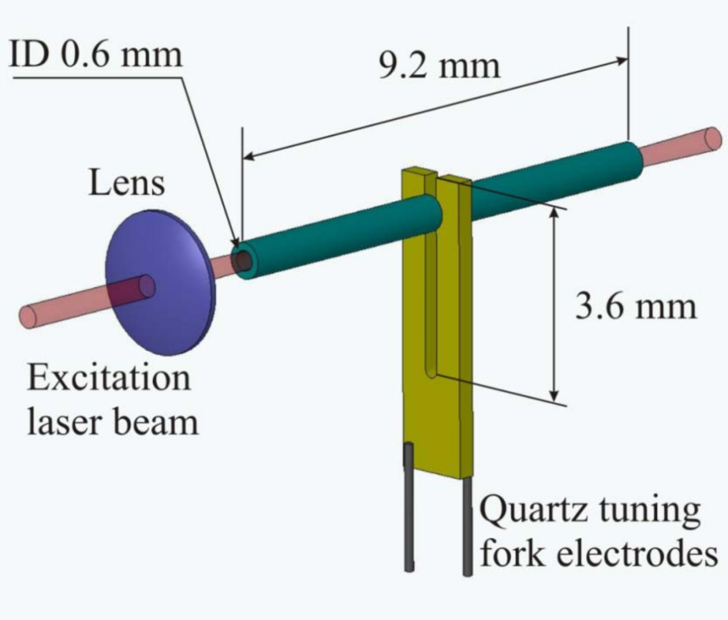
Piezoelectric crystal

Resonant at f

quality factor Q

$$NNEA = \frac{\alpha_{min} P}{\sqrt{\Delta f}} \left[\frac{\mathrm{cm}^{-1} \times \mathrm{W}}{\sqrt{\mathrm{Hz}}} \right]$$

Quartz Tuning Fork as a Resonant Microphone for QEPAS



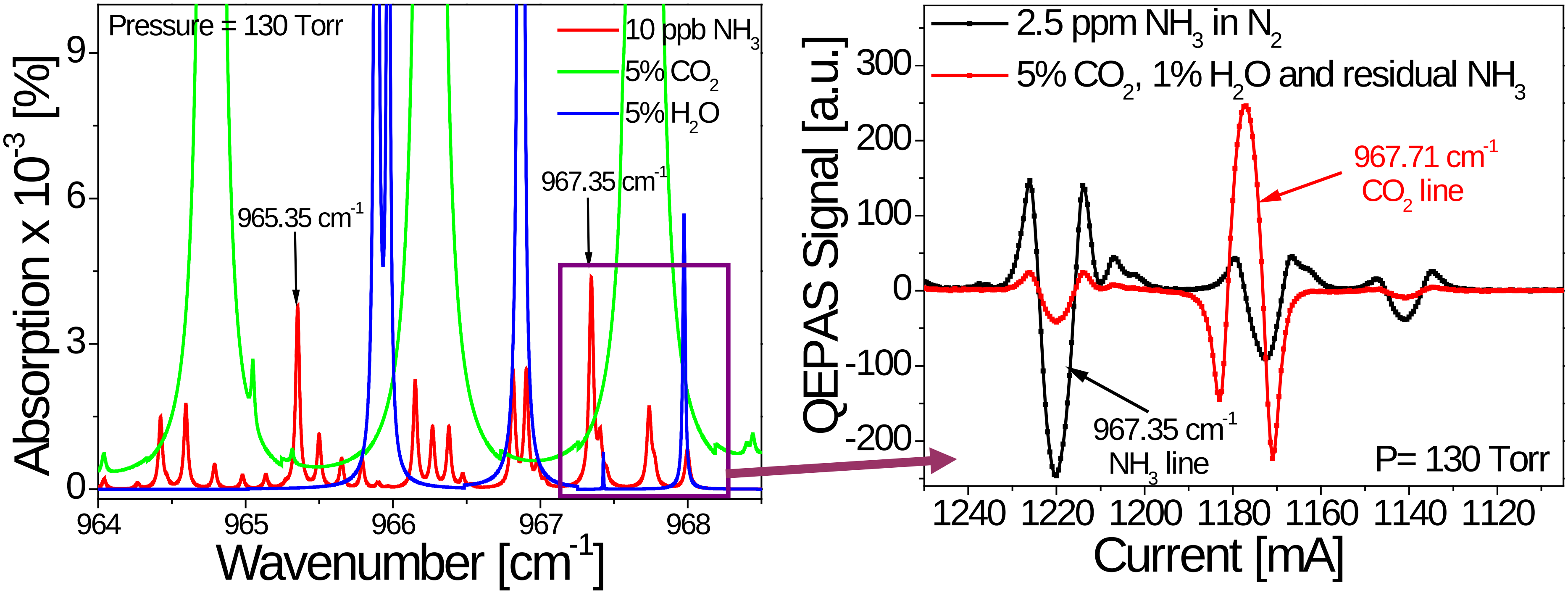
Unique properties

- Extremely low internal losses:
  - Q~10 000 at 1 atm
  - Q~100 000 in vacuum
- Acoustic quadrupole geometry
  - Low sensitivity to external sound
- Large dynamic range (~10^6) – linear from thermal noise to breakdown deformation
  - 300 K noise: x~10^{-11} cm & breakdown: x~10^{-2} cm
- Wide temperature range: from 1.6K to ~700K
- Low cost (< 1 zl)
- Resonant frequency;: ~ 32.8 KHz (2 × 10^{15})

Acoustic Micro-resonator (mR) tubes

- Optimum inner diameter:0.6 mm; mR-QTF gap is 25-50 µm
- Optimum mR tubes must be ~ 4.4 mm long (~λ/4<l<λ/2 for sound at 32.8 kHz)
- SNR of QTF with mR tubes: ×30 **(**depending on gas composition and pressure)

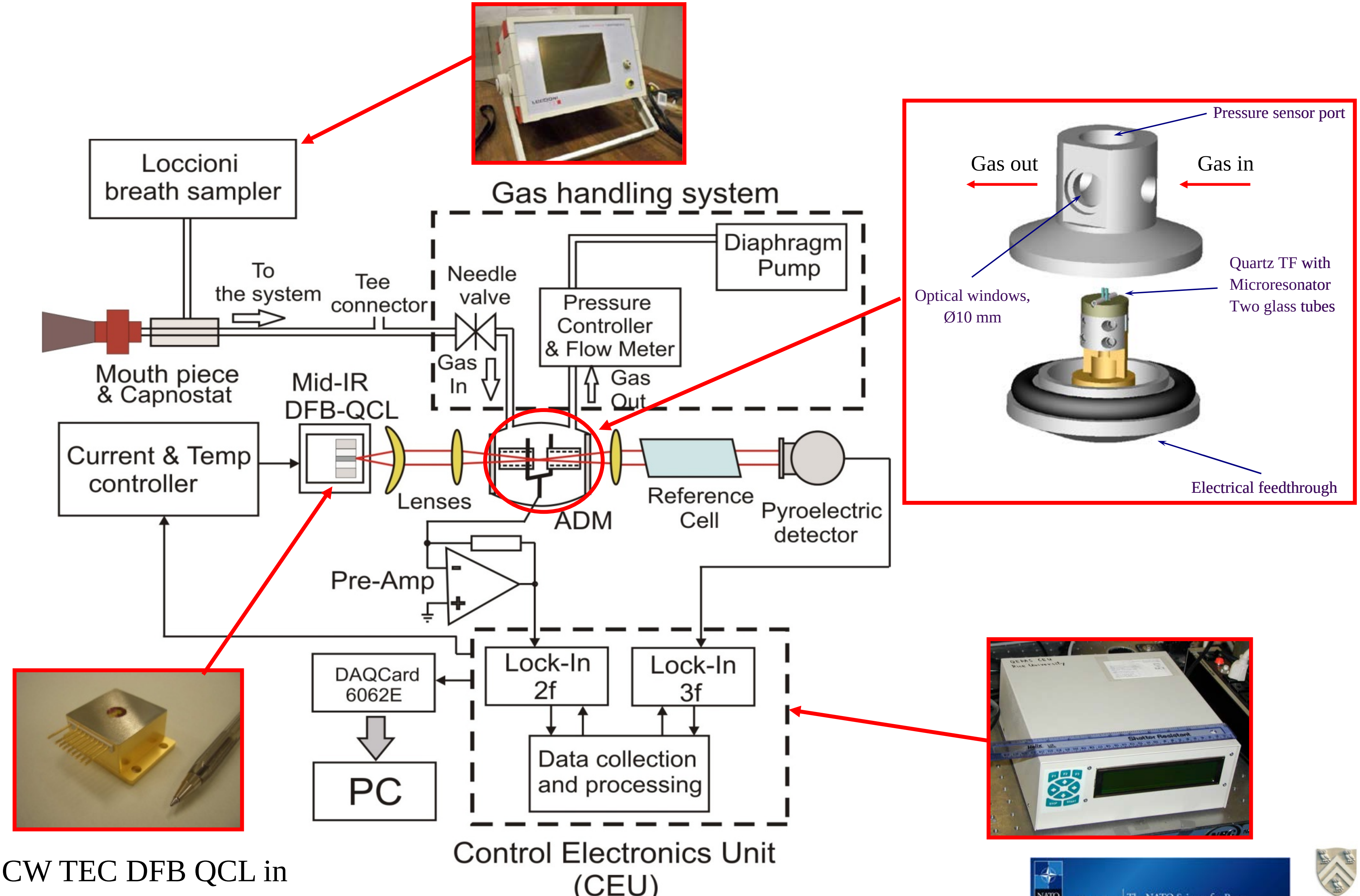
Optimum NH_3 Line Selection for a 10.34 μm CW TEC DFB QCL



Simulated HITRAN high resolution spectra @ 130 Torr indicating two NH_3 absorption lines of interest

No overlap between NH_3 and CO_2 absorption lines was observed for the selected **967.35 cm^{-1}** NH_3 absorption line in the ν_2 R band.

QEPAS based NH_3 Gas Sensor Architecture



CW TEC DFB QCL in
HHL package (Hamamatsu)

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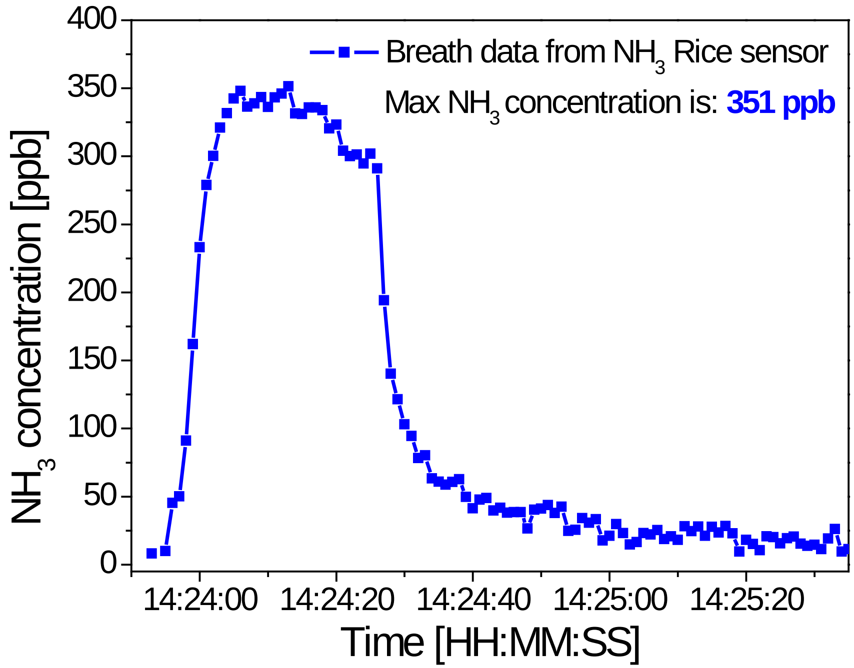
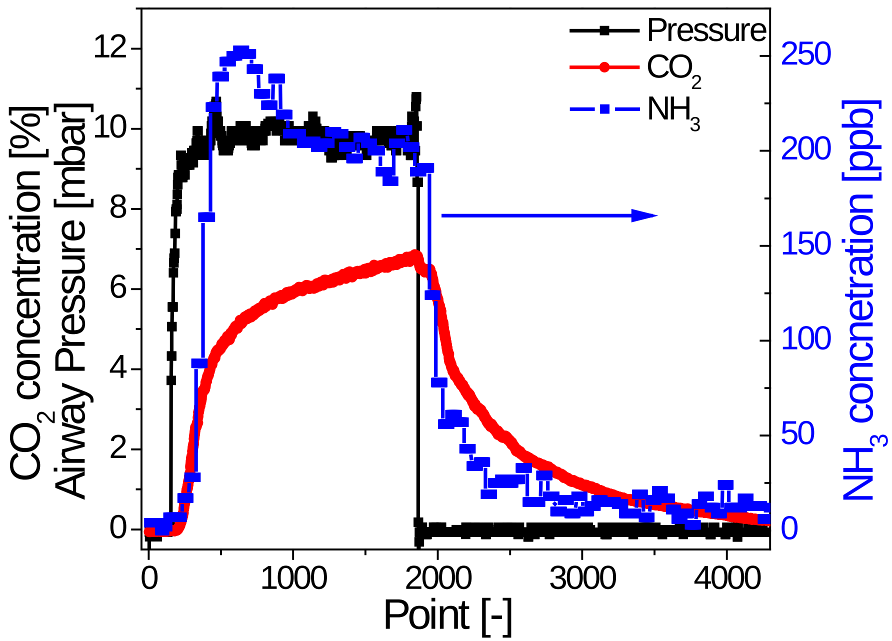
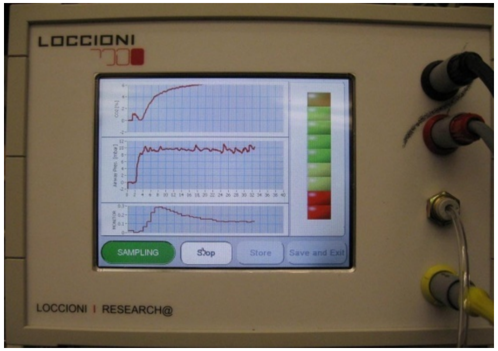
Real-time exhaled human NH_3 Breath Measurements





Airway pressure (black), CO_2 (red), and NH_3 (blue) profiles of a single breath exhalation lasting 40sec.



Successful testing of a 2nd generation breath ammonia monitor installed in a clinical environment.(Johns Hopkins, Baltimore, MD and St. Luke's Hospital, Bethlehem, PA)

Minimum detectable concentration of NH_3 is:
~ 6 ppbv at 967.35 cm^{-1} (1σ; 1 s time resolution)

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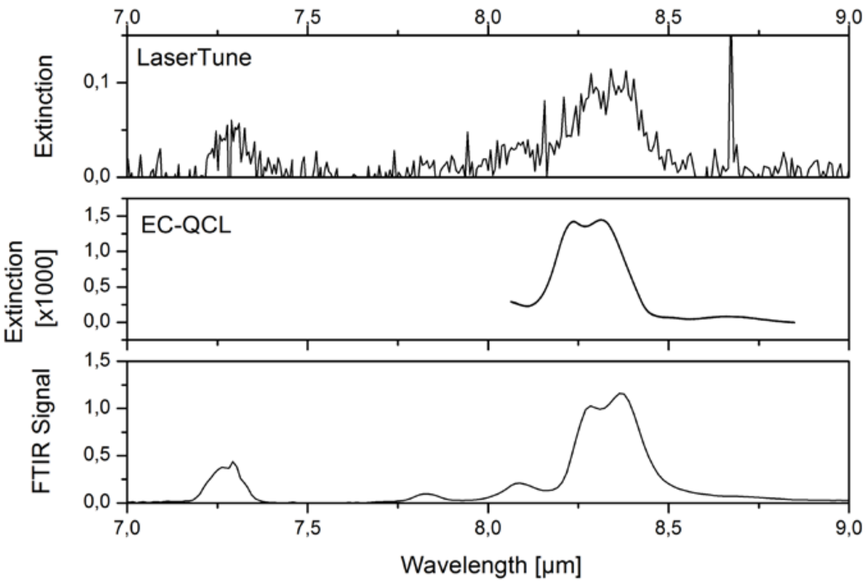
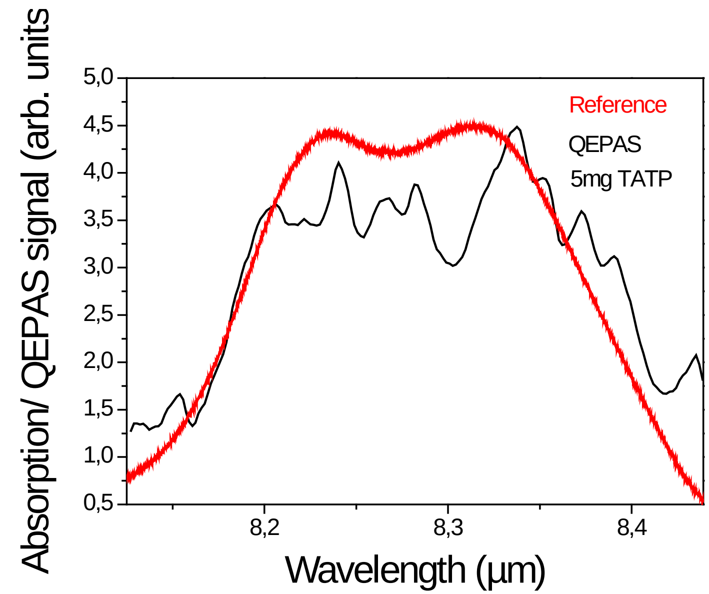
QEPAS Based TATP Detection

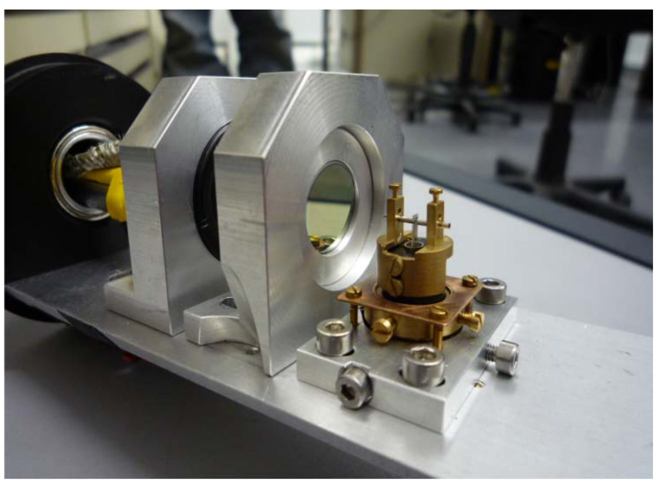


Multi pass 105 cm
Gas phase from
TATP stored in ionic
liquid

Single pass 10 cm
Gas phase from
TATP powder

Single pass 10
cm
Gas phase
from
TATP powder





DIEHL
BGT Defence

TU Clausthal

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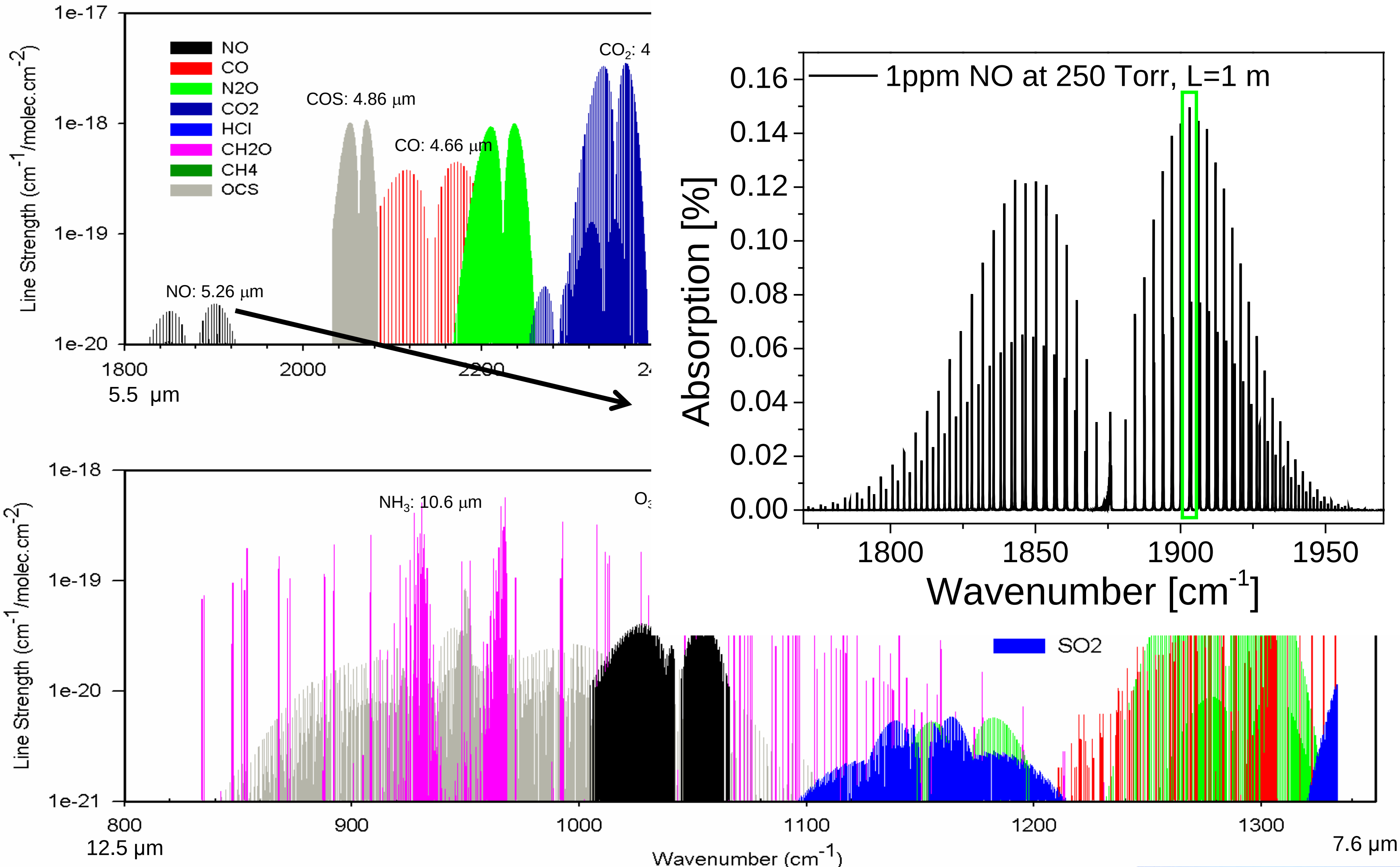
Motivation for Nitric Oxide Detection

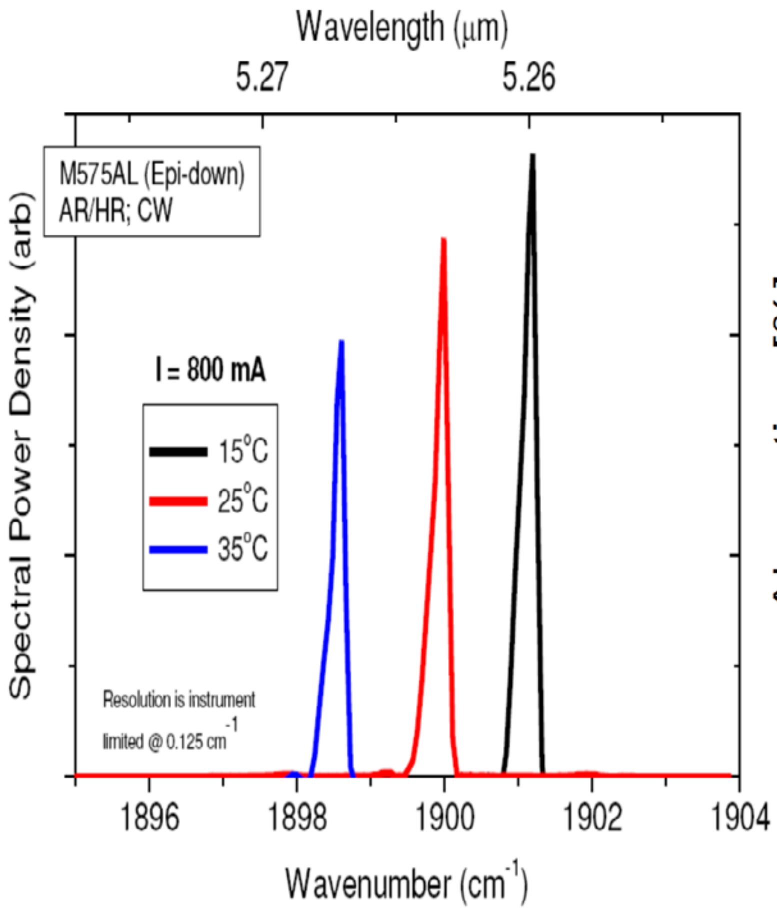
- Atmospheric Chemistry
- Environmental pollutant gas monitoring
  - NO_x monitoring from automobile exhaust and power plant emissions
  - Precursor of smog and acid rain
- Industrial process control
  - Formation of oxynitride gates in CMOS Devices
- NO in medicine and biology
  - Important signaling molecule in physiological processes in humans and mammals (1998 Nobel Prize in Physiology/Medicine)
  - Treatment of asthma, COPD, acute lung rejection
- Photofragmentation of nitro-based explosives

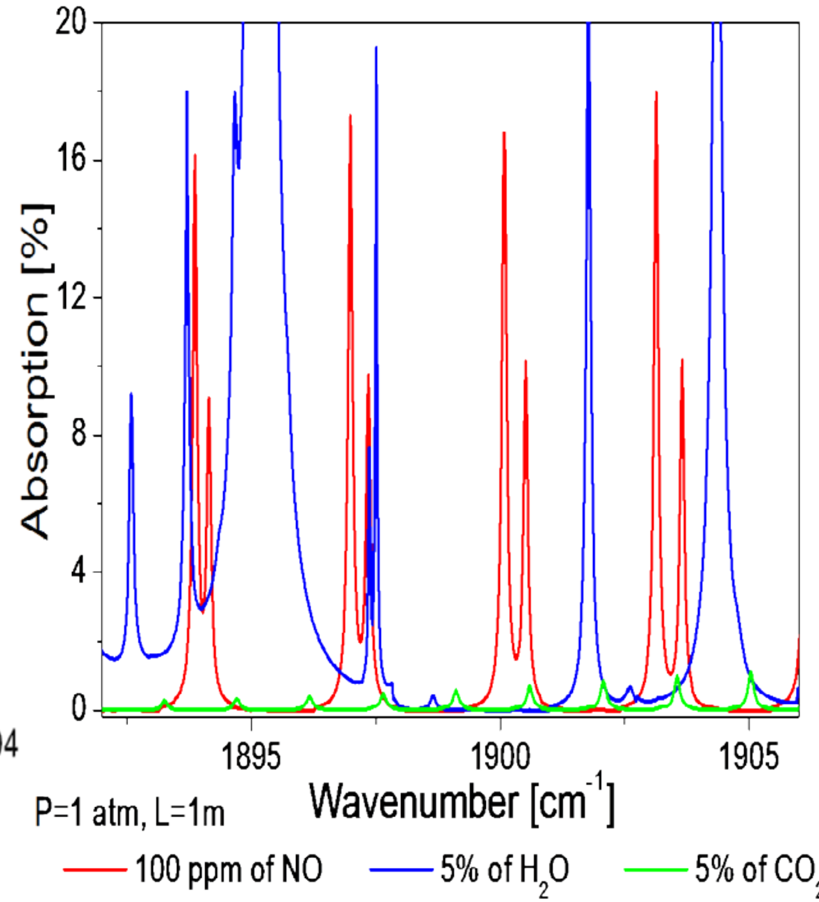
Molecular Absorption Spectra within two Mid-IR Atmospheric Windows and NO absorption @ 5.26µm



Source: HITRAN 2000 database

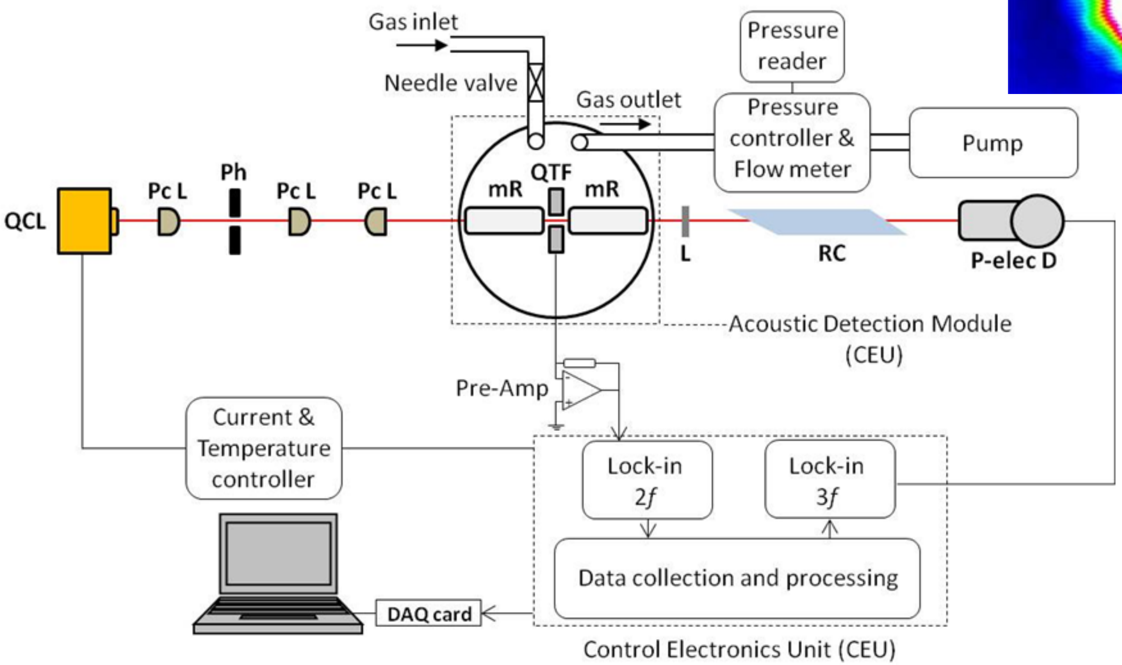
Emission spectra of a 1900cm^{-1} TEC CW DFB QCL and HITRAN Simulated spectra



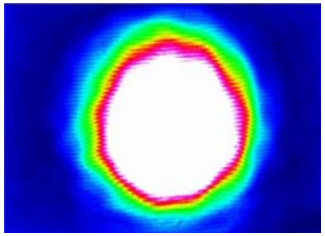


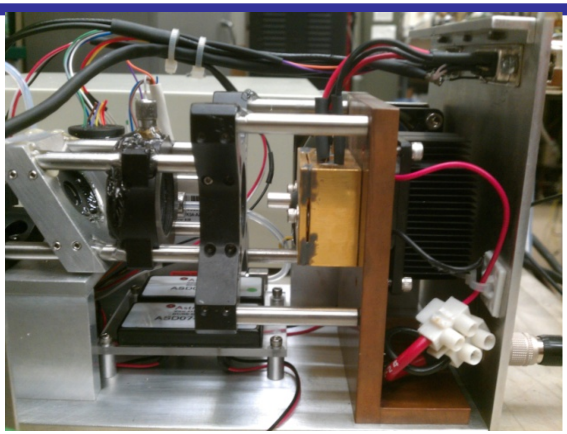
Output power: 117 mW @ 25 C

QCL based WMS QEPAS NO Gas Sensor Platform

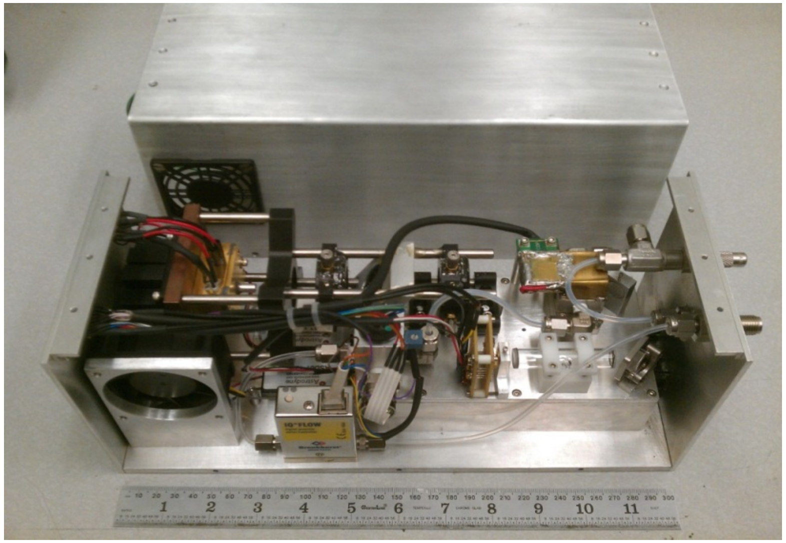


Schematic of a QCL QEPAS based Gas Sensor. M – mirror, PcL – plano-convez lens, Ph – pinhole, QTF – quartz tuning fork, mR – acoustic micro-resonator, RC – reference cell.



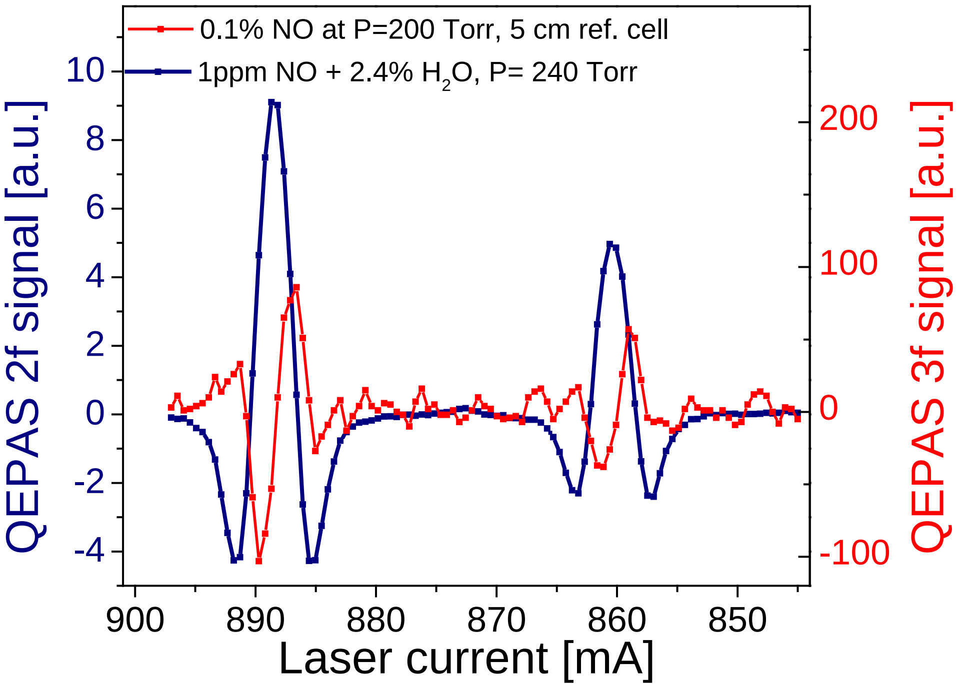


CW HHL TEC DFB-QCL package and IR camera image of the laser beam at 630 mA and 20.5 deg C through tubes after ADM

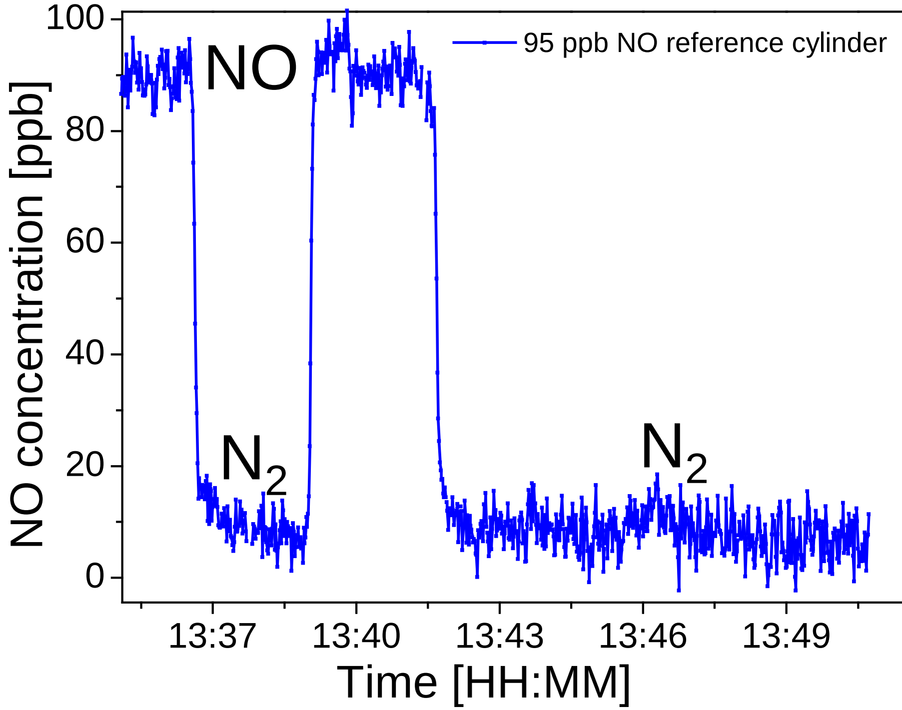


Compact Prototype NO Sensor (September 2012)

Performance of 2012 CW DFB-QCL based WMS QEPAS NO Sensor Platform



2f QEPAS signal (navy) and reference 3f signal (red) when laser was tuned across **1900.08 cm^{-1}** line.



2f QEPAS signal amplitude for 95 ppb NO when laser was locked to the **1900.08 cm^{-1}** line.

Minimum detectable NO concentration is:

~ 3 ppbv (1σ; 1 s time resolution)

Motivation for Carbon Monoxide Detection

- Atmospheric Chemistry
  - Incomplete combustion of natural gas, fossil fuel and other carbon containing fuels.
  - Impact on atmospheric chemistry through its reaction with hydroxyl (OH) for troposphere ozone formation and changing the level of greenhouse gases (e.g. CH_4).
- Public Health
  - Extremely dangerous to human life even at a low concentrations. Therefore CO must be carefully monitored at low concentration levels.
- CO in medicine and biology
  - Hypertension, neurodegenerations, heart failure and inflammation have been linked to abnormality in CO metabolism and function.

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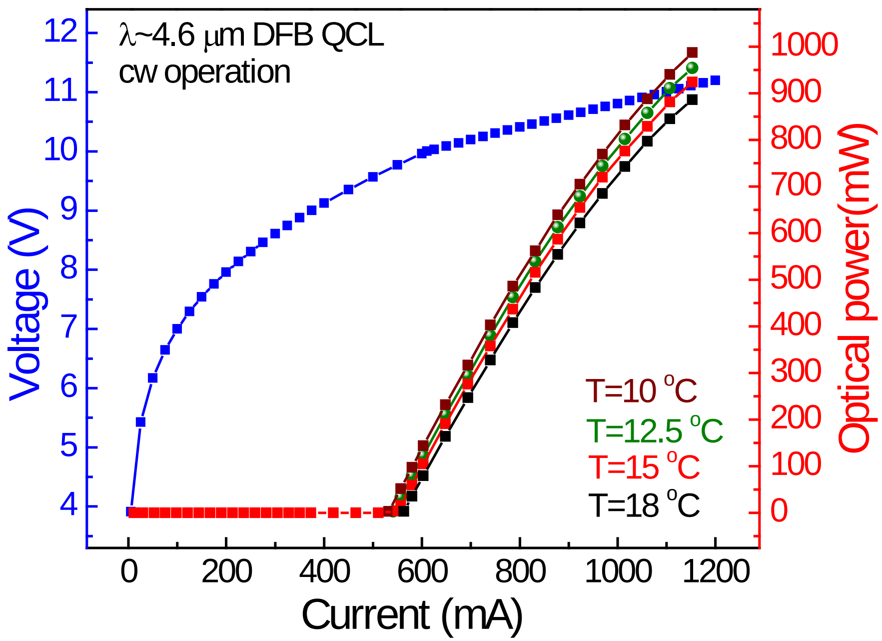
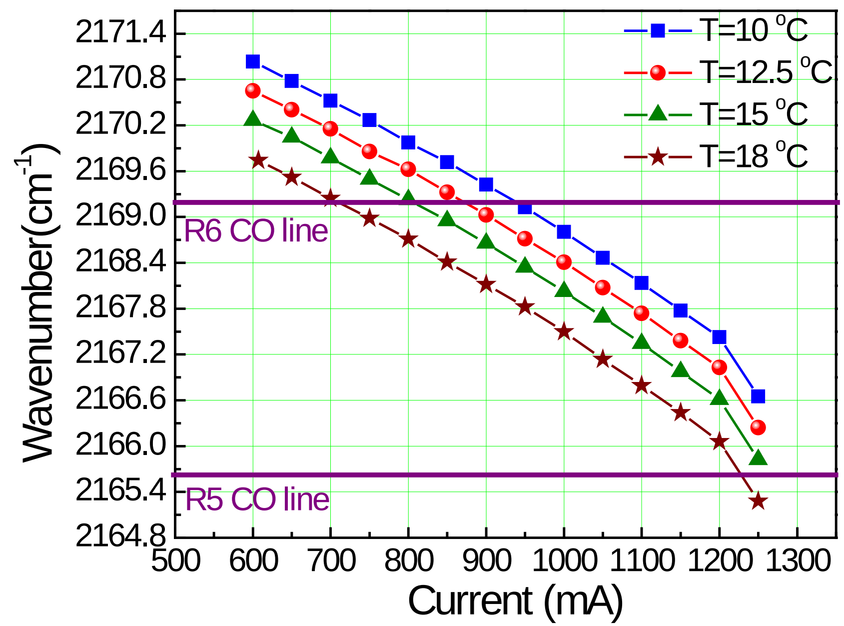
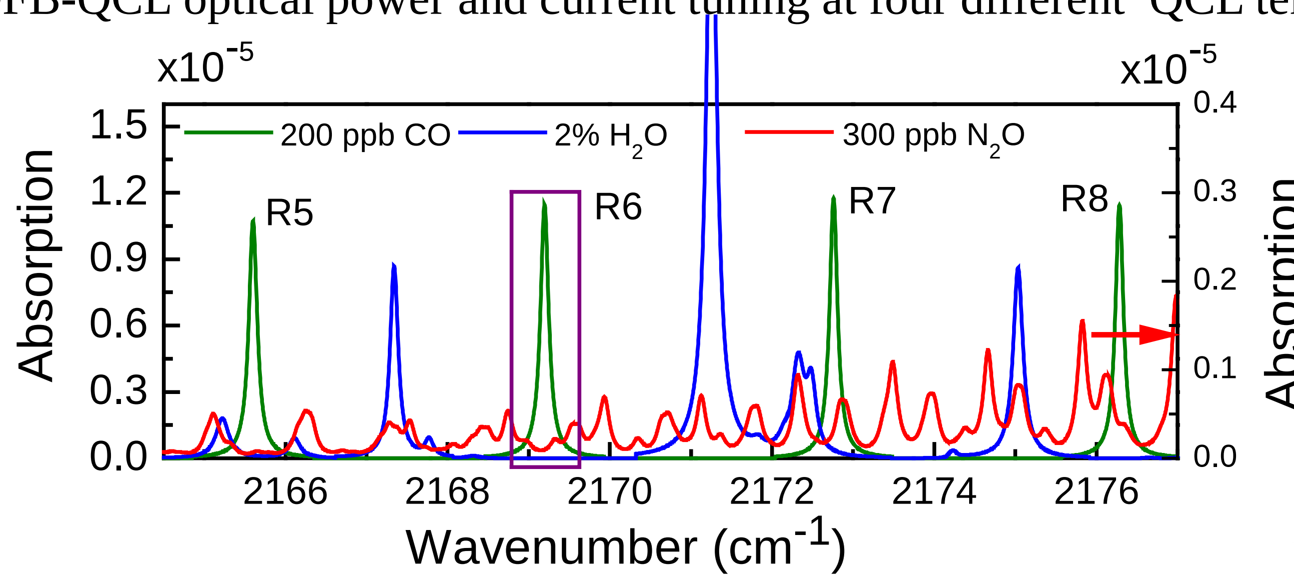
Performance of a NWU 4.6 μm high power CW TEC DFB QCL

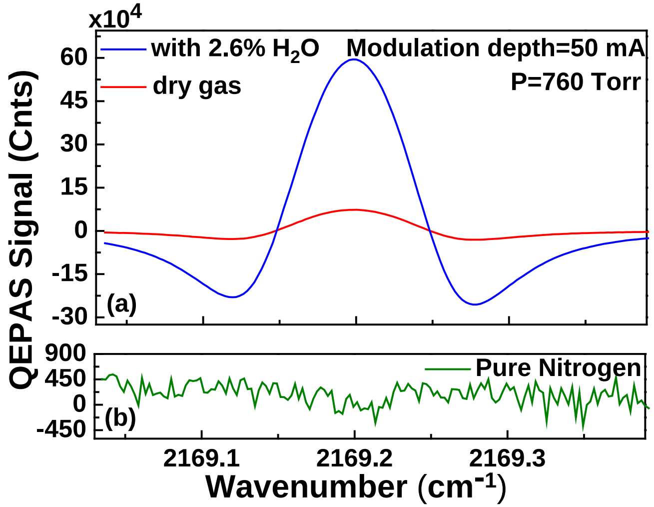




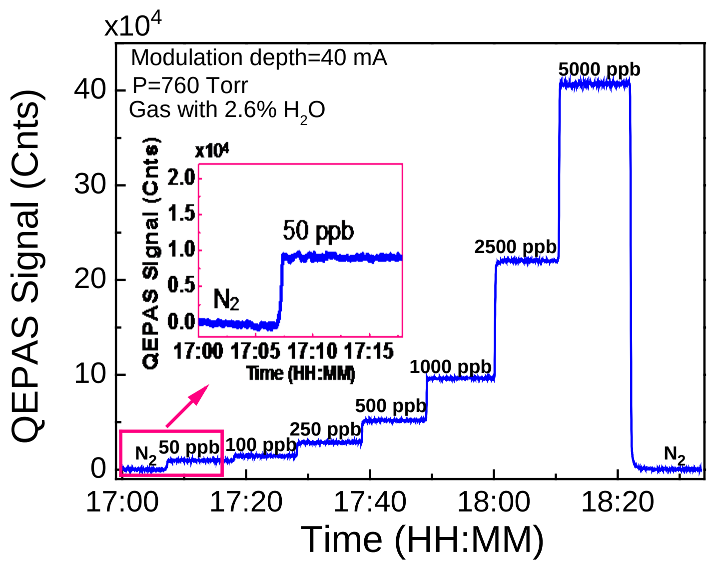
CW DFB-QCL optical power and current tuning at four different QCL temperatures.



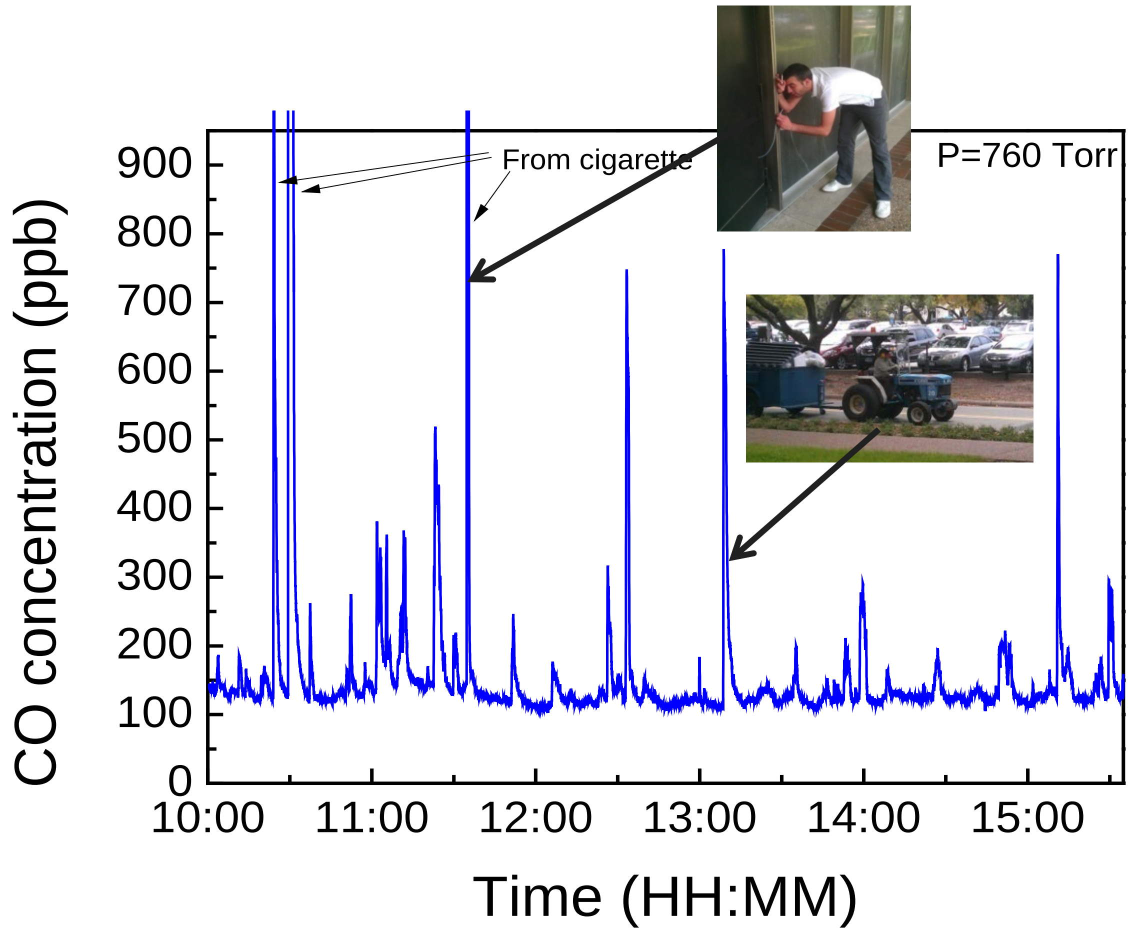
CW DFB-QCL based CO QEPAS Sensor Results



2f QEPAS signal for dry (red) and moisturized (blue) 5 ppm CO:N_2 mixture near **2169.2 cm^{-1}**.



Dilution of a 5 ppm CO reference gas mixture when the CW DFB-QCL is locked to the **2169.2 cm^{-1}** R6 CO line.



Atmospheric CO concentration levels on Rice University campus, Houston, TX

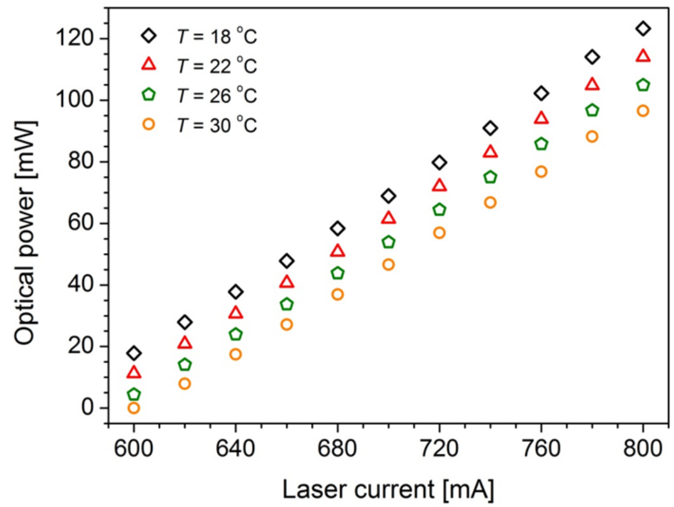
Minimum detectable CO concentration is:

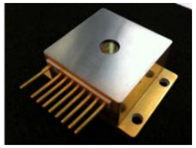
~ 2 ppbv (1σ; 1 s time resolution)

CW DFB-QCL based SO_2 QEPAS Results

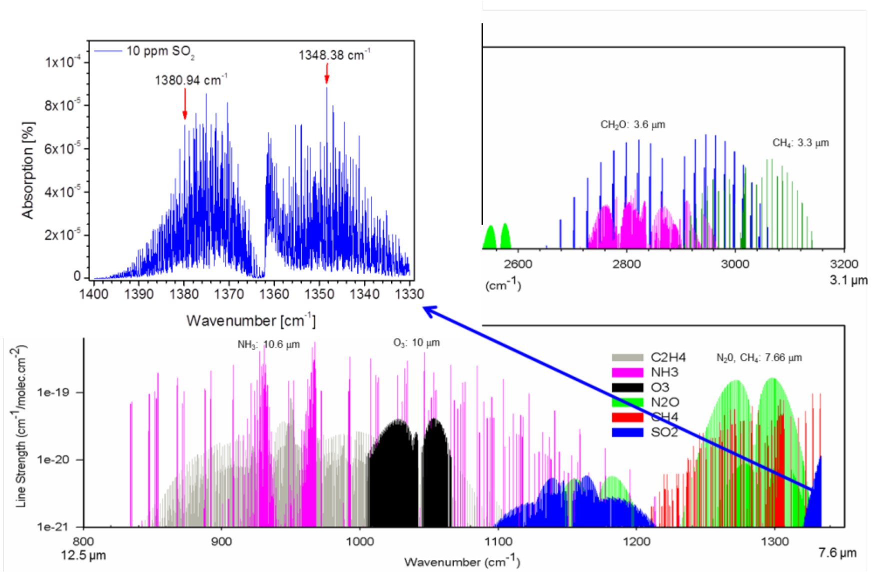
Motivation for Sulfur Dioxide Detection

- Prominent air pollutant
- Emitted from coal fired power plants (~73%) and other industrial facilities (~20%)
- In atmosphere SO_2 converts to sulfuric acid ➔ primary contributors to acid rain
- SO_2 reacts to form sulfate aerosols
- Primary SO_2 exposure for 1 hour is 75 ppb
- SO_2 exposure affects lungs and causes breathing difficulties
- Currently, reported annual average atmospheric SO_2 concentrations range from ~ 1 - 6 ppb

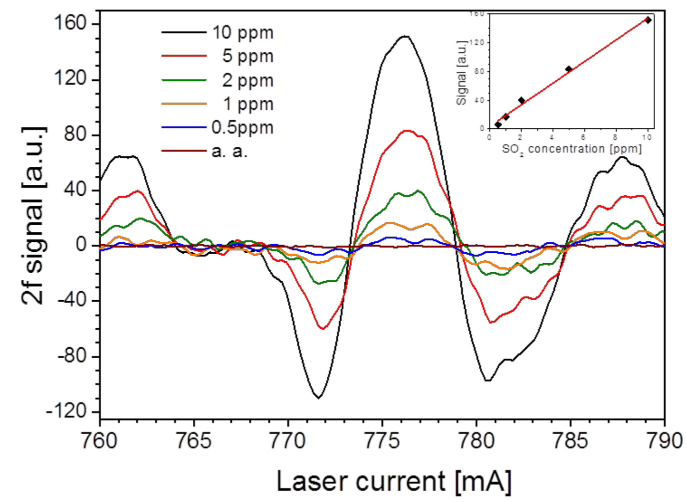




7.24 µm CW DFB-QCL optical power and current tuning at three different operating temperatures.



Molecular Absorption Spectra within two Mid-IR Atmospheric Windows

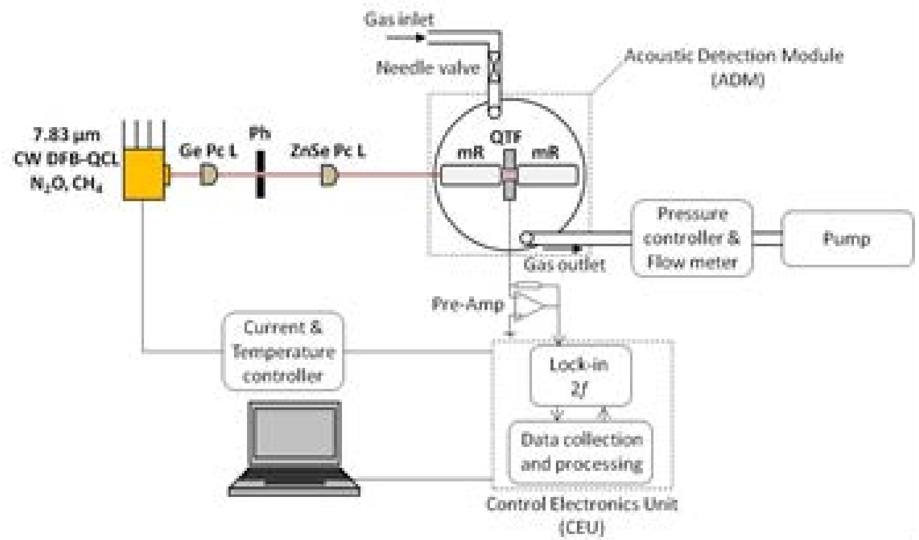


2f WMS QEPAS signals for different SO_2 concentrations when laser was tuned across **1380.9 cm^{-1}** line.

Minimum detectable SO_2 concentration is:

~ 100 ppbv (1σ; 1 s time resolution)

CW TEC DFB QCL based QEPAS CH_4 & N_2O Gas Sensor



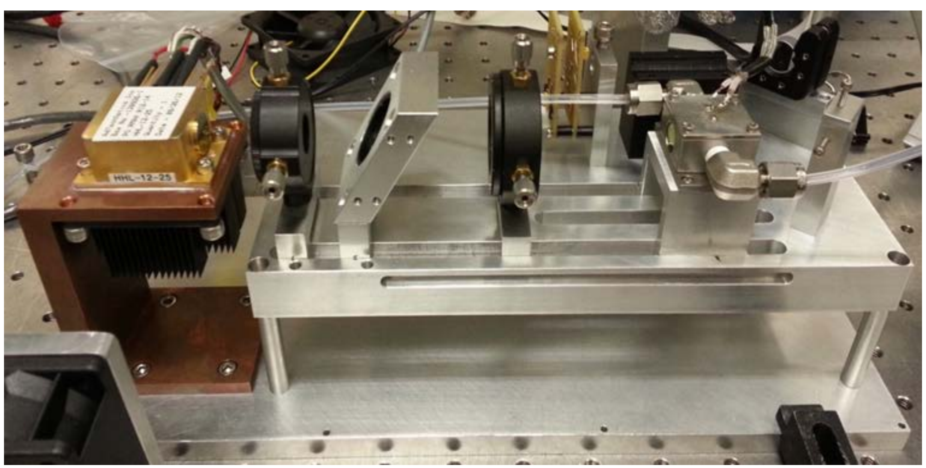
Ge Pc L and ZnSe Pc L – plano-convex lenses, Ph – pinhole, QTF – quartz tuning fork, mR – acoustic micro-resonator

Motivation for CH_4 Detection

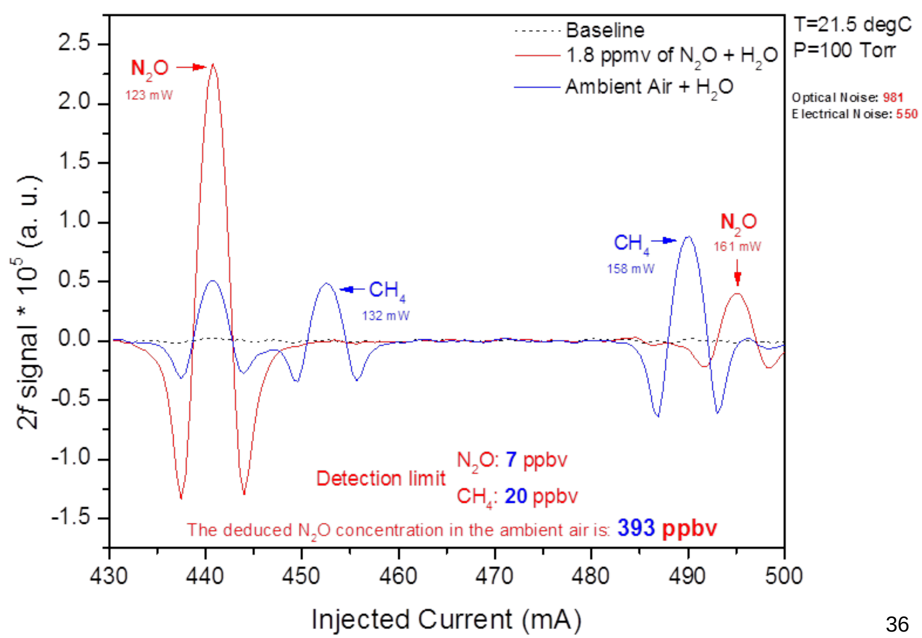
- Prominent greenhouse gas
- Leakage from Natural Gas Systems
- Animal Husbandry
- Fossil Fuel Production

Motivation for N_2O Detection

- Major greenhouse gas and air pollutant
- Agriculture
- Fossil Fuel Combustion
- Wastewater Management
- Industrial processes
- Medical Applications



Current CH_4 & N_2O Sensor Platform



QCL based QEPAS Performance for10 Trace Gas Species (February 2013)

Molecule (carrier gas)	Frequency cm^{-1}	Pressure Torr	NNEA $cm^{-1}W/Hz^{½}$	QCL Power mW	NEC (τ=1s) ppbV
CH_2O (N_2:75% RH)*	2804.90	75	8.7×10^{-9}	7.2	120
CO (N_2+ 2.2% H_2O)*	2176.28	100	1.57×10^{-8}	71	2
CO (propylene)	2196.66	50	7.4×10^{-8}	6.5	140
N_2O (air+5%SF_6)	2195.63	50	1.5×10^{-8}	19	7
N_2O (N_2+2.37%H_2O)	2201.75	200	2.9×10^{-8}	70	2.5
C_2H_5OH (N_2)**	1934.2	770	2.2×10^{-7}	10	$9\text{x}10^4$
NO (N_2+H_2O)	1900.07	250	7.5×10^{-9}	100	3.6
SO_2 (N_2+2.4%H_2O)	1380.94	100	2.0×10^{-8}	40	100
N_2O (air)	1275.49	230	5.3×10^{-8}	100	30
CH_4 (air)	1275.39	230	1.7×10^{-7}	100	118
C_2HF_5 (N_2)***	1208.62	770	7.8×10^{-9}	6.6	9
NH_3 (N_2)*	1046.39	110	1.6×10^{-8}	20	6
SF_6***	943.73	75	2.7×10^{-10}	40	5×10^{-2}

* - Improved microresonator
** - Improved microresonator and double optical pass through ADM
*** - With amplitude modulation and metal microresonator

NNEA – normalized noise equivalent absorption coefficient.
NEC – noise equivalent concentration for available laser power and τ=1s time constant, 18 dB/oct filter slope.

For comparison: conventional PAS 2.2 (2.6)×10^{-9} $cm^{-1}W/\sqrt{Hz}$ (1,800; 10,300 Hz) for NH_3*, (**)

* M. E. Webber et al, Appl. Opt. 42, 2119-2126 (2003); ** J. S. Pilgrim et al, SAE Intl. ICES 2007-01-3152; *** - V. Spagnolo, et al. University and Politecnico of Bari, Italy

Merits of QEPAS based Trace Gas Detection

- Very small sensing module and sample volume (a few mm^3 to ~$2cm^2$)
- Extremely low dissipative losses
- Optical detector is not required
- Wide dynamic range
- Frequency and spatial selectivity of acoustic signals
- Rugged transducer – quartz monocrystal; can operate in a wide range of pressures and temperatures
- Immune to environmental acoustic noise, sensitivity is limited by the fundamental thermal TF noise: $k_B T$ energy in the TF symmetric mode
- Absence of low-frequency noise: SNR scales as $\sqrt{t}$, up to t=3 hours as experimentally verified

QEPAS: some challenges

- Cost of Spectrophone assembly
- Sensitivity scales with laser power
- Effect of H_2O
- Responsivity depends on the speed of sound and molecular energy transfer processes
- Cross sensitivity issues

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Future Directions and Outlook

- New target analytes such as OCS, CH_2O, nitrous acid (HNO_2), H_2O_2, ethylene (C_2H_4), propane (C_3H_8), and benzene (C_6H_6)
- Ultra-compact, low cost, robust sensors (e.g. C_2H_6, NO, CO…)
- Monitoring of broadband absorbers: acetone (C_3H_6O), acetone peroxide (TATP) , UF_6,…
- Low divergence surface emitting quantum cascade lasers
- Finite element modeling for on-axis and off-axis micro-resonators for QEPAS
- Potential Integration of DFB-QCL or ICL& QEPAS Spectrophone
- Novel optical power build-up cavity designs
- Development of trace gas sensor networks

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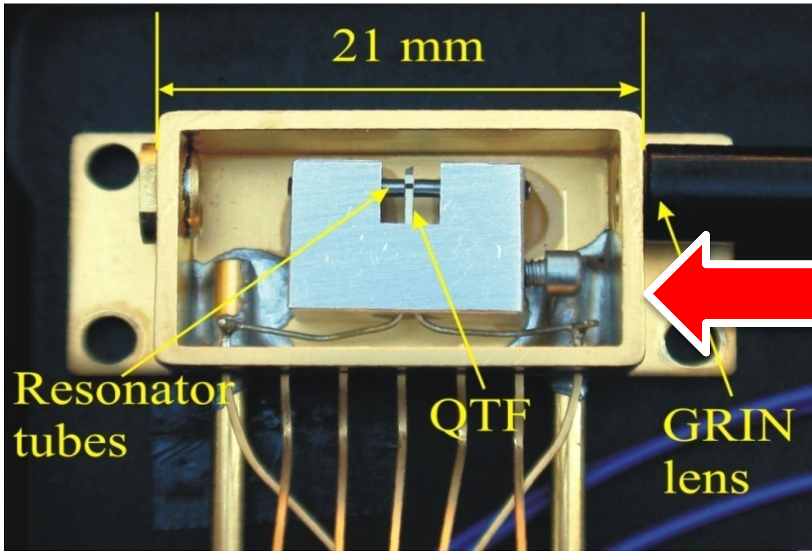
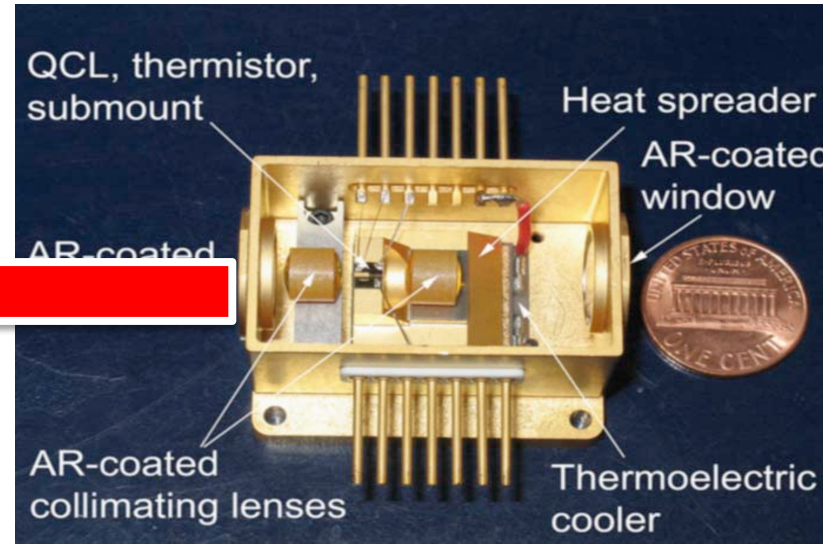
Potential Integration of a CW DFB- QCL and QEPAS Absorption Detection Module

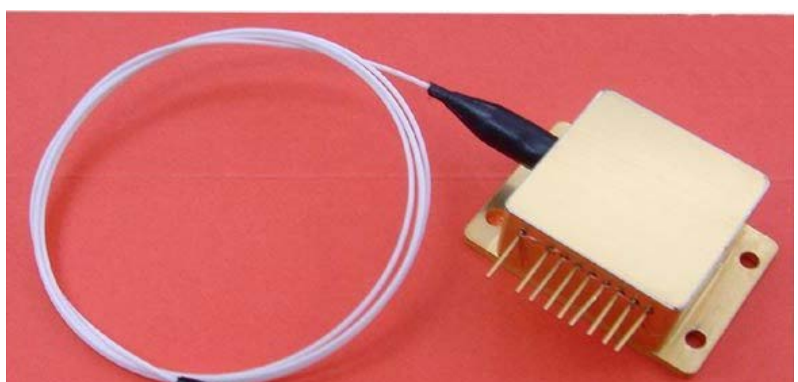


2012 QEPAS ADM

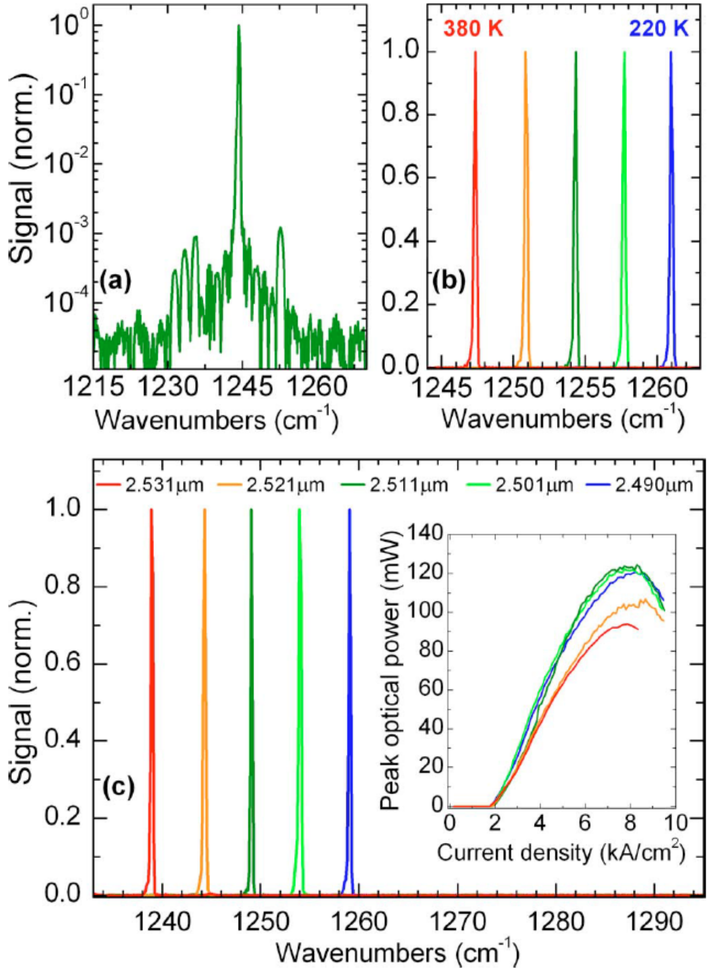


HHL package fiber coupled DFB-QCL

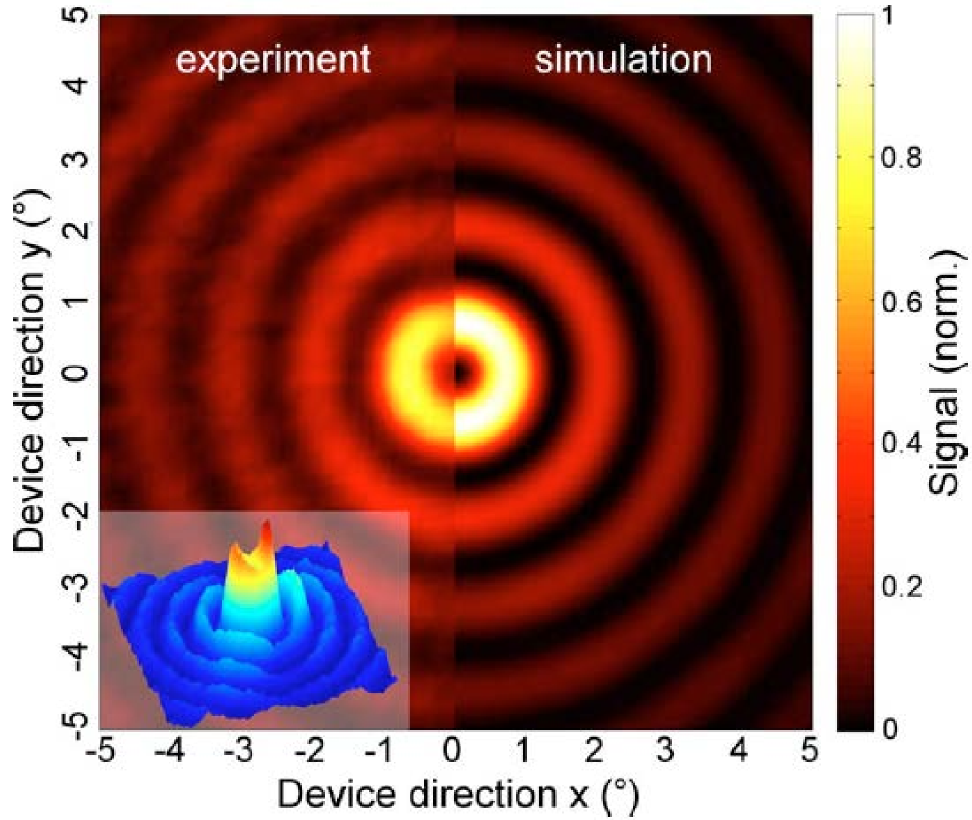
A. Lyakh, et al "1.6 W high wall plug efficiency, continuous-wave room temperature quantum cascade laser emitting at 4.6 μm", Appl. Phys. Lett. **92**, 111110 (2008)



Ring Resonator-based Surface Emitting QCL



(a) Single-mode spectrum (b) Surface emission spectra recorded at different temperatures. (c) Linear tuning of the resonance. The inset illustrates the corresponding optical power curves.

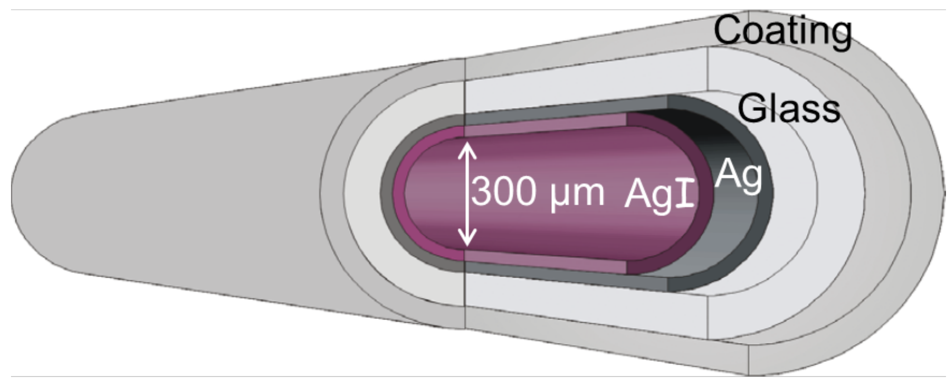


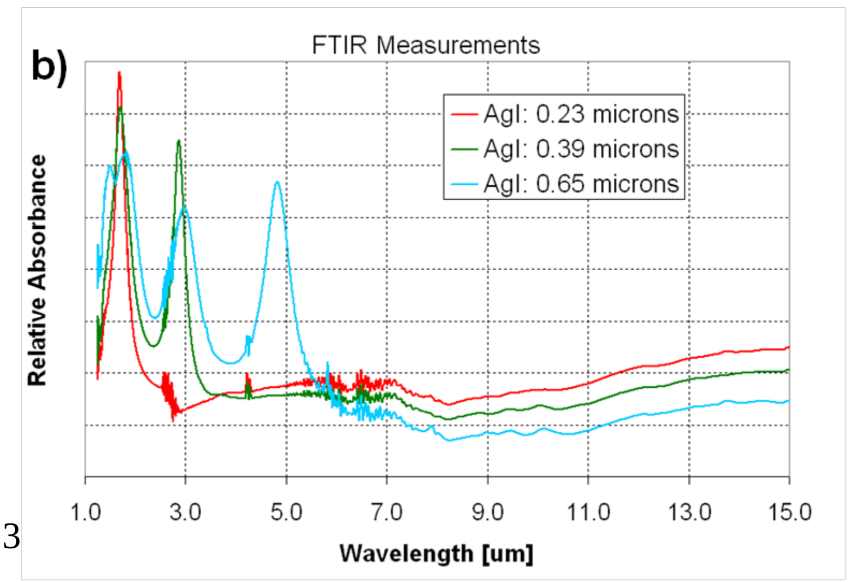
Measured (left half) and simulated (right half) surface emission far-field pattern.

G. Strasser et al , Appl. Phys Lett. 96.031111, 2010

Hollow Core Glass Waveguide

- Hollow Core Glass Waveguides
  - Excellent Infrared transmission out to 20 μm
  - Proven single mode delivery for bore size ~30λ
  - No end reflections
  - High damage threshold
  - Very Robust





For more details:V. Spagnolo , 9:50-10:10 am, Feb 28, 2013
Also to appear in Appl.Phys. B 2013

IFN Institute for Photonics and Nanotechnologies
OKSI OPTO-KNOWLEDGE SYSTEMS INC.
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Summary

- Laser spectroscopy with mid-infrared, TEC, CW, DFB laser diodes, high performance DFB QCLs and tunable EC-QCLs is a promising analytical approach for real time environmental, biomedical and industrial monitoring as well as technology for national security.
- Six mid-infrared from Nanoplus, Daylight Solutions, Maxion Technologies (Thor Labs), Hamamatsu, Northwestern University and Adtech Optics were used recently (2011-2013) in three sensor platforms: TDLAS, PAS and QEPAS
- Seven target trace gas species were detected with a 1 sec sampling time:
  - C_2H_6 at ~ 3.36 µm with a detection sensitivity of 130 pptv using TDLAS
  - NH_3 at ~ 10.4 µm with a detection sensitivity of ~1 ppbv (200 sec averaging time);
  - NO at ~5.26µm with a detection limit of 3 ppbv
  - CO at ~ 4.61µm with minimum detection limit of 2 ppbv
  - SO_2 at ~7.24µm with a detection limit of 100 ppbv
  - CH_4 and N_2O at ~7.28 µm concentration are <u>currently in progress</u> with detection limits of 20 and 7 ppbv, respectively.

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