Recent Advances of Trace Gas Sensors based on Infrared Semiconductor Lasers: Global Opportunities and Challenges

Frank K. Tittel
Rice Quantum Institute, Rice University, Houston, TX
http://ece.rice.edu/lasersci/

OUTLINE

Physics Seminar
Lund, Sweden
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- Motivation: Wide-range of Chemical Sensing
- Fundamentals of Laser Absorption Spectroscopy
- New Laser Sources and Sensing Technologies
- Selected Applications of Trace Gas Detection
  - Environmental Monitoring (H_2CO and C_2H_4)
  - Detection of nitric oxide and ethanol
  - QEPAS based monitoring of broadband absorbers
- Future Directions and Summary

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F. Harren (Nijmegen, NL)
C. Oppenheimer (Cambridge, UK)
M. Mendez (UDLA, Puebla, MX)

Wide Range of Trace Gas Sensing Applications

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

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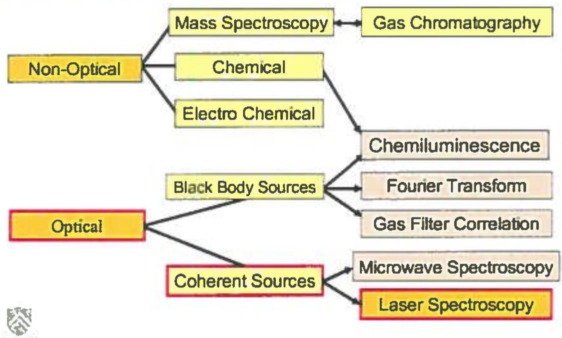
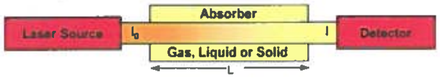
Existing Methods for Trace Gas Detection



Direct Laser Absorption Spectroscopy

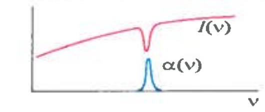


Beer-Lambert's Law of Linear Absorption

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

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

ν - frequency [cm^{-1}]; P_a- partial pressure [atm]



$$\alpha(\nu) = C \cdot S(T) \cdot g(\nu - \nu_0)$$

C - total number of molecules of absorbing gas/atm/cm³ [molecule·cm^{-3} ·atm^{1}]

S - molecular line intensity [cm ·$molecule^{-1}$]

$g(\nu - \nu_0)$ - normalized lineshape function [cm], (Gaussian, Lorentzian, Voigt)

Sensitivity Enhancement Techniques

- **Optimum Molecular Absorbing Transition**
  - Overtone or Combination Bands (NIR)
  - Fundamental Absorption Bands (MID-IR)
- **Long Optical Pathlengths**
  - Multipass Absorption Cell (White, Herriot)
  - Cavity Enhanced, Cavity Ringdown & Intracavity Spectroscopy
  - Open Path Monitoring (with retro-reflector)
  - Evanescent Wave Spectroscopy (Fibers & Waveguides)
- **Spectroscopic Detection Schemes**
  - Frequency or Wavelength Modulation
  - Balanced Detection
  - Zero-air Subtraction
  - Photoacoustic Spectroscopy
  - Noise Immune Cavity Enhanced-Optical Heterodyne Molecular Spectroscopy (NICE-OHMS)

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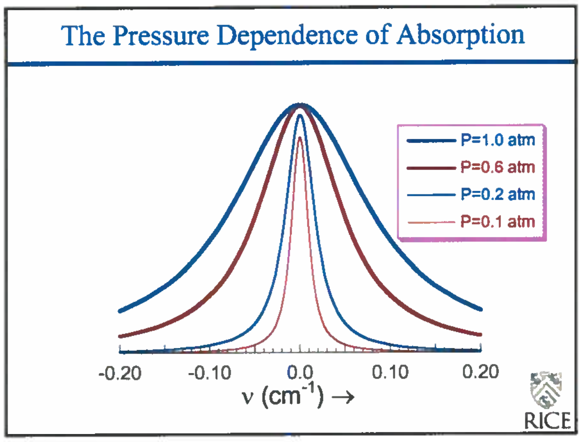
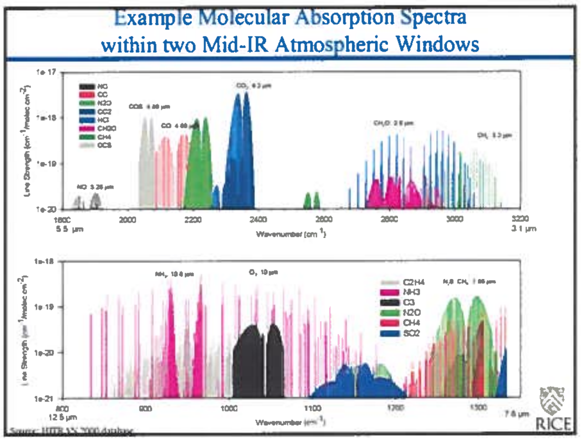
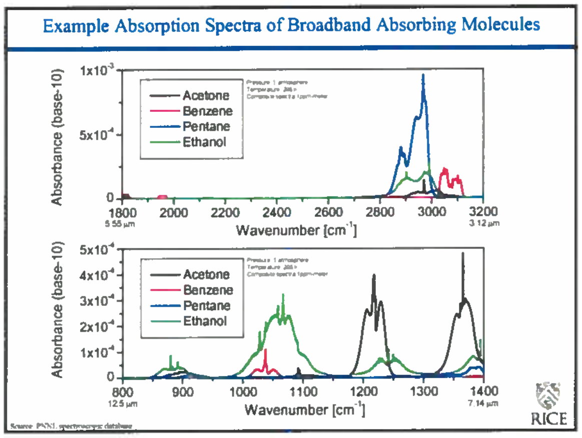


The Pressure Dependence of Absorption



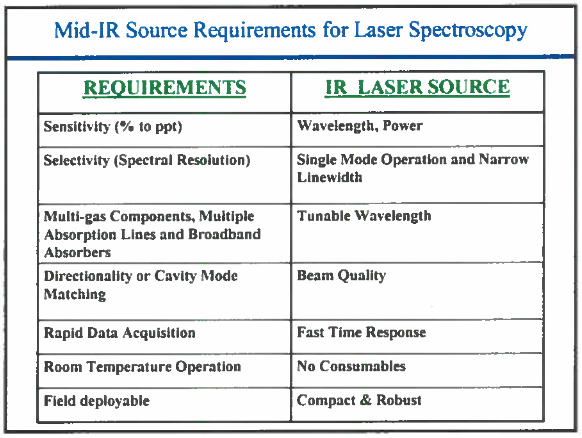
Example Molecular Absorption Spectra within two Mid-IR Atmospheric Windows

Source: HITRAN 2000 database



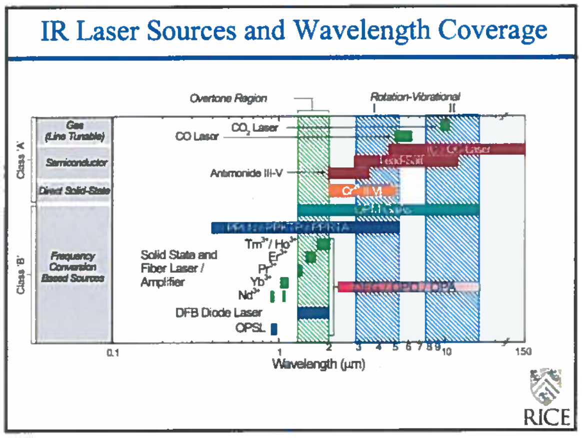
Example Absorption Spectra of Broadband Absorbing Molecules

Source: PNNL spectroscopic database

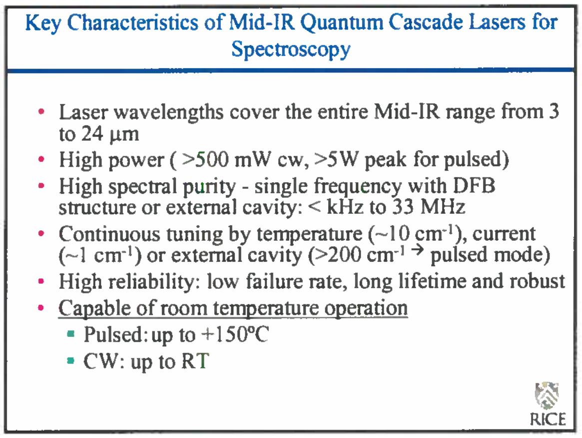


Mid-IR Source Requirements for Laser Spectroscopy

REQUIREMENTS	IR LASER SOURCE
Sensitivity (% to ppt)	Wavelength, Power
Selectivity (Spectral Resolution)	Single Mode Operation and Narrow Linewidth
Multi-gas Components, Multiple Absorption Lines and Broadband Absorbers	Tunable Wavelength
Directionality or Cavity Mode Matching	Beam Quality
Rapid Data Acquisition	Fast Time Response
Room Temperature Operation	No Consumables
Field deployable	Compact & Robust



IR Laser Sources and Wavelength Coverage



Key Characteristics of Mid-IR Quantum Cascade Lasers for Spectroscopy

- Laser wavelengths cover the entire Mid-IR range from 3 to 24 µm
- High power (>500 mW cw, >5W peak for pulsed)
- High spectral purity - single frequency with DFB structure or external cavity: < kHz to 33 MHz
- Continuous tuning by temperature (~10 cm^{-1}), current (~1 cm^{-1}) or external cavity (>200 cm^{-1} → pulsed mode)
- High reliability: low failure rate, long lifetime and robust
- Capable of room temperature operation
  - Pulsed: up to +150°C
  - CW: up to RT

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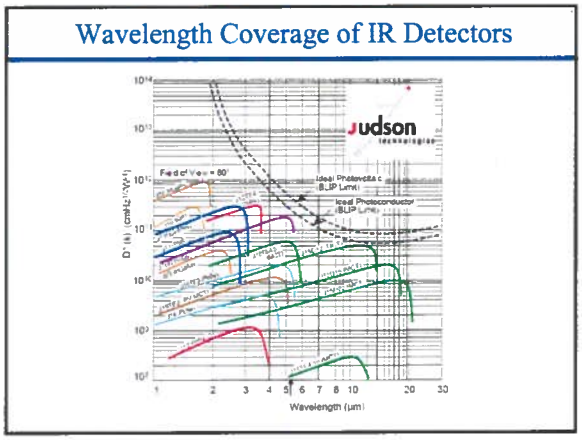
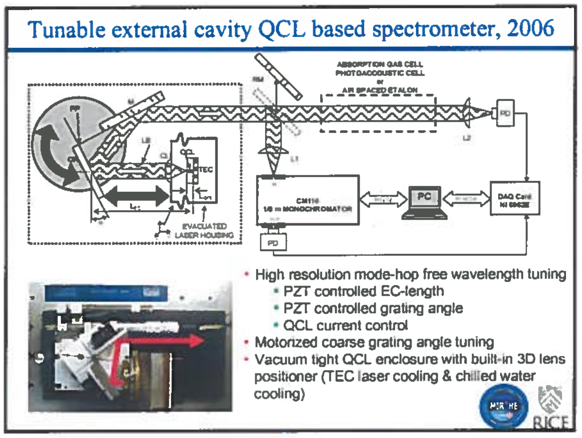


Wavelength Coverage of IR Detectors

Widely Tunable, CW, TEC Quantum Cascade Lasers



Tunable external cavity QCL based spectrometer, 2006

- High resolution mode-hop free wavelength tuning
  - PZT controlled EC-length
  - PZT controlled grating angle
  - QCL current control
- Motorized coarse grating angle tuning
- Vacuum tight QCL enclosure with built-in 3D lens positioner (TEC laser cooling & chilled water cooling)

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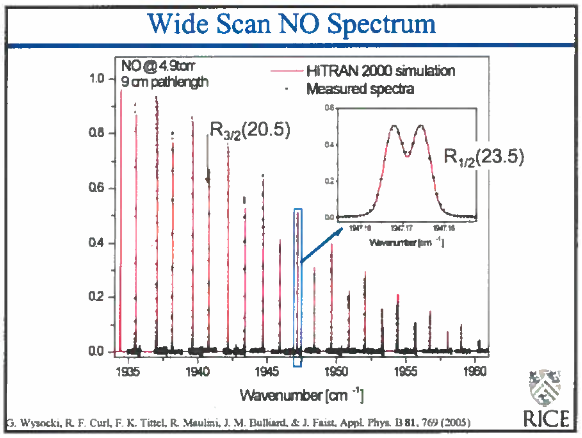

Wide Scan NO Spectrum

G. Wysocki, R. F. Curl, F. K. Tittel, R. Maulini, J. M. Bulliard, & J. Faist, Appl. Phys. B 81, 769 (2005)

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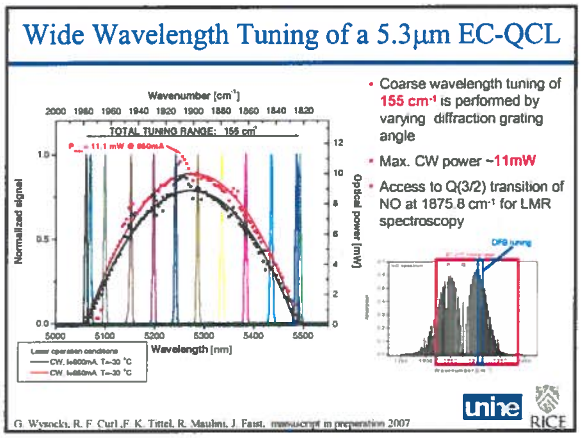

Wide Wavelength Tuning of a 5.3μm EC-QCL

- Coarse wavelength tuning of **155 cm^{-1}** is performed by varying diffraction grating angle
- Max. CW power ~**11mW**
- Access to Q(3/2) transition of NO at 1875.8 cm^{-1} for LMR spectroscopy

G. Wysocki, R. F. Curl, F. K. Tittel, R. Maulini, J. Faist, manuscript in preparation 2007

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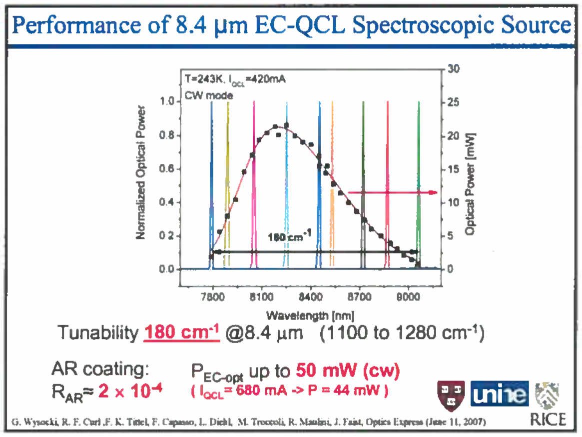

Performance of 8.4 μm EC-QCL Spectroscopic Source

Tunability **180 cm^{-1}** @8.4 μm (1100 to 1280 cm^{-1})

AR coating: R_{AR}≈ **2 × 10^{-4}**

P_{EC-opt} up to **50 mW (cw)**
(I_{QCL}= 680 mA -> P = 44 mW)

G. Wysocki, R. F. Curl, F. K. Tittel, F. Capasso, L. Diehl, M. Troccoli, R. Maulini, J. Faist, Optics Express (June 11, 2007)

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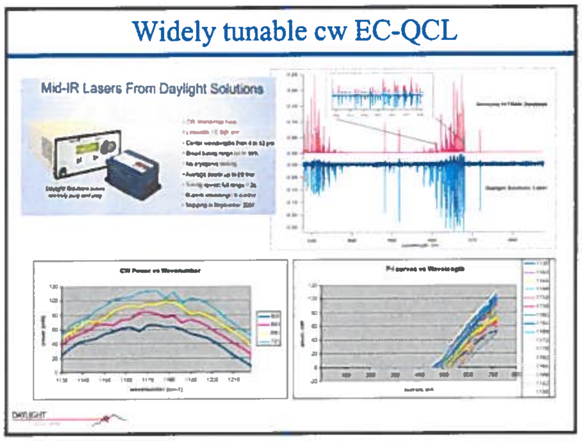
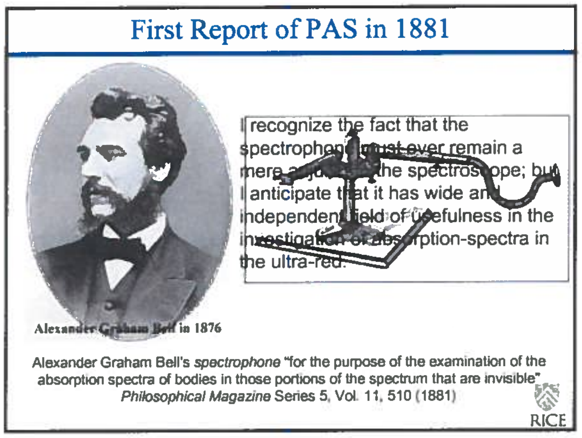


Widely tunable cw EC-QCL

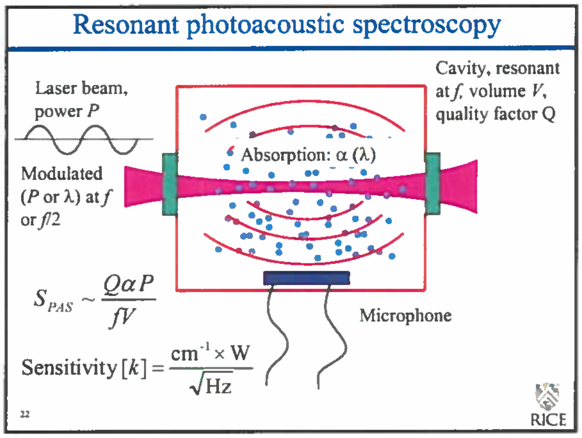
Quartz Enhanced Photoacoustic Spectroscopy (QEPAS)



First Report of PAS in 1881

I recognize the fact that the spectrophone must ever remain a mere adjunct to the spectroscope; but I anticipate that it has wide and independent field of usefulness in the investigation of absorption-spectra in the ultra-red.

Alexander Graham Bell's *spectrophone* "for the purpose of the examination of the absorption spectra of bodies in those portions of the spectrum that are invisible"
Philosophical Magazine Series 5, Vol. 11, 510 (1881)



Resonant photoacoustic spectroscopy

$$S_{PAS} \sim \frac{Q\alpha P}{fV}$$

$$\text{Sensitivity}\,[k] = \frac{\text{cm}^{-1} \times \text{W}}{\sqrt{\text{Hz}}}$$

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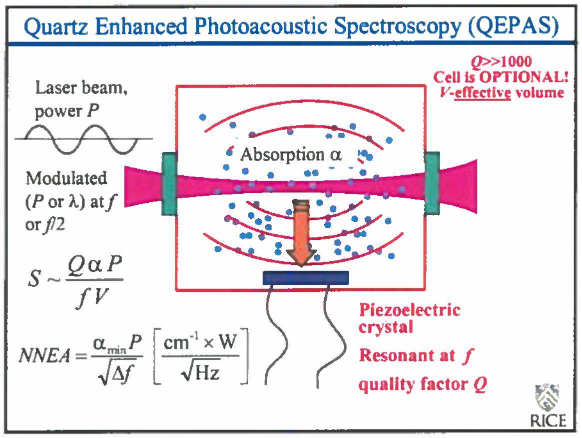
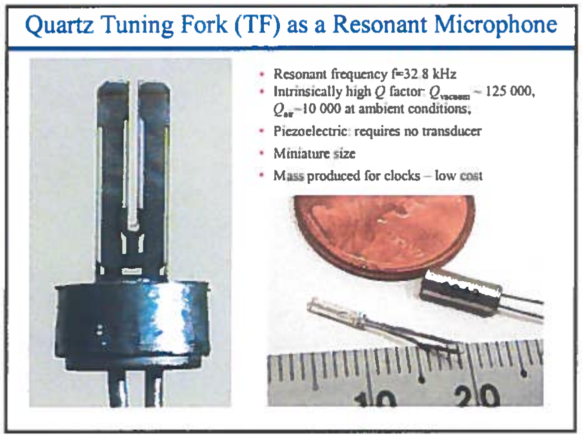


Quartz Enhanced Photoacoustic Spectroscopy (QEPAS)

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

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



Quartz Tuning Fork (TF) as a Resonant Microphone

- Resonant frequency f=32.8 kHz
- Intrinsically high Q factor: Q_{vacuum} ~ 125 000, Q_{air}~10 000 at ambient conditions;
- Piezoelectric: requires no transducer
- Miniature size
- Mass produced for clocks – low cost

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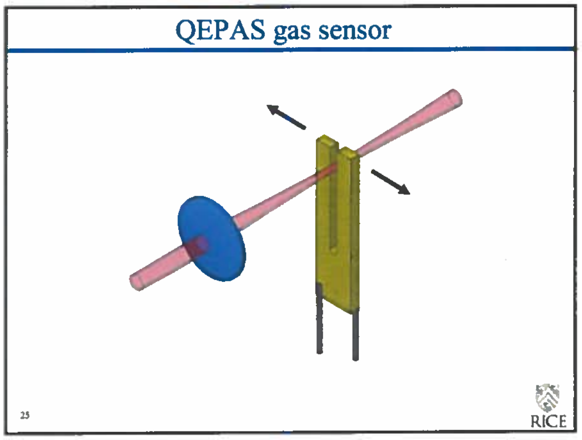
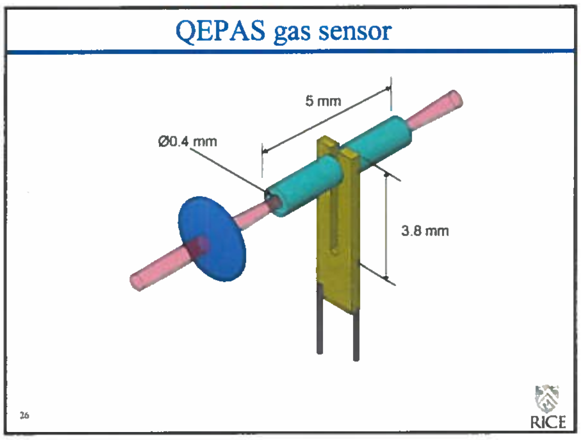
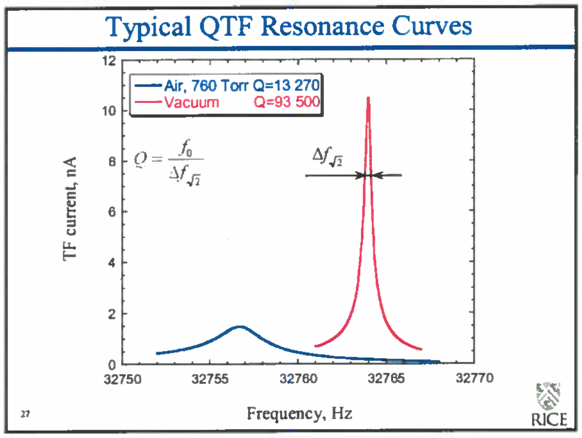


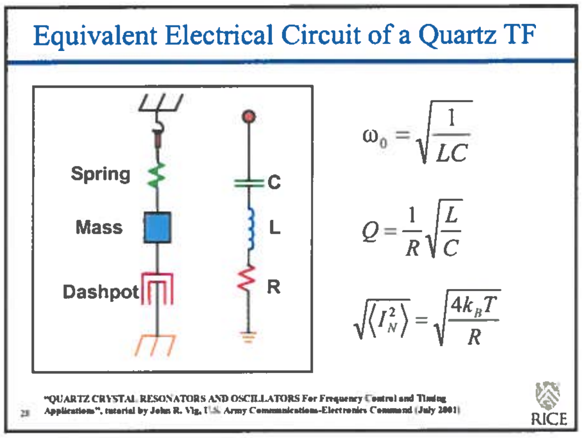
QEPAS gas sensor



QEPAS gas sensor



Typical QTF Resonance Curves



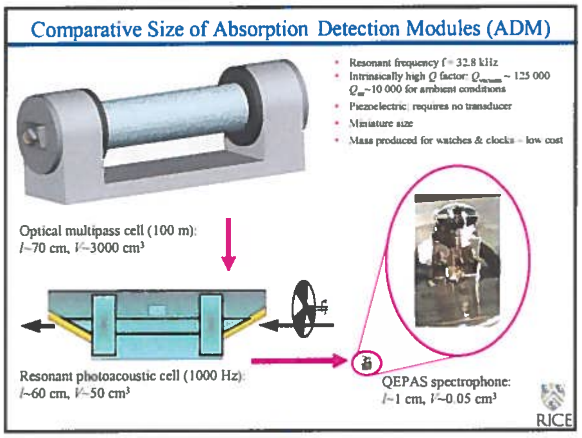
Equivalent Electrical Circuit of a Quartz TF

$$\omega_0 = \sqrt{\frac{1}{LC}}$$

$$Q = \frac{1}{R}\sqrt{\frac{L}{C}}$$

$$\sqrt{\langle I_N^2 \rangle} = \sqrt{\frac{4k_B T}{R}}$$

"QUARTZ CRYSTAL RESONATORS AND OSCILLATORS For Frequency Control and Timing Applications", tutorial by John R. Vig, U.S. Army Communications-Electronics Command (July 2001)



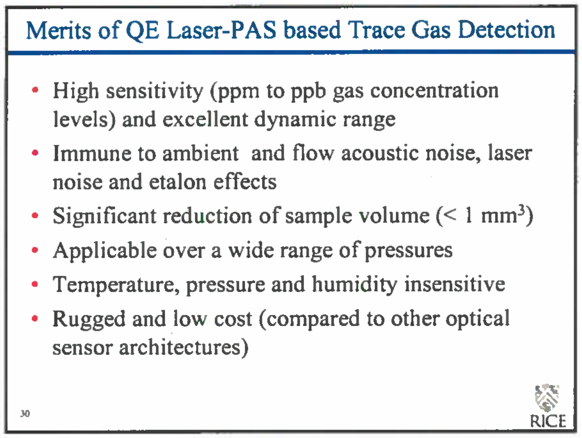
Comparative Size of Absorption Detection Modules (ADM)

- Resonant frequency f = 32.8 kHz
- Intrinsically high Q factor: Q_{vacuum} ~ 125 000
  Q_{air}~10 000 for ambient conditions
- Piezoelectric: requires no transducer
- Miniature size
- Mass produced for watches & clocks – low cost

Optical multipass cell (100 m):
l~70 cm, V~3000 cm^3

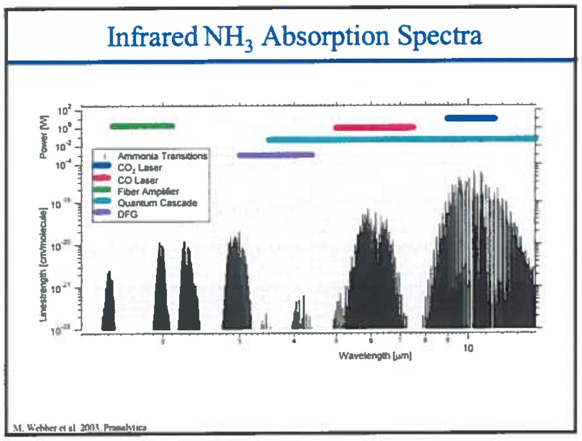
Resonant photoacoustic cell (1000 Hz):
l~60 cm, V~50 cm^3

QEPAS spectrophone:
l~1 cm, V~0.05 cm^3



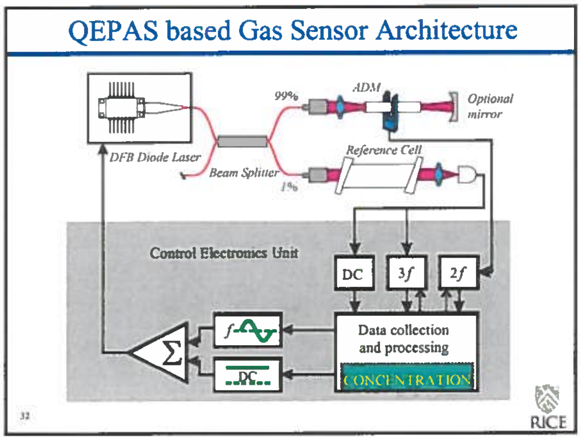
Merits of QE Laser-PAS based Trace Gas Detection

- High sensitivity (ppm to ppb gas concentration levels) and excellent dynamic range
- Immune to ambient and flow acoustic noise, laser noise and etalon effects
- Significant reduction of sample volume (< 1 mm^3)
- Applicable over a wide range of pressures
- Temperature, pressure and humidity insensitive
- Rugged and low cost (compared to other optical sensor architectures)



Infrared NH_3 Absorption Spectra

M. Webber et al. 2003, Pranalytica



QEPAS based Gas Sensor Architecture

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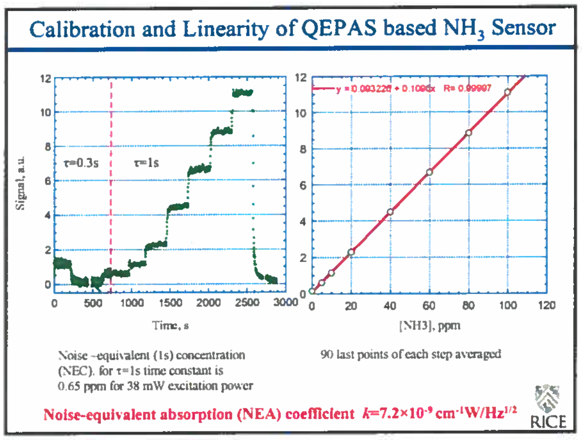

Calibration and Linearity of QEPAS based NH_3 Sensor

Noise-equivalent (1s) concentration (NEC), for τ=1s time constant is 0.65 ppm for 38 mW excitation power

90 last points of each step averaged

Noise-equivalent absorption (NEA) coefficient $k=7.2\times10^{-9}$ **cm⁻¹W/Hz½**

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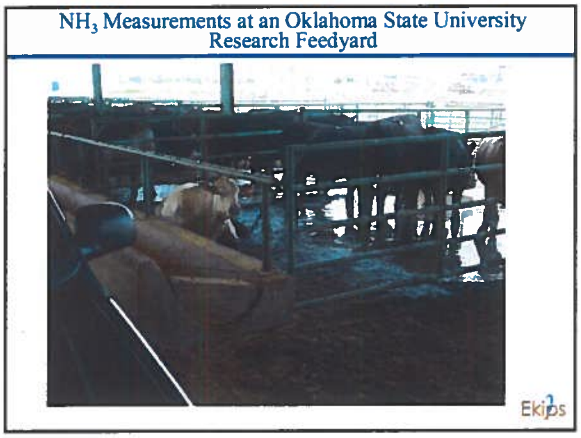
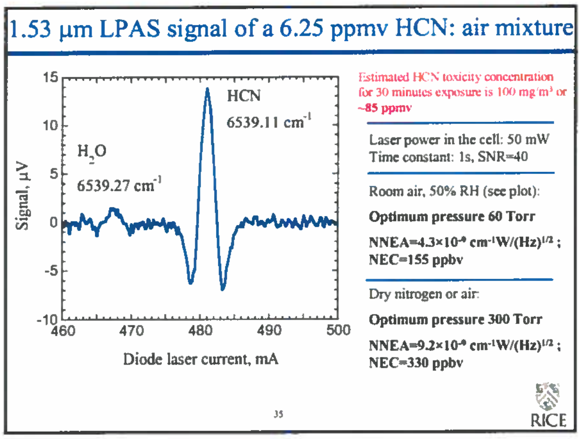


NH_3 Measurements at an Oklahoma State University Research Feedyard

Ekips



1.53 μm LPAS signal of a 6.25 ppmv HCN: air mixture

Estimated HCN toxicity concentration for 30 minutes exposure is 100 mg/m³ or ~85 ppmv

Laser power in the cell: 50 mW
Time constant: 1s, SNR=40

Room air, 50% RH (see plot):

Optimum pressure 60 Torr

NNEA=4.3×10⁻⁹ cm⁻¹W/(Hz)½ ;
NEC=155 ppbv

Dry nitrogen or air:

Optimum pressure 300 Torr

NNEA=9.2×10⁻⁹ cm⁻¹W/(Hz)½ ;
NEC=330 ppbv

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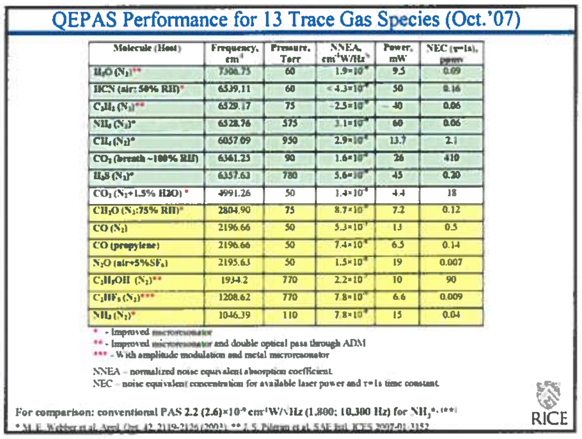

QEPAS Performance for 13 Trace Gas Species (Oct.'07)

Molecule (Host)	Frequency, cm^{-1}	Pressure, Torr	NNEA, $cm^{-1}W/Hz^{1/2}$	Power, mW	NEC (τ=1s), ppmv
H_2O (N_2)**	7306.75	60	1.9×10^{-9}	9.5	0.09
HCN (air: 50% RH)*	6539.11	60	$<4.3\times10^{-9}$	50	0.16
C_2H_2 (N_2)**	6529.17	75	$\sim2.5\times10^{-9}$	~ 40	0.06
NH_3 (N_2)*	6528.76	575	3.1×10^{-9}	60	0.06
CH_4 (N_2)*	6057.09	950	2.9×10^{-8}	13.7	2.1
CO_2 (breath ~100% RH)	6361.25	90	1.6×10^{-8}	26	410
H_2S (N_2)*	6357.63	780	5.6×10^{-9}	45	0.20
CO_2 (N_2+1.5% H2O) *	4991.26	50	1.4×10^{-8}	4.4	18
CH_2O (N_2:75% RH)*	2804.90	75	8.7×10^{-9}	7.2	0.12
CO (N_2)	2196.66	50	5.3×10^{-7}	13	0.5
CO (propylene)	2196.66	50	7.4×10^{-8}	6.5	0.14
N_2O (air+5%SF_6)	2195.63	50	1.5×10^{-8}	19	0.007
C_2H_5OH (N_2)**	1934.2	770	2.2×10^{-7}	10	90
C_2HF_5 (N_2)***	1208.62	770	7.8×10^{-9}	6.6	0.009
NH_3 (N_2)*	1046.39	110	7.8×10^{-9}	15	0.04

* - 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.

For comparison: conventional PAS 2.2 (2.6)×10⁻⁹ cm⁻¹W/√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

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Sensor Areas Explored at Rice

- Methods employed
  - Extended pathlengths
  - Cavity ringdown
  - Integrated Off-Axis Spectroscopy
  - Wavelength Modulation
  - Pulse-to-pulse fluctuation removal by comparing the same pulse on the same or another detector
  - Tuning fork photoacoustic spectroscopy
- 16 gases detected: NH_3, CH_4, H_2S, N_2O, CO_2, CO, NO,C_2H_2 H_2O, OCS, C_2H_4, SO_2, C_2H_5OH, C_2HF_5, H_2CO, C_2H_6, HCN
- Practical applications
  - Crew Health Maintenance & Life Support - H_2CO, NH_3
  - Radioactive site remediation
  - Medical breath analysis - OCS, NO, CO_2, acetone
  - Industry catalyst poison - CO
  - Urban air smog - H_2CO

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Trace Gas Sensing Examples

Motivation for Precision Monitoring of H_2CO

- Precursor to atmospheric O_3 production
- Pollutant due to incomplete fuel combustion processes
- Potential trace contaminant in industrial manufactured products
- Medically important gas

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Megacity Air Pollution: Houston, TX

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Houston Ozone Chemistry

- Rapid oxidation of highly reactive VOCs leads to ozone formation in urban areas
- As a major petrochemical center, the Houston region produces ~30 billion pounds of ethylene annually

TexAQS II Field Campaign Summer 2006

- To study ozone formation and transport, a coordinated field study was conducted during August to September 2006 in the Greater Houston area
- 5 aircraft, one ship, two ground chemistry sites, ~20 periphery and meteorological sites were employed during TexAQS II
- Participation by ~300 scientists from academia, national laboratories, industry and government agencies

Moody Tower, UH Campus

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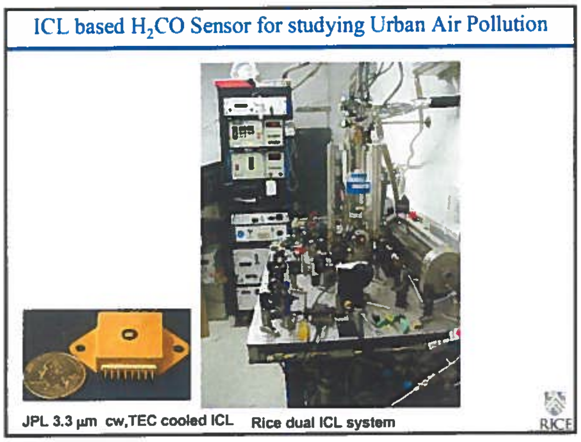
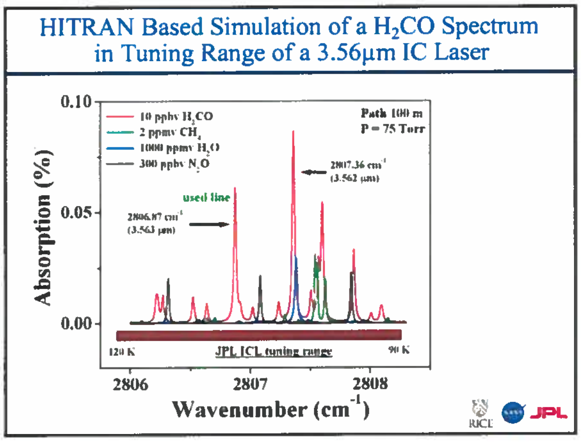
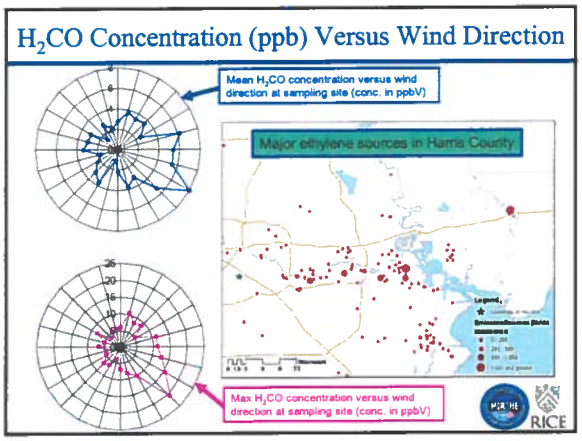


ICL based H_2CO Sensor for studying Urban Air Pollution

JPL 3.3 μm cw,TEC cooled ICL Rice dual ICL system



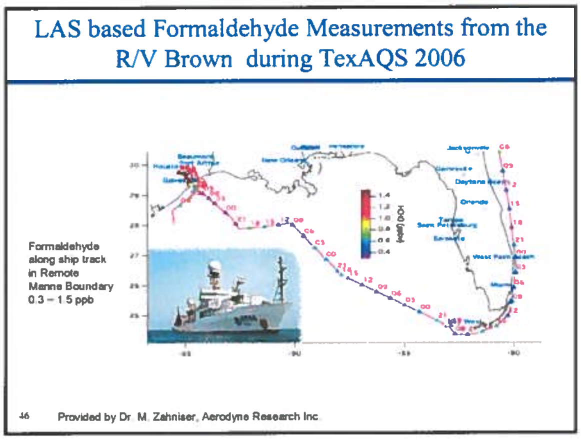
HITRAN Based Simulation of a H_2CO Spectrum in Tuning Range of a 3.56μm IC Laser



H_2CO Concentration (ppb) Versus Wind Direction

Mean H_2CO concentration versus wind direction at sampling site (conc. in ppbV)

Max H_2CO concentration versus wind direction at sampling site (conc. in ppbV)



LAS based Formaldehyde Measurements from the R/V Brown during TexAQS 2006

Formaldehyde along ship track in Remote Marine Boundary 0.3 – 1.5 ppb

46 Provided by Dr. M. Zahniser, Aerodyne Research Inc

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

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NO as a Biomarker

- NO is biochemically involved in most tissues and physiological processes in the human body
- NO excretion increases in exhaled breath in lung diseases such as :
  - ✓ Asthma[1]
  - ✓ Chronic Obstructive Pulmonary Disease[2]
  - ✓ Acute lung rejection[3]
  - ✓ Acute respiratory distress syndrome[4]
  - ✓ Pneumonia (useful for intubated patients)[5]

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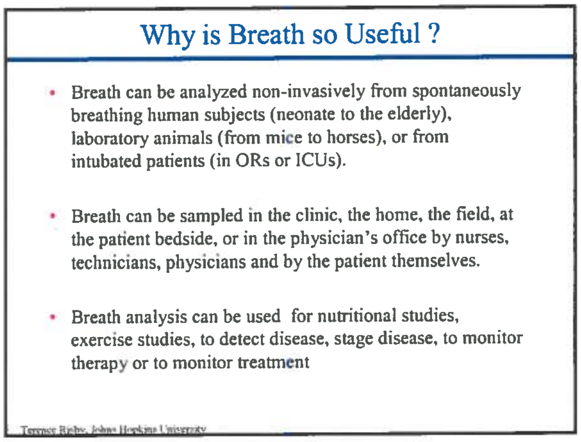
[1] Alving K, E Weitzberg, JM Lundberg. Increased amount of NO in exhaled air of asthmatics. Eur Respir J 1993; 6: 1368-1370

[2] Wasem M, S Loukides, S Culpitt, P Sullivan, S Kharitonov, P Barnes. Exhaled NO in COPD. Am J Respir Crit Care Med 1998, 157: pp 998-1002.

[3] Silkoff PE et al. Exhaled NO in human lung transplantation. A noninvasive marker of acute rejection. Am J Respir Crit Care Med 1998, 157(6): 1822-1828

[4] Brett SJ, Evans TW. Measurement of endogenous NO in the lungs of patients with the ARDS. Am J Respir Crit Care Med 1998, 157 (3 Pt 1): 993-7

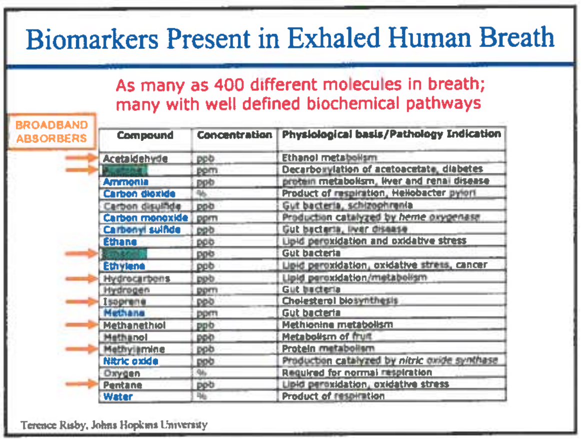
[5] Adrie C et al. Exhaled and nasal NO as a marker of pneumonia in ventilated patients. Am J Respir Crit Care Med 2001, 163(5):1143-9



Why is Breath so Useful ?

- Breath can be analyzed non-invasively from spontaneously breathing human subjects (neonate to the elderly), laboratory animals (from mice to horses), or from intubated patients (in ORs or ICUs).
- Breath can be sampled in the clinic, the home, the field, at the patient bedside, or in the physician's office by nurses, technicians, physicians and by the patient themselves.
- Breath analysis can be used for nutritional studies, exercise studies, to detect disease, stage disease, to monitor therapy or to monitor treatment

Terence Risby, Johns Hopkins University



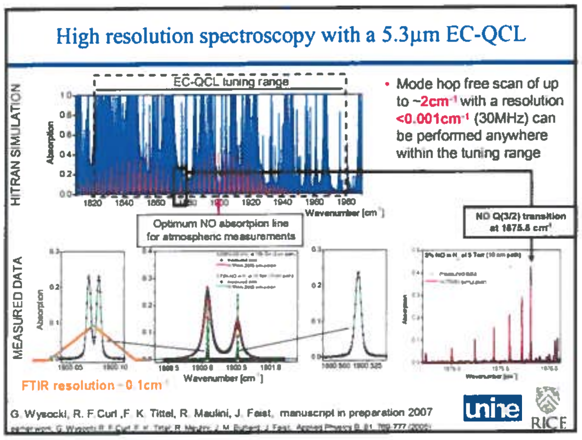
Biomarkers Present in Exhaled Human Breath

As many as 400 different molecules in breath; many with well defined biochemical pathways

BROADBAND ABSORBERS

Compound	Concentration	Physiological basis/Pathology Indication
Acetaldehyde	ppb	Ethanol metabolism
[illegible]	ppm	Decarboxylation of acetoacetate, diabetes
Ammonia	ppb	protein metabolism, liver and renal disease
Carbon dioxide	%	Product of respiration, Helicobacter pylori
Carbon disulfide	ppb	Gut bacteria, schizophrenia
Carbon monoxide	ppm	Production catalyzed by *heme oxygenase*
Carbonyl sulfide	ppb	Gut bacteria, liver disease
Ethane	ppb	Lipid peroxidation and oxidative stress
[illegible]	ppb	Gut bacteria
Ethylene	ppb	Lipid peroxidation, oxidative stress, cancer
Hydrocarbons	ppb	Lipid peroxidation/metabolism
Hydrogen	ppm	Gut bacteria
Isoprene	ppb	Cholesterol biosynthesis
Methane	ppm	Gut bacteria
Methanethiol	ppb	Methionine metabolism
Methanol	ppb	Metabolism of fruit
Methylamine	ppb	Protein metabolism
Nitric oxide	ppb	Production catalyzed by *nitric oxide synthase*
Oxygen	%	Required for normal respiration
Pentane	ppb	Lipid peroxidation, oxidative stress
Water	%	Product of respiration

Terence Risby, Johns Hopkins University

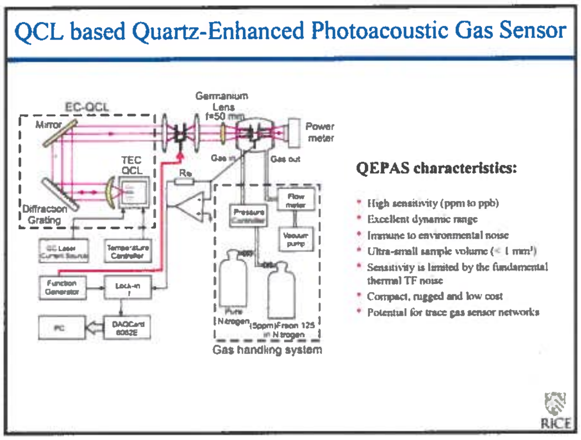


High resolution spectroscopy with a 5.3µm EC-QCL

- Mode hop free scan of up to ~**2cm⁻¹** with a resolution **<0.001cm⁻¹** (30MHz) can be performed anywhere within the tuning range

G. Wysocki, R. F. Curl, F. K. Tittel, R. Maulini, J. Faist, manuscript in preparation 2007

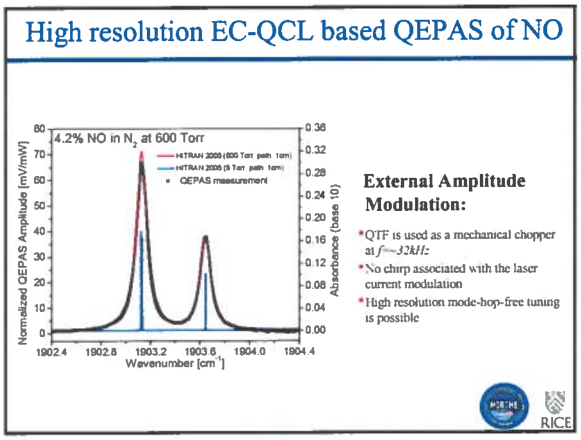
earlier work: G. Wysocki, R. F. Curl, F. K. Tittel, R. Maulini, J. M. Bulliard, J. Faist, Applied Physics B 81, 769-777 (2005)



QCL based Quartz-Enhanced Photoacoustic Gas Sensor

QEPAS characteristics:

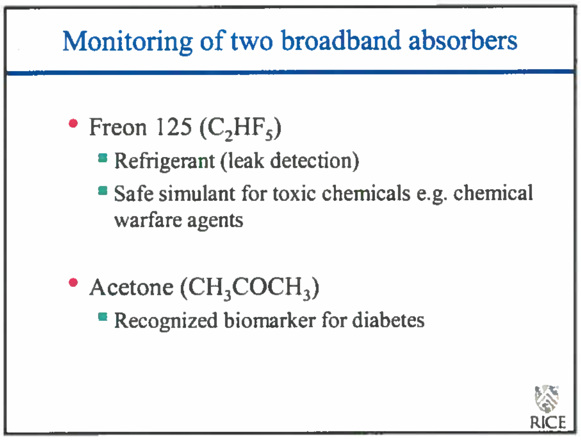
- High sensitivity (ppm to ppb)
- Excellent dynamic range
- Immune to environmental noise
- Ultra-small sample volume (< 1 mm³)
- Sensitivity is limited by the fundamental thermal TF noise
- Compact, rugged and low cost
- Potential for trace gas sensor networks



High resolution EC-QCL based QEPAS of NO

External Amplitude Modulation:

- QTF is used as a mechanical chopper at *f*~*32kHz*
- No chirp associated with the laser current modulation
- High resolution mode-hop-free tuning is possible



Monitoring of two broadband absorbers

- Freon 125 (C_2HF_5)
  - Refrigerant (leak detection)
  - Safe simulant for toxic chemicals e.g. chemical warfare agents
- Acetone (CH_3COCH_3)
  - Recognized biomarker for diabetes

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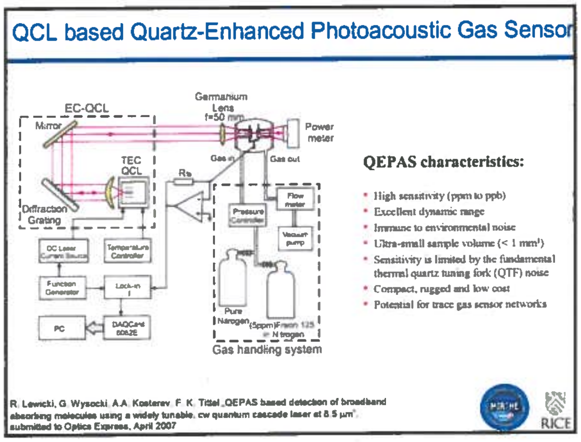

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QEPAS characteristics:

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- Sensitivity is limited by the fundamental thermal quartz tuning fork (QTF) noise
- Compact, rugged and low cost
- Potential for trace gas sensor networks

R. Lewicki, G. Wysocki, A.A. Kosterev, F. K. Tittel „QEPAS based detection of broadband absorbing molecules using a widely tunable, cw quantum cascade laser at 8.5 µm", submitted to Optics Express, April 2007

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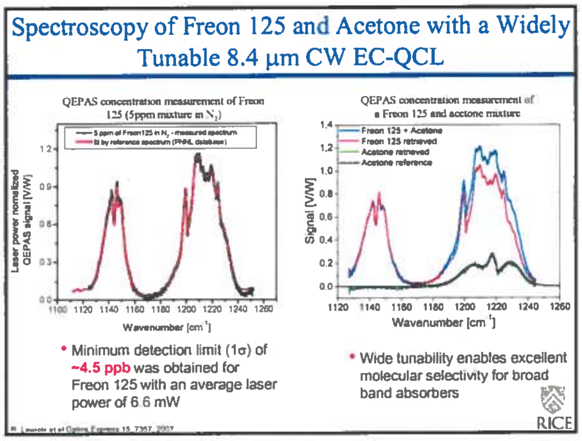

Spectroscopy of Freon 125 and Acetone with a Widely Tunable 8.4 µm CW EC-QCL

- Minimum detection limit (1σ) of **~4.5 ppb** was obtained for Freon 125 with an average laser power of 6.6 mW
- Wide tunability enables excellent molecular selectivity for broad band absorbers

R. Lewicki et al Optics Express 15, 7357, 2007

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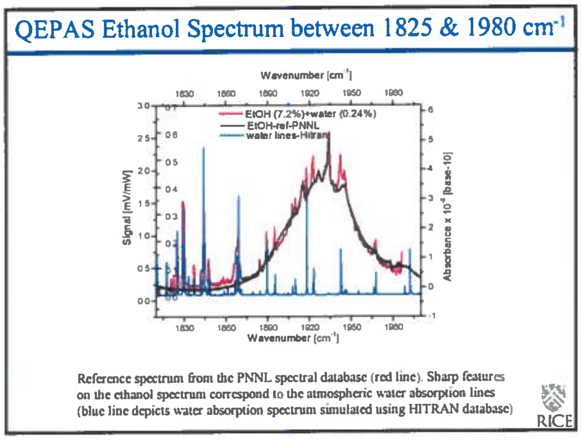

QEPAS Ethanol Spectrum between 1825 & 1980 cm⁻¹

Reference spectrum from the PNNL spectral database (red line). Sharp features on the ethanol spectrum correspond to the atmospheric water absorption lines (blue line depicts water absorption spectrum simulated using HITRAN database)

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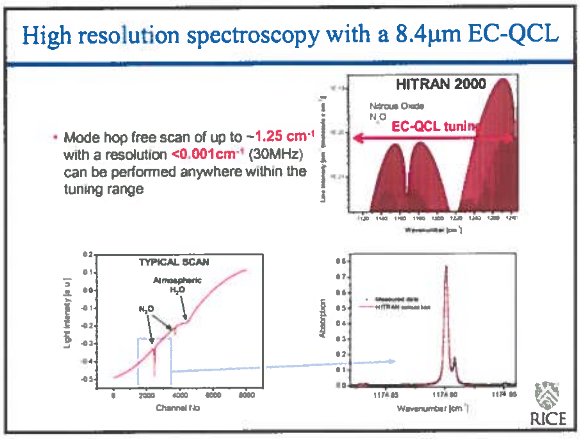

High resolution spectroscopy with a 8.4µm EC-QCL

- Mode hop free scan of up to ~**1.25 cm⁻¹** with a resolution **<0.001cm⁻¹** (30MHz) can be performed anywhere within the tuning range

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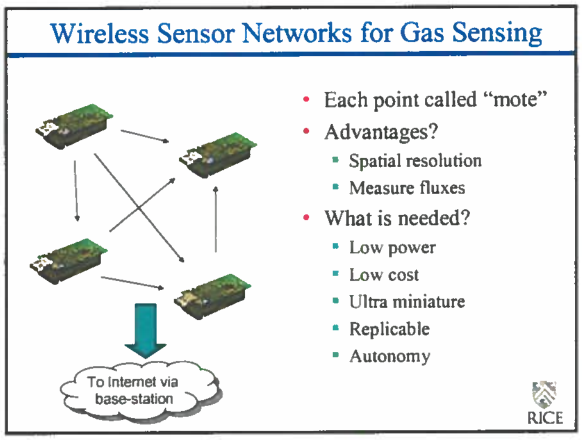
Future of Chemical Trace Gas Sensing



Wireless Sensor Networks for Gas Sensing

- Each point called "mote"
- Advantages?
  - Spatial resolution
  - Measure fluxes
- What is needed?
  - Low power
  - Low cost
  - Ultra miniature
  - Replicable
  - Autonomy

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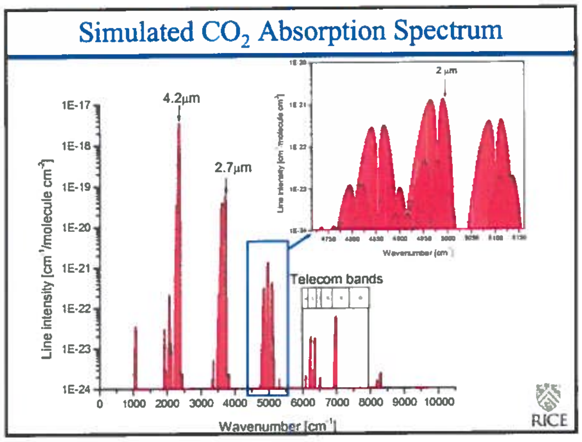
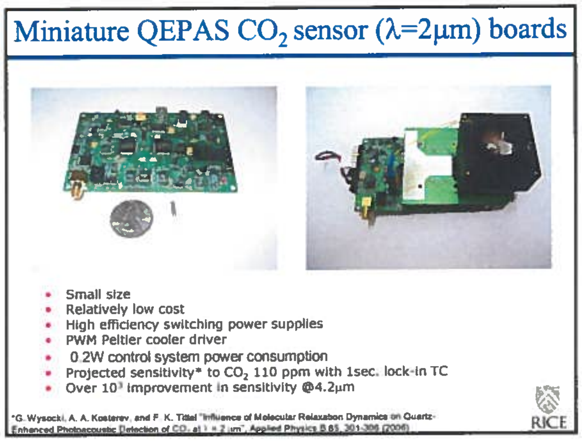


Simulated CO_2 Absorption Spectrum

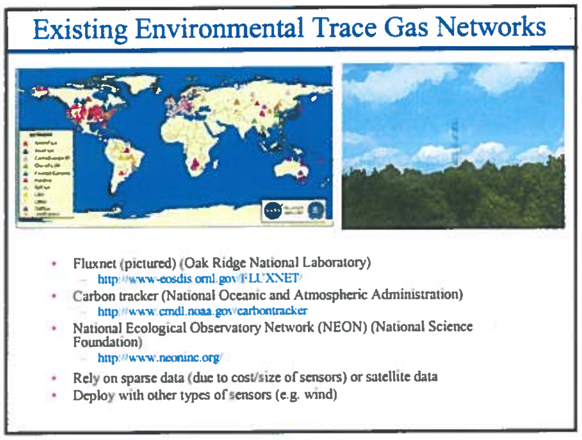


Miniature QEPAS CO_2 sensor (λ=2μm) boards

- Small size
- Relatively low cost
- High efficiency switching power supplies
- PWM Peltier cooler driver
- 0.2W control system power consumption
- Projected sensitivity* to CO_2 110 ppm with 1sec. lock-in TC
- Over 10^3 improvement in sensitivity @4.2μm

*G. Wysocki, A. A. Kosterev, and F. K. Tittel "Influence of Molecular Relaxation Dynamics on Quartz-Enhanced Photoacoustic Detection of CO_2 at λ = 2 μm", Applied Physics B 85, 301-306 (2006)

new design



Existing Environmental Trace Gas Networks

- Fluxnet (pictured) (Oak Ridge National Laboratory)
  - http://www-eosdis.ornl.gov/FLUXNET/
- Carbon tracker (National Oceanic and Atmospheric Administration)
  - http://www.cmdl.noaa.gov/carbontracker
- National Ecological Observatory Network (NEON) (National Science Foundation)
  - http://www.neoninc.org/
- Rely on sparse data (due to cost/size of sensors) or satellite data
- Deploy with other types of sensors (e.g. wind)

Future Directions of Mid-IR Sensor Technology

- Improvements of the existing sensing technologies using novel, thermoelectrically cooled, cw, high power, and broadly wavelength tunable mid-IR interband and intersubband quantum cascade lasers
- New applications enabled by novel broadly wavelength tunable quantum cascade lasers (especially sensitive concentration measurements of broadband absorbers, in particular VOCs and HCs)
- Development of optically multiplexed gas sensor networks based on QEPAS

New Applications of Trace Gas Detection

- Distributed sensor networks for environmental monitoring (NH_3, CO, CH_4, C_2H_4, N_2O, CO_2 and H_2CO)
- Inexpensive and sensitive sensors for industrial process control and chemical analysis (HCN, NO, NH_3, H_2O)
- Wearable sensors for medical & biomedical diagnostics (NO, CO, COS, CO_2, NH_3, C_2H_4)
- Hand-held sensors and sensor network technologies for law enforcement

Summary and Future Directions

- **Near and Mid-Infrared Semiconductor Laser based Trace Gas Sensors**
  - Compact, robust sensor technology based on multipass cell absorption, cavity enhanced and quartz enhanced photoacoustic spectroscopy (QEPAS)
  - High sensitivity ($<10^{-4}$) and selectivity (3 to 500 MHz)
  - Fast data acquisition and analysis
  - Detected 13 trace gases to date: NH_3, CH_4, H_2S, N_2O, CO_2, CO, NO, H_2O, COS, C_2H_4, SO_2, C_2H_5OH, C_2HF_5 and isotopic species of C, O, N and H.
- **New Applications of Trace Gas Detection**
  - Distributed sensor networks for environmental monitoring (NH_3, CO, CH_4, C_2H_4, N_2O, CO_2 and H_2CO)
  - Inexpensive and sensitive sensors for industrial process control and chemical analysis (HCN, NO, NH_3, H_2O)
  - Sensors for medical & biomedical diagnostics (NO, CO, COS, CO_2, NH_3, C_2H_4)
- **Future Directions and Collaborations**
  - Further improvements of the existing sensor technologies using novel, thermoelectrically cooled, cw, high power mid-IR interband and intersubband quantum cascade lasers and QEPAS
  - New applications enabled by novel widely tunable quantum cascade lasers (especially sensitive concentration measurements of broadband absorbers, in particular VOCs and HCs)
  - Development of optically multiplexed gas sensor networks based on QEPAS

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