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Compact multi-pollutant mid-IR laser spectroscopic trace-gas sensor

towards applications in distributed wireless sensor networks

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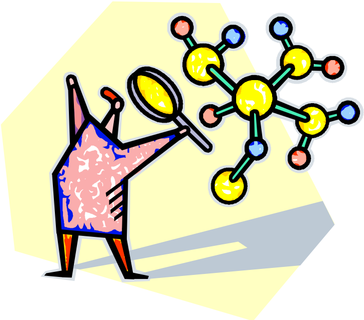
Trace Gas Sensing Applications

Environmental Monitoring

Remote sensing and
Space exploration

Urban and Industrial Emission
Measurements

Fundamental Science



Industrial Process Control

Law Enforcement and National Security

Motivation

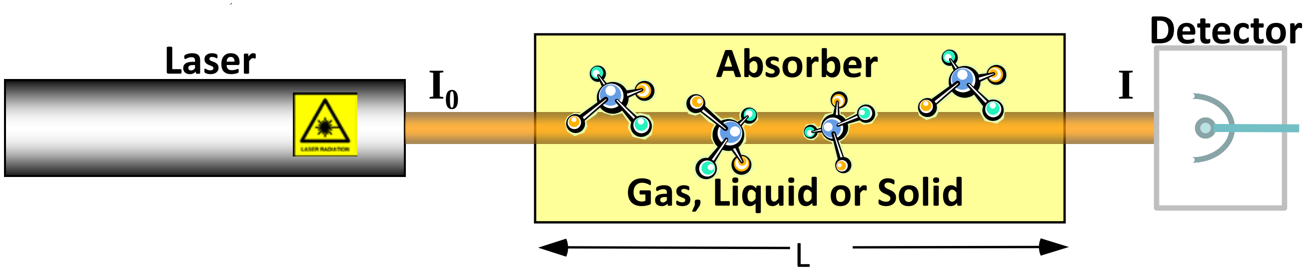
- Sensing of airborne chemicals is of importance in a number of atmospheric monitoring applications and will play a major role in further improvement of emissions inventories

- Recent studies indicate that industrial emissions may be 10-20x greater than the amount estimated using current standard emission factors

- Development of new, sensitive, multi-species sensing technologies, which can be configured into wireless sensor networks (WSNs) to create dynamic pollutant concentration maps will be a critical step towards improvement of the emission control and monitoring

Laser Spectroscopy

- High sensitivity
- High selectivity
- Non-destructive
- Fast
- No sample preparation
- Remote sensing
- Field deployable

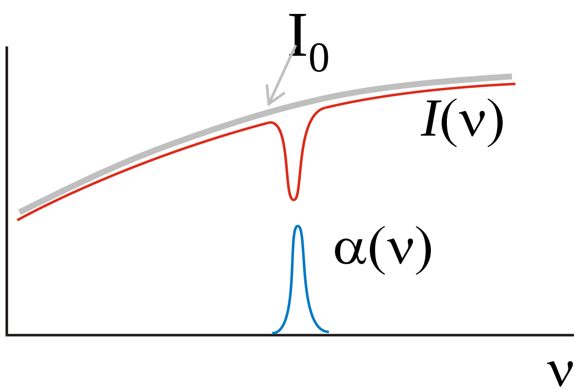


Beer-Lambert's Law of Linear Absorption

$$I = I_0 \cdot e^{-\alpha(\nu) \cdot L}$$

$\alpha(\nu)$ - absorption coefficient [cm^{-1}]; L – path length [cm]

ν - frequency [cm^{-1}];



$$\alpha(\nu) = S(T) \cdot g(\nu - \nu_0) \cdot \mathrm{N}$$

N – concentration [molecule·cm^{-3}]

S - molecular line intensity [cm^{-1}/(molecule·cm^{-2})]

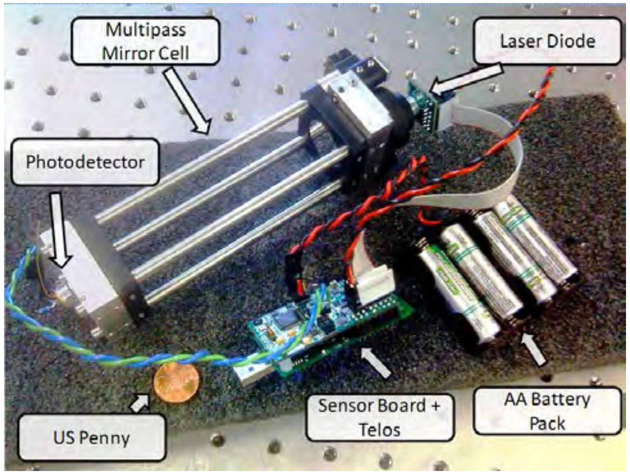
g(ν- ν_0) - normalized lineshape function [cm], (Gaussian, Lorentzian, Voigt)

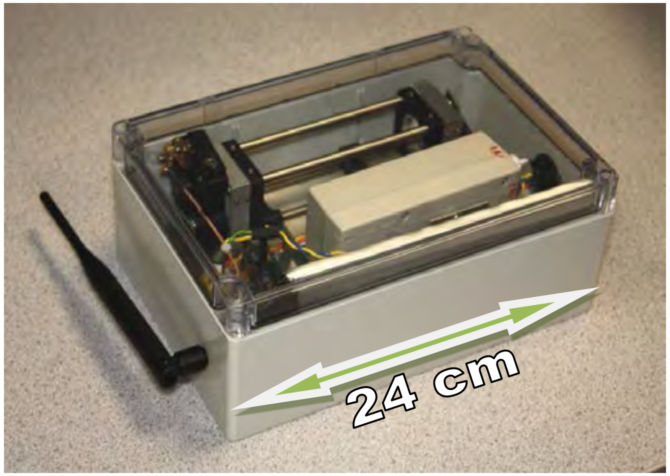
Existing WSN platform

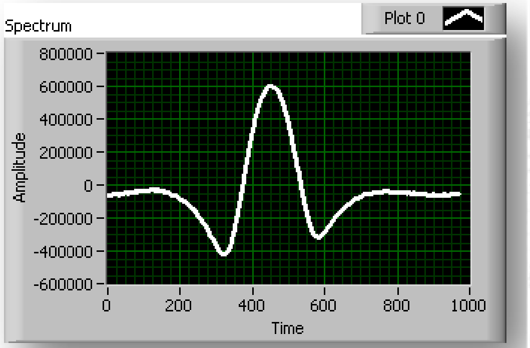
- Semiconductor lasers used as spectroscopic sources can yield compact, sensitive and selective spectroscopic trace-gas sensors
- We have developed a ultra-low-power embedded laser spectroscopic sensor systems employing telecommunication diode lasers for atmospheric CO_2 monitoring
- Modular expansion design allows for flexibility in configuration for specific applications as well as for efficient adoption of new laser technologies

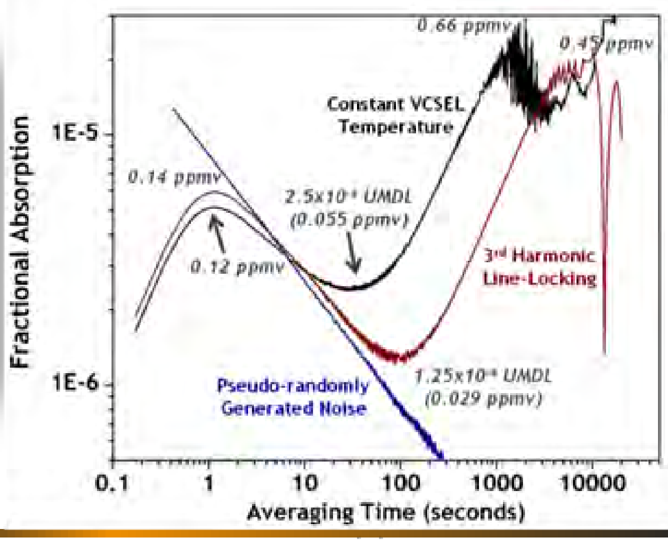
Demo of CO_2 Sensor @ 2 microns

- Fully autonomous, fully digital
- ~0.3W total consumption (continuous) w/ wireless transmission
- >16 Hour run time on NiMH AA batteries (continuous)
- CO_2 sensor node:
  - Sensitivity **~120ppb in 1sec.**
  - 3.5 meter multipass cell



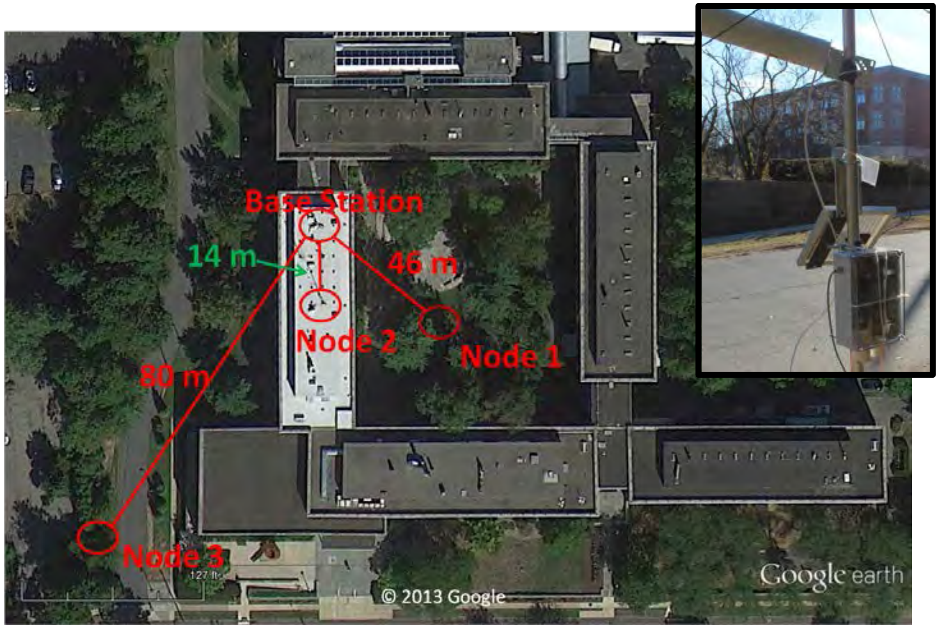




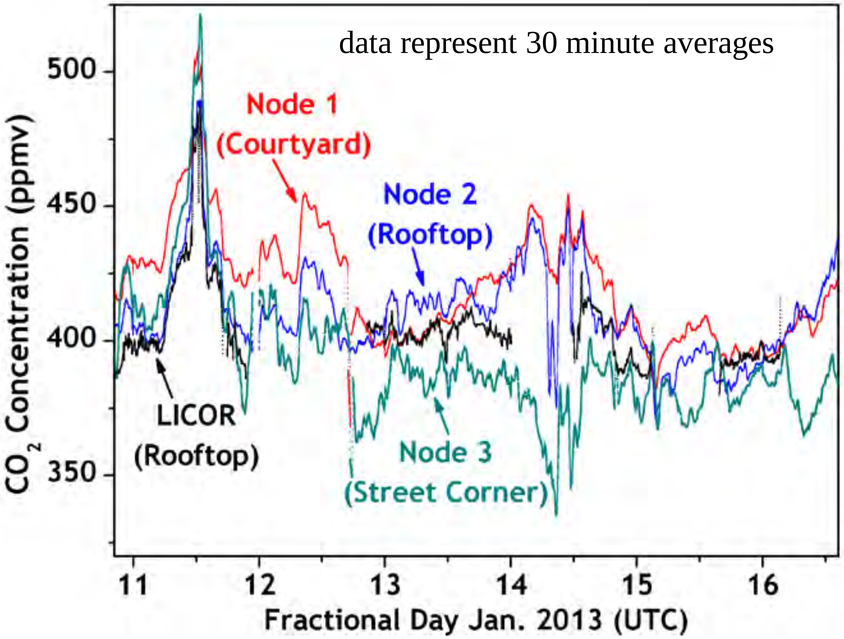


Existing WSN platform

Laser spectroscopic WSN for CO_2 monitoring around the E-QUAD at Princeton University



Data from the WSN shown with the commercial CO_2 analyzer available on site



- Time-division-multiple-access network (TDMA) scheme based on commercial wireless communications cards coupled with the sensor electronics via UART
- Nodes 1 and 3 were solar-powered during the entire deployment.
- The sensors show consistent results and the network interaction is virtually transparent.

Challenges in multi-species detection

- Most chemical compounds in gas phase (including volatile organic compounds, or hydrocarbons) have their strongest fundamental ro-vibrational transitions in the mid-infrared region (~3-16 μm).
- To perform spectroscopic multi-component analysis of chemical species, widely tunable mid-IR laser sources are needed
- Similarly spectroscopic instrumentation that is capable of identification and quantification of large molecular compounds with broadband spectral signatures (e.g. VOCs and other environmentally important molecules) require wide spectral tuning

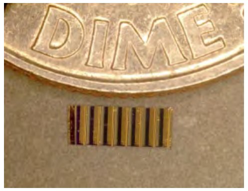
Therefore:

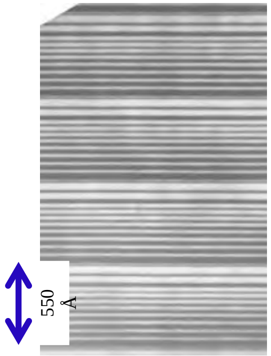
- Mid-IR spectroscopy and spectroscopic WSNs can greatly benefit from the development and implementation of new widely tunable laser sources for multi-component chemical analysis

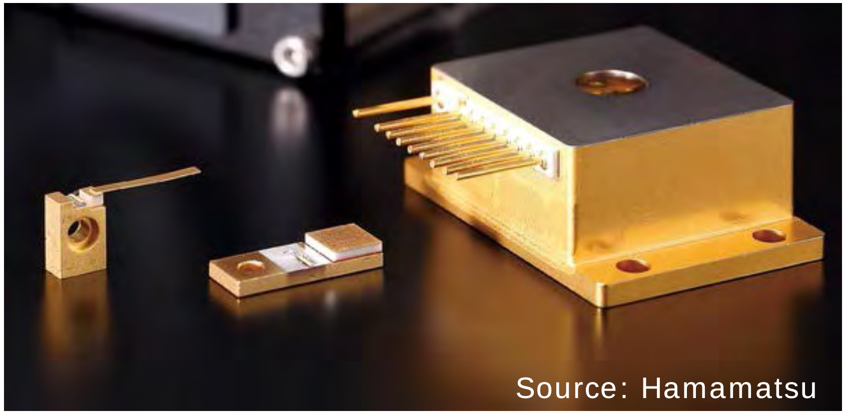
Quantum Cascade Lasers: Basic Facts

- Laser wavelengths in the Mid-IR range : (~3 – 24μm, band structure engineering)
- High laser power : (>500mW cw, >5W peak for pulsed)
- Tunable single frequency operation (DFB up to ~10 cm^{-1}, EC >300 cm^{-1})
- Linewidth (<0.001cm^{-1} for CW and <0.03 cm^{-1} for pulsed)

  (Cascading: 1 electron = N photons; WPE ~50% recently reported)
- High reliability, long lifetime
- Room temperature operation : (CW: above RT)
- Compact
- Commercially available







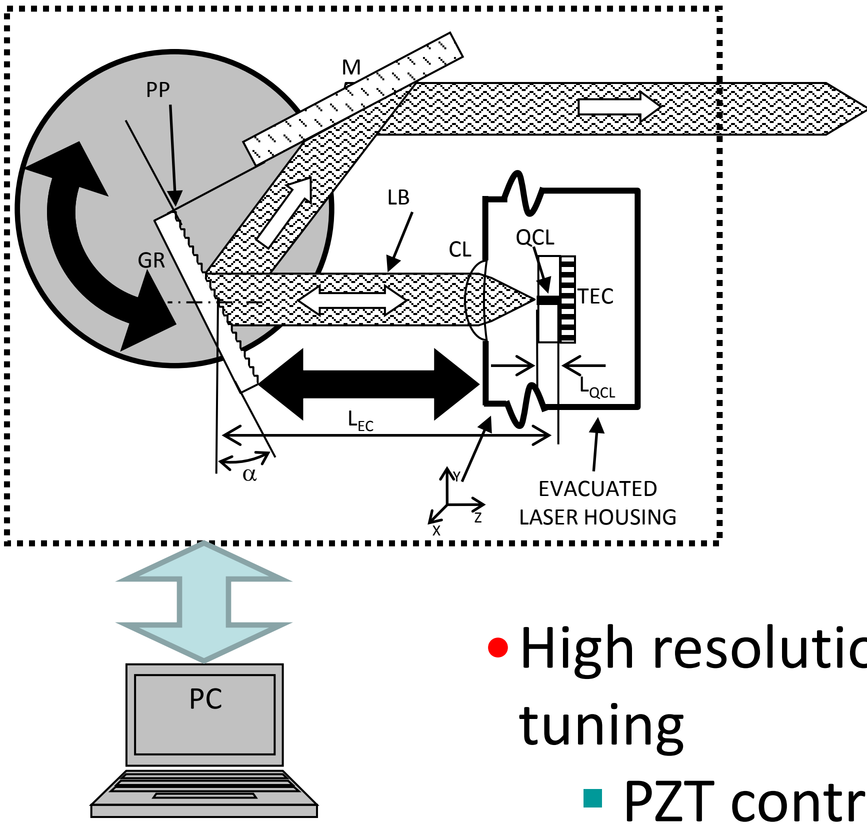
Project Goal and research tasks

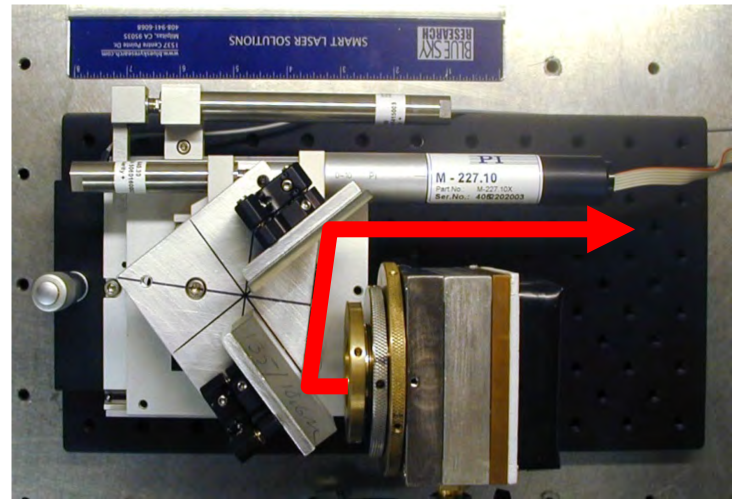
- Develop a sensor node with WSN capabilities for detection of multiple trace-gas pollutants

Specific tasks:

- ➢ Adopt widely tunable quantum cascade laser technology for spectroscopy of broadband absorbers
- ➢ Build a proof-of-concept prototype spectrometer targeting Benzene (C_6H_6) and Ammonia (NH_3) to demonstrate multi-species detection
- ➢ Preform instrument field test and inter-comparison with other established technologies

Mode-hop Free Tunable External Cavity QCL



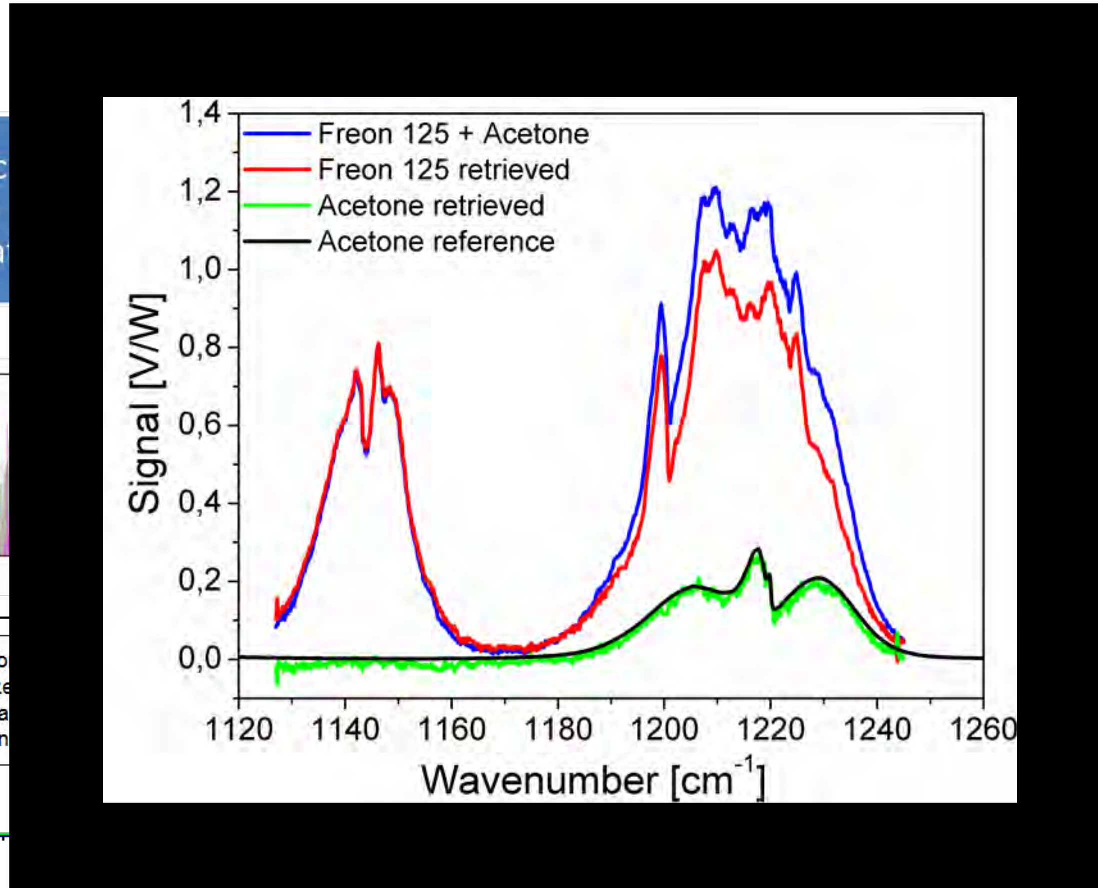


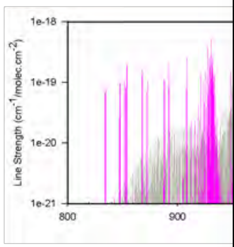
- High resolution mode-hop free wavelength tuning
  - PZT controlled EC-length
  - PZT controlled grating angle
  - QCL current control
- Motorized coarse grating angle tuning

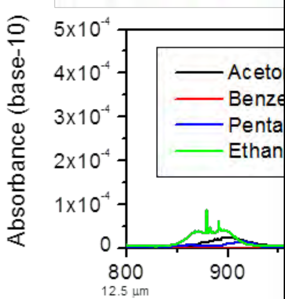
G. Wysocki et al. APB92 p.305 (2008)

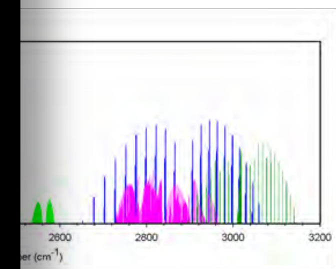
EC-QCLs for Atmospheric Trace-gas Sensing

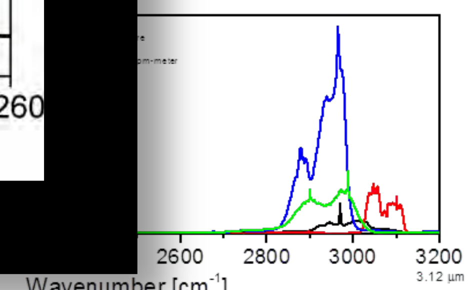
Atmospheric
absorption
(100m open pa

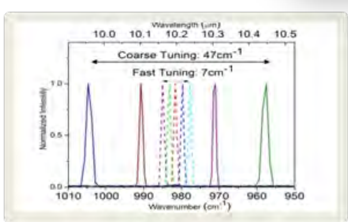


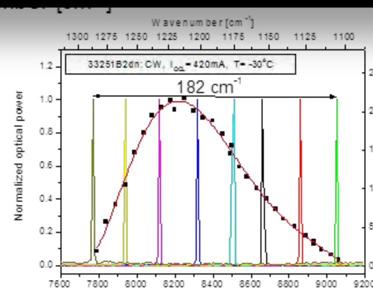


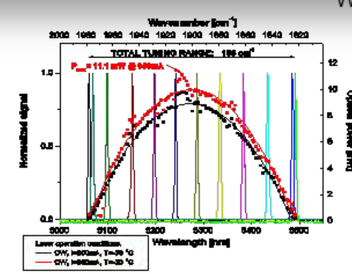


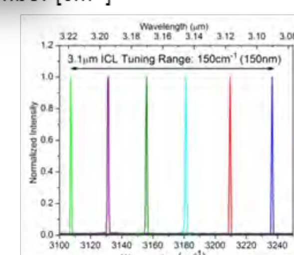




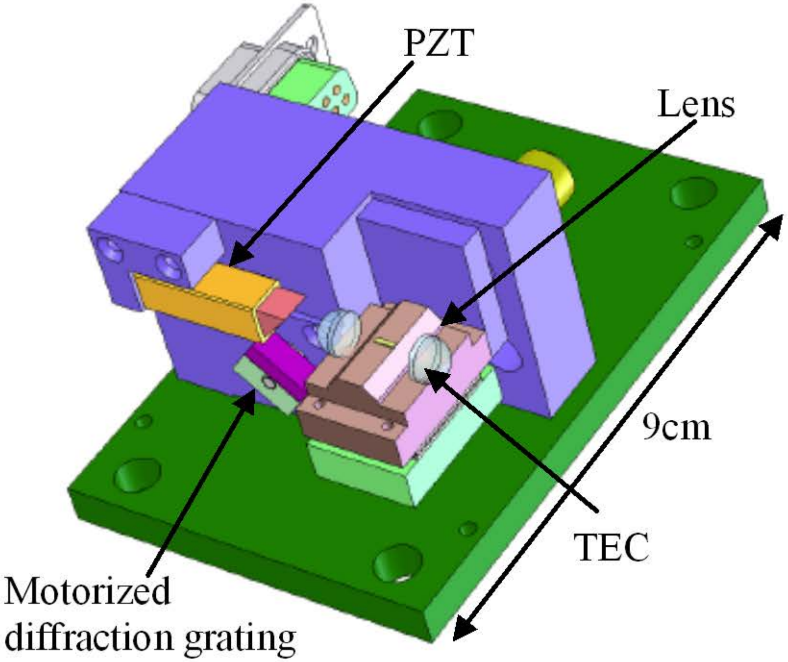




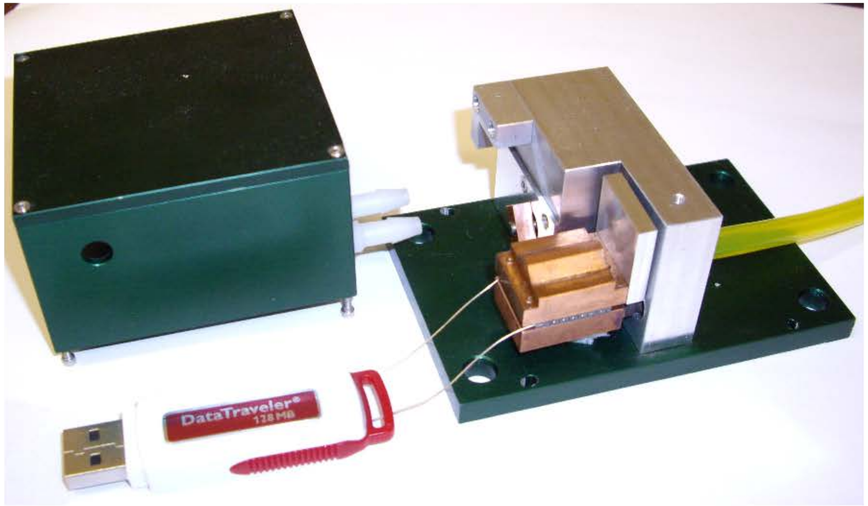




Miniature EC-QCL



(a)

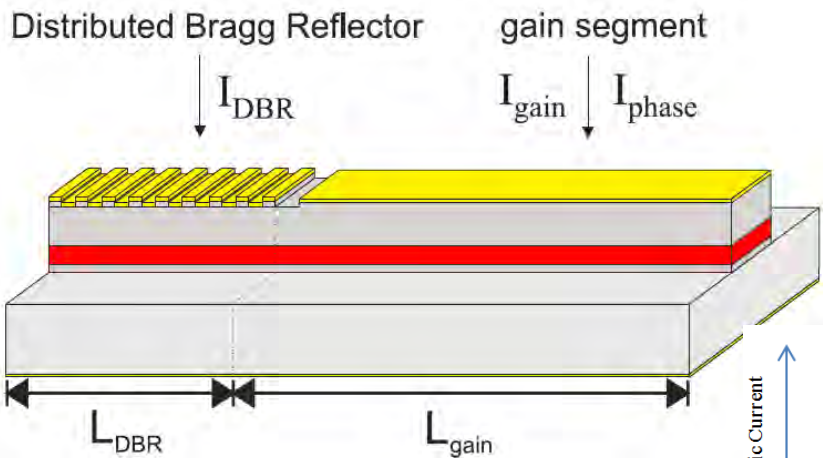


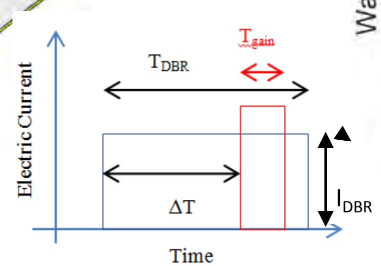
(b)

- High efficiency thermal management
- Integrated micro-aligned optics
- >200ml total size of the laser head
- High mechanical and thermal stability

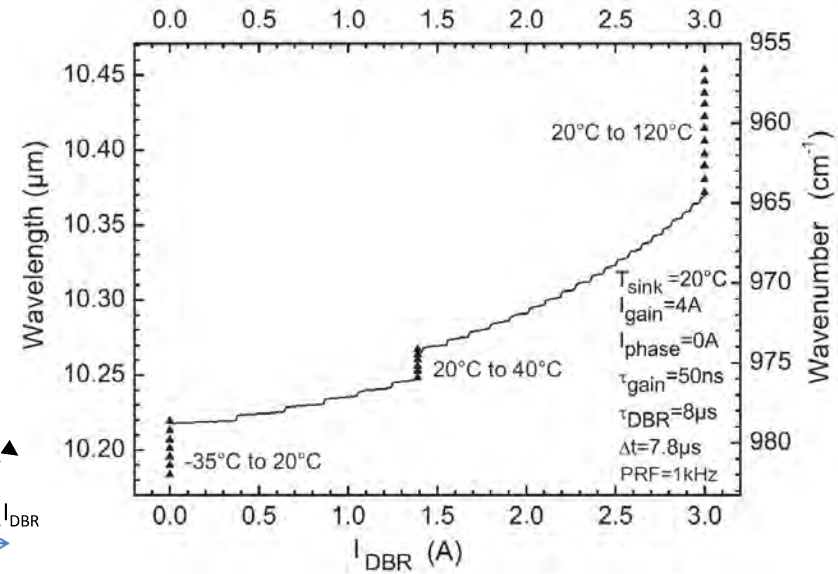
New technology for QCL tuning

Distributed Bragg grating QCL Schematic





Tuning range



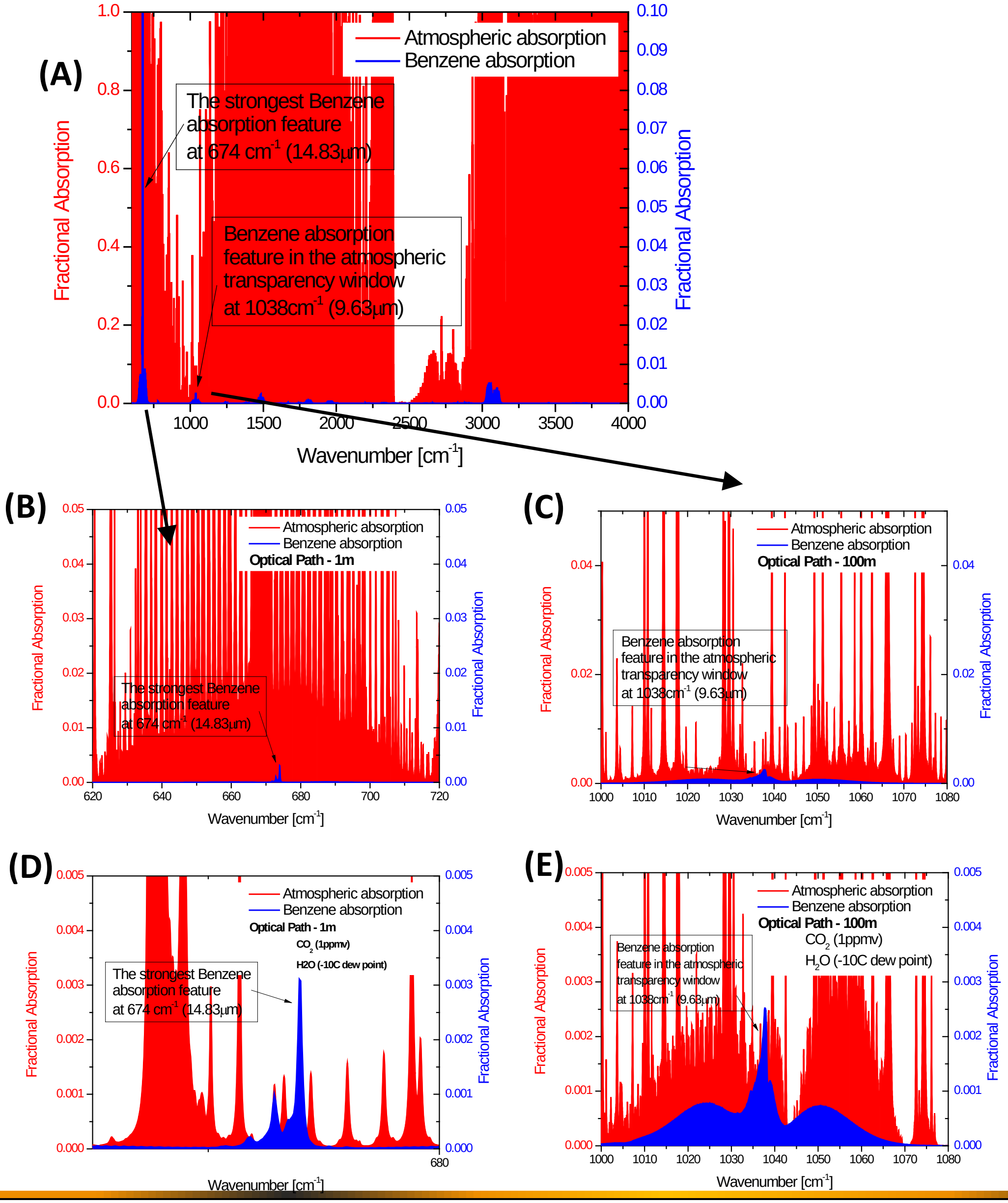
- No moving parts
  - Excellent opto-mechanical stability
  - Ideal for field deployments
- Fully electrical broadband tuning
  - Gain current tuning: narrow, continuous
  - DBR current tuning: wide, discrete (controlled longitudinal mode hopping)

Source: P. Fuchs, et. al, Opt. Express **20**, 3890-3897 (2012).

Comparison of tunable QCL technologies

Parameters	External Cavity EC-QCL	Distributed Bragg Grating DBR-QCL	Distributed feedback DFB-QCL
Maximum Tunability	up to $400 cm^{-1}$	~$10 cm^{-1}$ (electrical); >$20 cm^{-1}$ (thermal)	1-$2 cm^{-1}$ (electrical); ~$10 cm^{-1}$ (thermal)
Scan repetition rate	Slow (<100Hz)	Fast (10-100kHz) (thermal- slow)	Fast (10-100kHz) (thermal- slow)
Construction / tuning	Moving parts / Opto-mechanical	No moving parts / electrical	No moving parts / electrical

Spectroscopy of C_6H_6 in the mid-IR



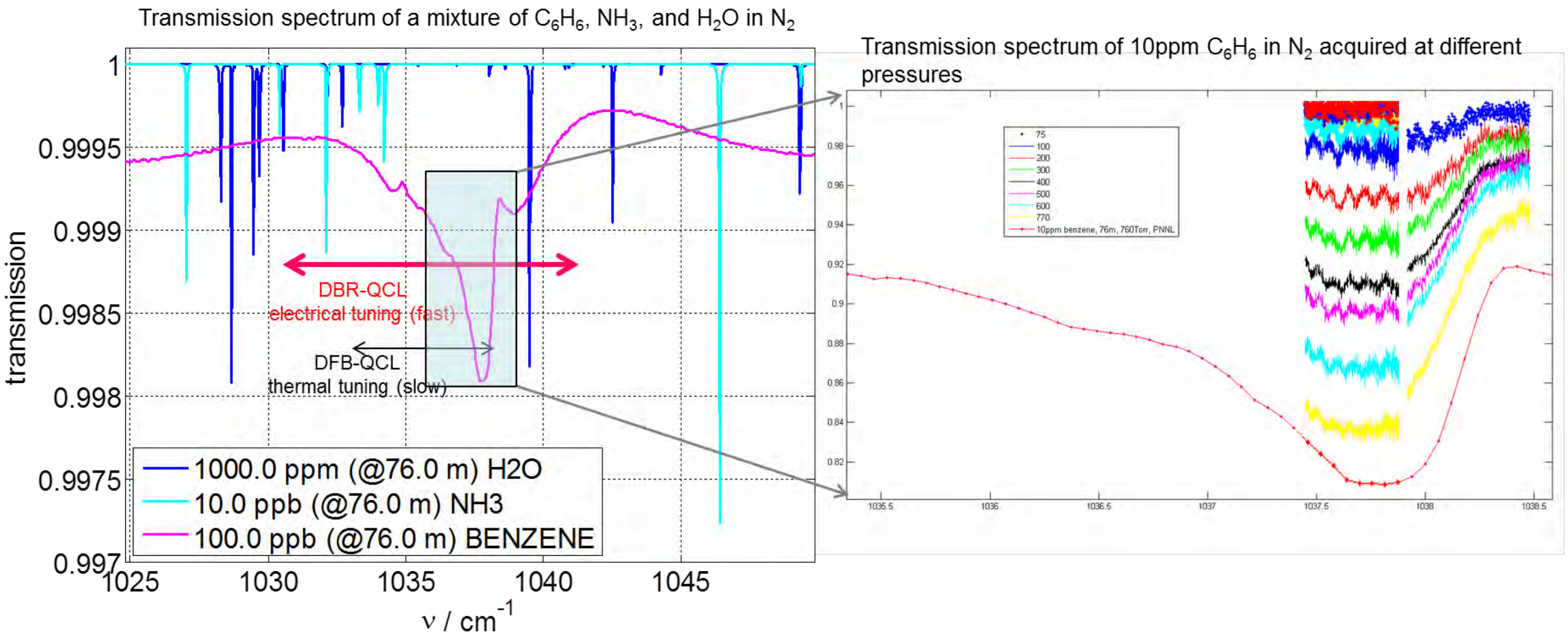
(A) Absorption features of 100ppb Benzene (blue) over 100m optical path plotted together with average atmospheric absorption (red).

(B) The strongest absorption band of Benzene (blue) and the atmospheric interference (red) calculated for 1m optical path

(C) The absorption band of Benzene (blue) at 9.63μm and the atmospheric interference (red) calculated for 100m optical path

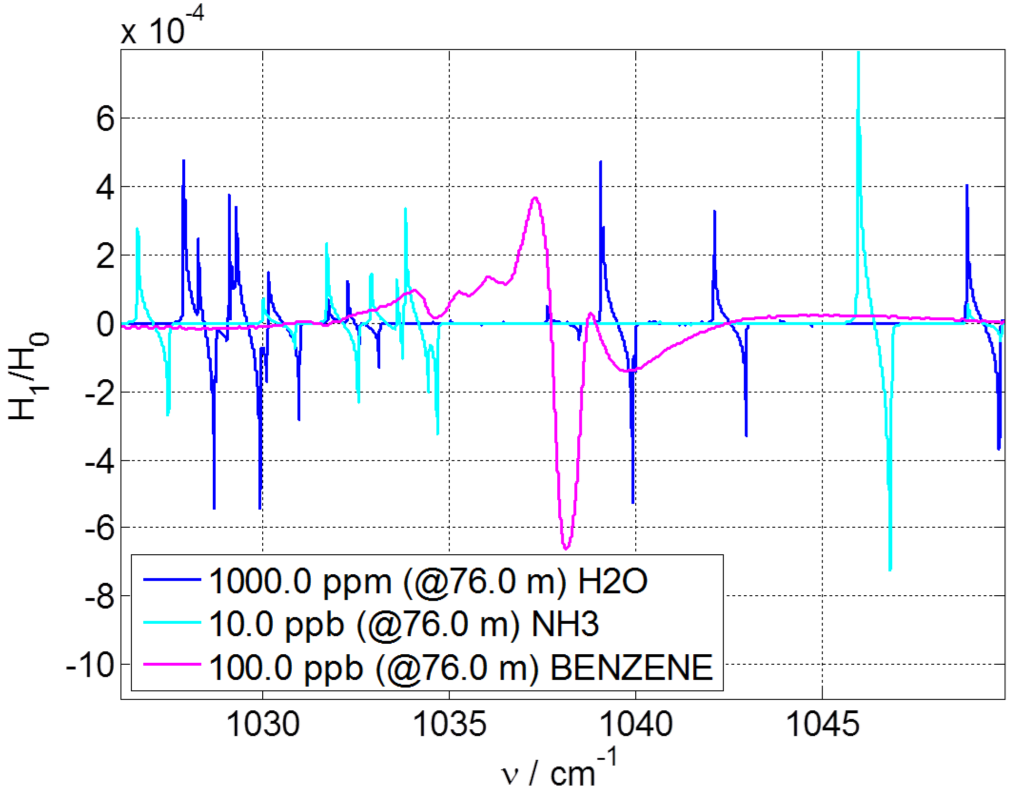
(D) and (E) pre-conditioned air sample with CO_2 scrubbed to 1ppm level and moisture removed down to -10°C dew point.

Preliminary spectroscopy of C_6H_6 at 9.6μm



- Spectral simulations of the C_6H_6 band at 9.6 μm
  - The entire feature spans ~50cm^{-1}
  - The Q-branch at 1037cm^{-1} is narrow (~3cm^{-1}) and shows relatively small interference from other species
- Preliminary transmission data collected using a DFB-QCL operating at 1037cm^{-1}
- The 5 cm^{-1} thermal tuning range of a DFB QCL gives access to both species (C_6H_6 and NH_3) and could be used for detection
- **DBR-QCL with >10cm^{-1} fast electrical tuning – best for trace-gas WSN-node**

Simulation of wavelength modulated spectra of C_6H_6 at 9.6 μm



- Wavelength modulation spectroscopy (WMS) shifts the demodulated spectroscopic signal to higher frequencies
- Reduction of the 1/f noise and smaller detection bandwidth than in direct-LAS will result in higher sensitivity
- A DFB-QCL current modulation amplitude of ~54 mA provides optimum (~0.5cm^{-1}) modulation depth

Summary

- The spectroscopic WSN platform has been tested in the field and showed results consistent with other commercial sensors
- Preliminary spectroscopy of C_6H_6 with DFB-QCL has been performed
- DBR-QCL technology has been identified as the most promising broadband mid-IR source for WSN applications
- DBR-QCL is currently under test in our laboratory

Acknowledgements

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