Semiconductor Laser based Trace Gas Sensor Technology: Advances and Opportunities

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OUTLINE

Oklahoma University
Norman, OK
Jan 23, 2006

- Motivation: Wide Range of Chemical Sensing
- Fundamentals of Laser Absorption Spectroscopy
- Selected Applications of Trace Gas Detection
  - LAS with a Multipass absorption Cell
  - Quartz Enhanced Laser-PAS
  - OA-ICOS NO based Sensor Technology
- Outlook and Conclusions

Work supported by NASA, PNNL, NSF, NIH and Welch Foundation

Motivation: Wide Range of Gas Sensing Applications

- **Urban and Industrial Emission Measurements**
  - Industrial Plants
  - Combustion Sources and Processes (eg. early fire detection)
  - Automobile and Aircraft Emissions
- **Rural Emission Measurements**
  - Agriculture and Animal Facilities
- **Environmental Gas Monitoring**
  - Atmospheric Chemistry (eg ecosystems and airborne)
  - Volcanic Emissions
- **Chemical Analysis and Industrial Process Control**
  - Chemical, Pharmaceutical, Food & Semiconductor Industry
  - Toxic Industrial Chemical Detection
- **Spacecraft and Planetary Surface Monitoring**
  - Crew Health Maintenance & Advanced Human Life Support Technology
- **Biomedical and Clinical Diagnostics** (eg. breath analysis)
- **Forensic Science and Security** (explosive, CW detection
- **Fundamental Science and Photochemistry**

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Trace Gas Monitoring in a Petrochemical Plant

University of Szeged, Hungary

Worldwide Megadirty Mega Cities

	Population, m 1990, ext.	Population, m 2000, proj.	Sulphur dioxide	Particulate matter	Lead	Carbon monoxide	Nitrogen dioxide	Ozone
Bangkok	7.16	10.26	O	●	Ø	O	O	O
Beijing	9.74	11.47	●	●	O	-	O	Ø
Bombay	11.13	15.43	O	●	O	O	O	-
Buenos Aires	11.58	13.05	-	Ø	O	-	-	-
Cairo	9.06	11.77	-	●	●	Ø	-	-
Calcutta	11.83	15.94	O	●	O	-	O	-
Delhi	8.62	12.77	O	●	O	O	O	-
Jakarta	9.42	13.23	O	●	Ø	Ø	O	Ø
Karachi	7.67	11.57	O	●	●	-	-	-
London	10.57	10.79	O	O	O	Ø	O	O
Los Angeles	10.47	10.91	O	Ø	O	Ø	Ø	●
Manila	8.40	11.48	O	●	Ø	-	-	-
Mexico City	19.37	24.44	●	●	Ø	●	Ø	●
Moscow	9.39	10.11	-	Ø	O	Ø	Ø	-
New York	15.65	16.10	O	O	O	Ø	O	Ø
Rio de Janeiro	11.12	13.00	Ø	Ø	O	O	-	-
Sao Paolo	18.42	23.60	O	Ø	O	Ø	Ø	●
Seoul	11.33	12.97	●	●	O	O	O	O
Shanghai	13.30	14.69	O	●	-	-	-	-
Tokyo	20.52	21.32	O	O	-	O	O	●

Source: United Nations ● High pollution Ø Moderate to heavy pollution O Low pollution - No data available

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Megacity Air Pollution: Houston, TX

NASA–JSC Human-Rated Simulation Chamber

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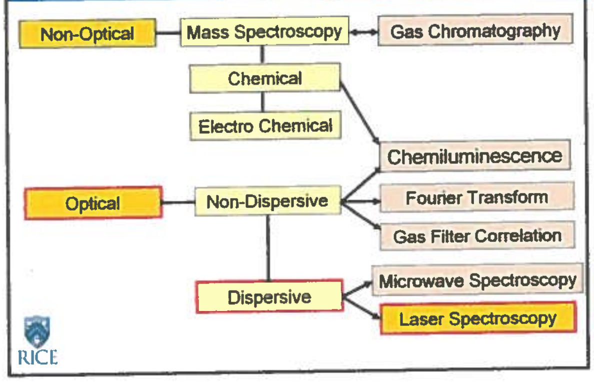
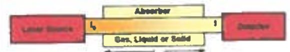
Existing Methods for Trace Gas Detection



Fundamentals of Laser Absorption Spectroscopy

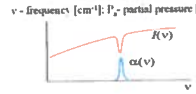


Beer-Lambert's Law of Linear Absorption

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

$\alpha(\nu)$ - 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 cm^{-3} [molecule·cm^{-3}·atm^{-1}]

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

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

Optimum Molecular Absorbing Transition

- Overtone or Combination Bands (NIR)
- Fundamental Absorption Bands (MID-IR)

Long Optical Pathlengths

- Multipass Absorption Cell
- Cavity Enhanced, Cavity Ringdown & Intracavity Spectroscopy
- Open Path Monitoring (with retro-reflector)
- Evanescent Field Monitoring (fibers & waveguides)

Spectroscopic Detection Schemes

- Frequency or Wavelength Modulation
- Balanced Detection
- Zero-air Subtraction
- Photoacoustic Spectroscopy

Mid-IR Source Requirements for Laser Spectroscopy

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

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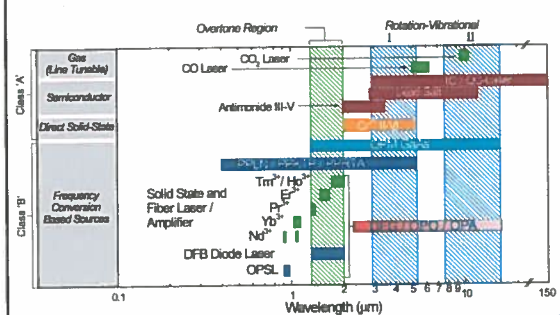
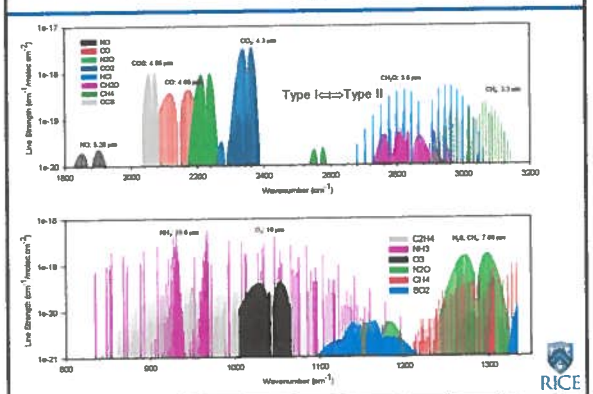
IR Laser Sources and Wavelength Coverage

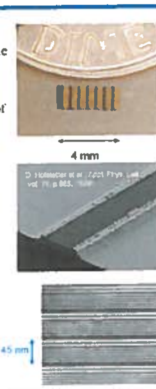


HITRAN Simulation of Absorption Spectra (3.1-5.5 & 7.6-12.5 µm)

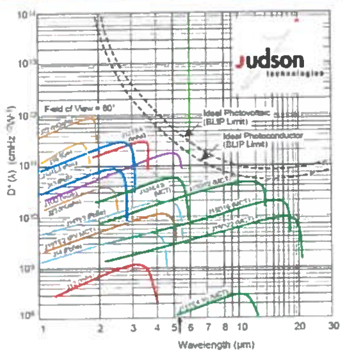


Quantum and Interband Cascade Laser: Basic Facts

- Band – structure engineered devices (emission wavelength is determined by layer thickness – MBE or MOCVD) QCLs operate from 4 to 160 µm (limited by the CB offset on the short wavelength side)
  - Unipolar devices
  - Cascading (each electron creates N laser photons and the number of periods N determines laser power)
- Compact, reliable, stable, long lifetime, commercial availability
- Fabry-Perot (FP) or single mode (DFB)
- Broad spectral tuning range in the mid-IR (4-24 µm for QCLs and 3-5 µm for ICLs)
  - 1.5 cm^{-1} using current
  - 10-20 cm^{-1} using temperature
  - > 150 cm^{-1} using an external grating element
- Narrow spectral linewidth cw, 0.1 - 3 MHz & <10Khz with frequency stabilization
  Linewidth is ~ 300 MHz of pulsed QCLs (chirp from heating)
- High output powers at TEC/RT temperatures
  - Pulsed peak powers of 1.6 W; high temperature operation ~ 425 K
  - Average power levels: 1-600 mW
  - ~ 50 mW, TEC CW DFB @ 5 and 10 microns (Alpes &Unine)
  - >600 mW (CW FP) and >150 mW (CW DFB) at 298 K (Northwestern)



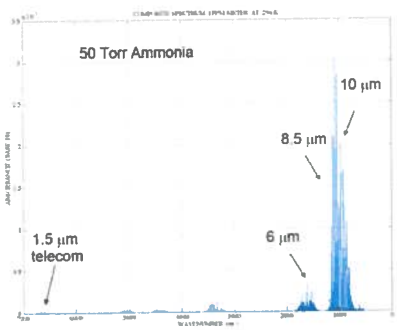
Wavelength Coverage of IR Detectors



Motivation for NH_3 Detection

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

Simulated NH_3 Absorption Spectrum (Near-IR to Mid-IR)



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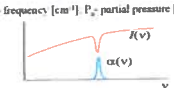

$$\alpha(\nu) = C \cdot S(T) \cdot g(\nu - \nu_0)$$

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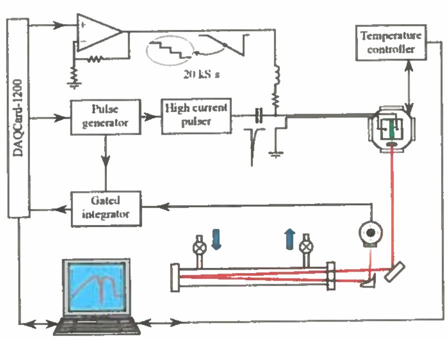
Pulsed QC Laser Based Gas Sensor



A. Kosterev et al, Applied Optics 41, 573 2002

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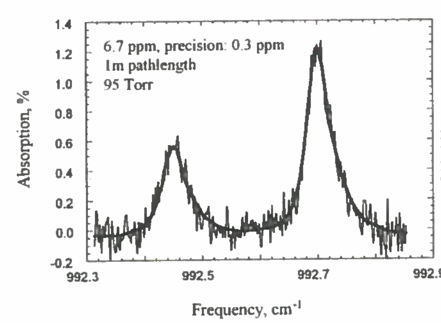
Ammonia Absorption Spectrum @ 993 cm-1



$y_i = Cf(i-x) + b$
where:
y-absorption
C-concentration
i-pulse number
x-peak shift
b-baseline shift

A. Kosterev et al, Applied Optics 41, 573 2002

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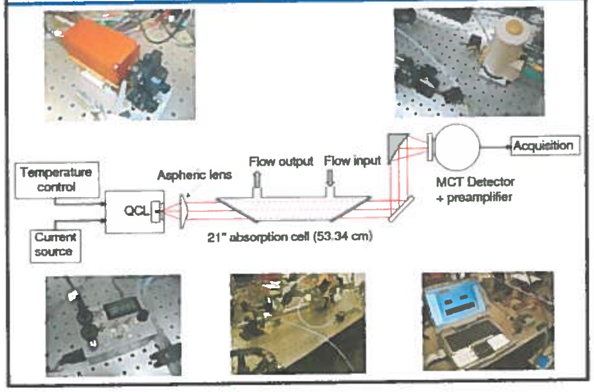
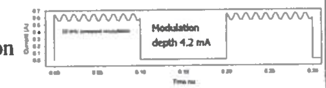
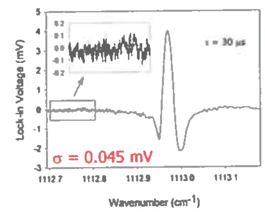
CW RT DFB QC laser based NH_3 Sensor @ 9 μm (1113 cm^{-1})



Wavelength Modulation Spectroscopy of NH_3

- QCL Drive Current : Quasi CW + Wavelength modulation





- Calibration with a 1038 ppm NH_3:N_2 mixture

1σ extrapolated sensitivity
82 ppb.m/√Hz

⇒ Improvement by a factor of 3 compared to direct absorption spectroscopy

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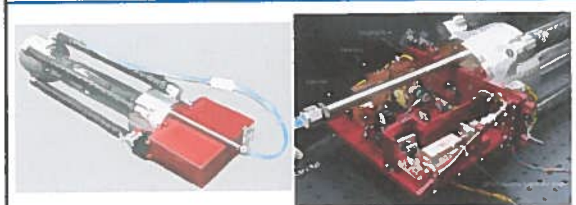
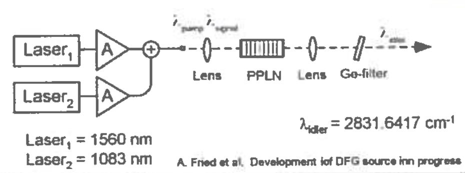
Motivation for Precision Monitoring of H_2CO

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

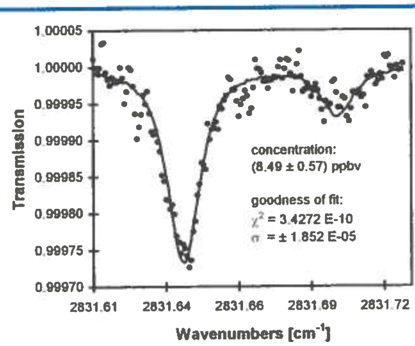
Advanced DFG System for H_2CO Detection





A. Fried et al. Development of DFG source in progress

H_2CO Detection in Ambient Air at 3.53 μm



[1] Rehle et al. Applied Physics B72, 947-952 (2001)

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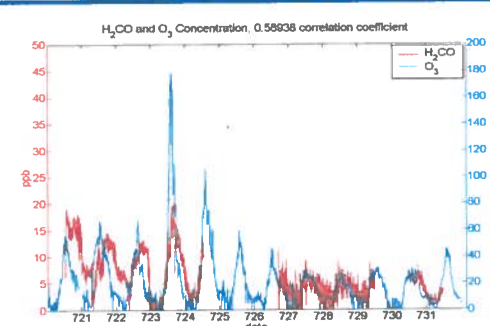
H_2CO and O_3 Concentrations at Deer Park, TX for July 20-31, 2003



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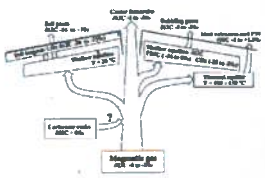
Volcanological applications

- CO_2 the most abundant component of volcanic gases after H_2O
- $\delta^{13}C$ is a sensitive tracer of magmatic vs. hydrothermal or groundwater contributions to volcanic gases
- Monitoring $\delta^{13}C$ can be used in eruption forecasting and volcanic hazard assessment



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Isotopic Ratio Measurement Techniques

- Current standard technique: Isotope Ratio Mass Spectrometry (IRMS) $\Delta\delta$~0.01-0.05 $^0/_{00}$
  - Small mass differences are difficult to measure
  - Not real time
  - Not field deployable
  - Complex sample preparation and sample destruction
- Fourier Transform Spectroscopy $\Delta\delta$~0.1-0.2 $^0/_{00}$
  - Not selective for compact and intermediate sized platform
- Tunable Laser Absorption Spectroscopy $\Delta\delta$~0.2 $^0/_{00}$
  - Lead salt lasers
  - Difference Frequency Generation
  - Near-infrared diode
  - Mid-infrared quantum cascade lasers

CO_2 Absorption Line Selection Criteria

- Three strategies:
  - Similar strong absorption of $^{12}CO_2$ and $^{13}CO_2$ lines
    - Very sensitive to temperature variations
  - Similar transition lower energies
    - Requires a dual path length approach to compensate for the large difference in concentration between major and minor isotopic species-or-
    - Can be realized if different vibrational transitions are selected for the two isotopes (4.35 µm for $^{13}CO_2$ and 2.76 µm for $^{12}CO_2$)*
- For the first 2 strategies both absorption lines must lie in a laser frequency scan window
- Avoid presence of other interfering atmospheric trace gas species

* Proposed scheme by Curl, Uehara, Kosterev and Tittel, Oct. 2002

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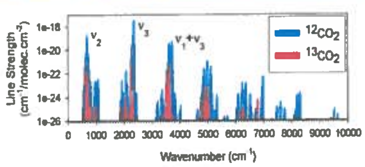
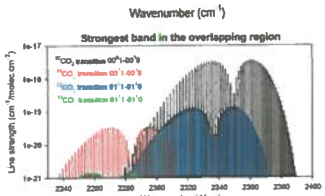
Comparison of CO_2 line selection and strategy for different current US mid-IR laser-based isotopic ratiometers

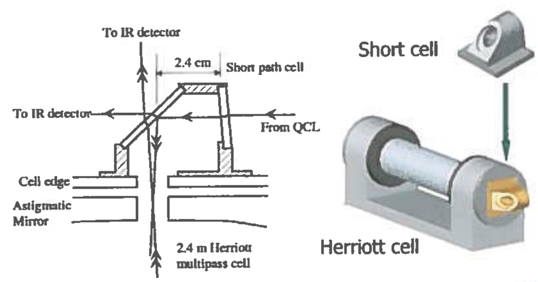
Group	Technology	Frequency 12/13 [cm⁻¹]	δT [K]	Precision
NCAR, UC and Rice U. A. Fried et al; Erdelyi	DFG with NIR TDLs and fiber amplifiers	2299.642 2299.795	0.005	0.8 ‰*
Aerodyne, Harvard U. M. Zahniser et al.	Direct Scan PbSalt TDL, QCL, DFG; Dual optical paths	2314.304 2314.408	0.213	0.2 ‰
Physical Sciences D. Sonnenfroh et al	QCL	2318.1		0.5 to 1‰
Rice University Tittel et al	QCL Dual optical paths	2311.105 2311.399	181 Very large	<1 ‰
U. of Utah Bowling, Picarro	PbSalt TDLs Campbell Scientific Instrum.	2308.225 2308.171	0.006	0.2 ‰
JPL C. Webster	TDLs and QCL, LAS	2303.7 2303.5	0.007	TBD ‰
NASA-Ames Becker et al; Jost, LGR	Direct Scan PbSalt TDLs & QCLs with ICOS	2291.542 2291.680	0.004	4 ‰

HITRAN based Simulation of Ro-vibrational bands suitable for $^{12}CO_2$/$^{13}CO_2$ ratio measurements





Dual path length gas cell design for infrared ratio spectrometry



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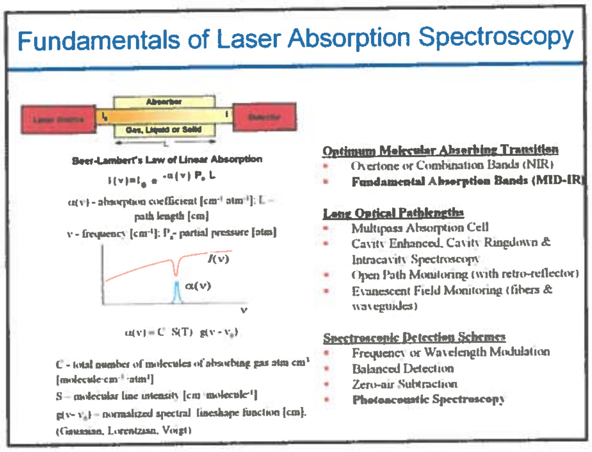
Fundamentals of Laser Absorption Spectroscopy
Absorber
I_0
I
Gas, Liquid or Solid
L
Beer-Lambert's Law of Linear Absorption
$I(v) = I_0 e^{-\alpha(v) P_a L}$
$\alpha(v)$ - absorption coefficient [$cm^{-1} atm^{-1}$]; L – path length [cm]
v - frequency [cm^{-1}]; P_a - partial pressure [atm]
$I(v)$
$\alpha(v)$
v
$\alpha(v) = C \cdot S(T) \cdot g(v - v_0)$
C - total number of molecules of absorbing gas atm cm^3 [molecule·cm^{-3}·atm^1]
S – molecular line intensity [cm·$molecule^{-1}$]
$g(v - v_0)$ – normalized spectral lineshape function [cm]. (Gaussian, Lorentzian, Voigt)
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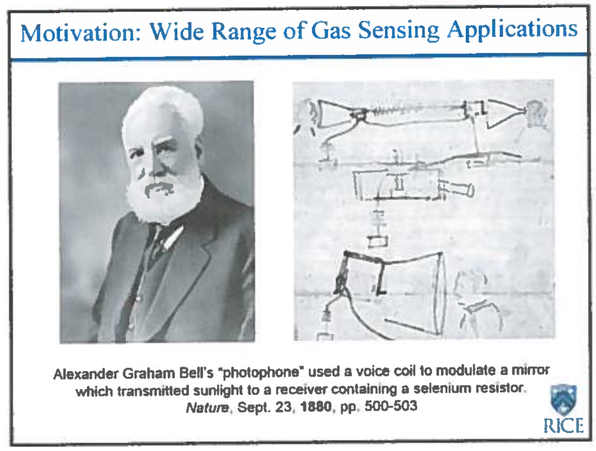
Motivation: Wide Range of Gas Sensing Applications
Alexander Graham Bell's "photophone" used a voice coil to modulate a mirror which transmitted sunlight to a receiver containing a selenium resistor.
Nature, Sept. 23, 1880, pp. 500-503
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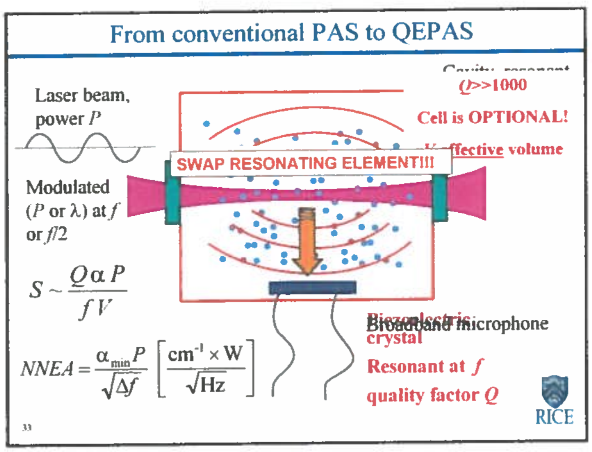
From conventional PAS to QEPAS
Laser beam, power P
Modulated (P or λ) at f or $f/2$
$S \sim \frac{Q \alpha P}{f V}$
$NNEA = \frac{\alpha_{min} P}{\sqrt{\Delta f}} \left[\frac{cm^{-1} \times W}{\sqrt{Hz}} \right]$
Q>>1000
Cell is OPTIONAL!
Effective volume
SWAP RESONATING ELEMENT!!!
Piezoelectric crystal
Broadband microphone
Resonant at f
quality factor Q
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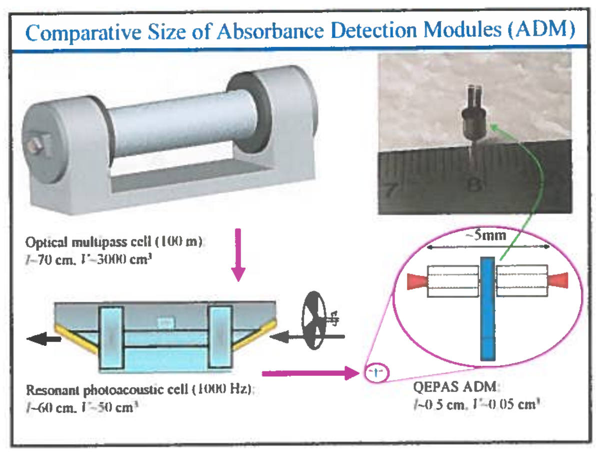
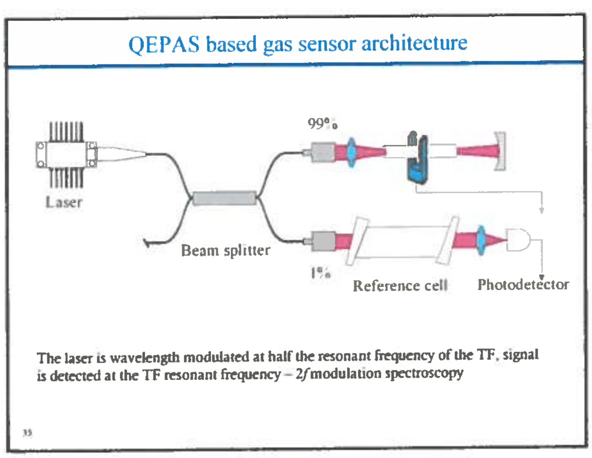
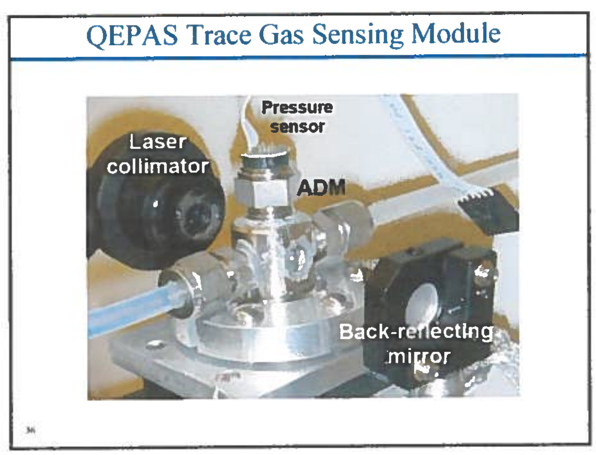
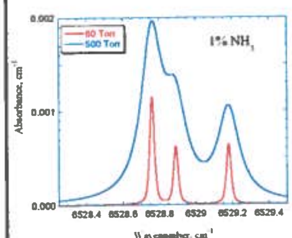
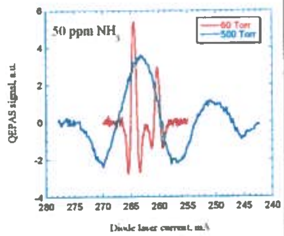

Comparative Size of Absorbance Detection Modules (ADM)
Optical multipass cell (100 m): l~70 cm, V~3000 cm^3
~5mm
Resonant photoacoustic cell (1000 Hz): l~60 cm, V~50 cm^3
QEPAS ADM: l~0.5 cm, V~0.05 cm^3


QEPAS based gas sensor architecture
Laser
99%
Beam splitter
1%
Reference cell
Photodetector
The laser is wavelength modulated at half the resonant frequency of the TF, signal is detected at the TF resonant frequency – 2f modulation spectroscopy


QEPAS Trace Gas Sensing Module
Pressure sensor
Laser collimator
ADM
Back-reflecting mirror

Ammonia Detection using a 1.53 μm Telecom Diode Laser



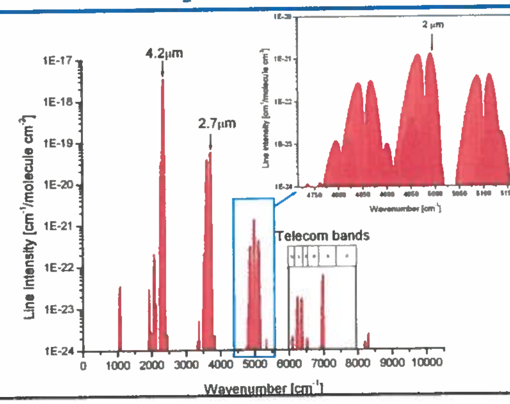


Spectral simulations based on data from Webber et al., APPLIED OPTICS 40, 2031-2042 (2001)]

QEPAS spectra at different pressures of NH_3:N_2 gas mixture; τ=0.3s, 38 mW diode laser excitation power at 6529 cm^{-1}

Applied Optics 43, 6213-6217, 2004

CO_2 Detection at 2 μm



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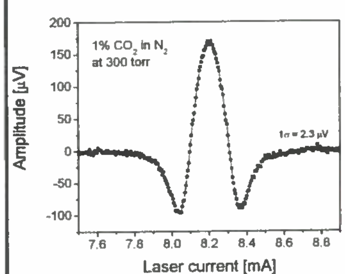
CO_2 detection limit



- SNR : ~74 (~135 ppm of CO_2)
- Laser power: ~ 4.6 mW at 2 μm
- Lock-in time constant: 1 s
- Peak absorbance: ~ 1.4×10^{-3} cm^{-1}
- Normalized noise equivalent sensitivity for CO_2 in N_2:

$$NES = 1.54\times10^{-7}\ cm^{-1}W/\sqrt{Hz}$$

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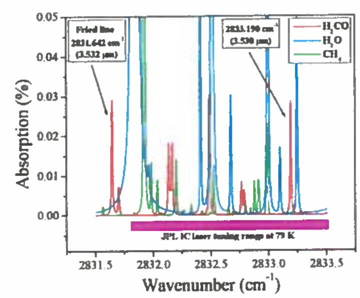
HITRAN Based Simulation of a H_2CO-H_2O-CH_4 Spectrum in Tuning Range of a 3.53μm IC Laser



- H_2CO: 10 ppb
- H_2O: 3%
- CH_4: 2 ppm
- Optical path: 100 m
- Total pressure: 30 Torr

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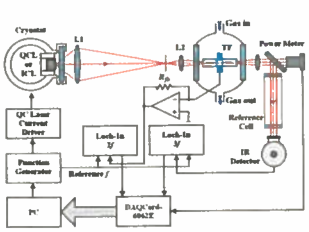
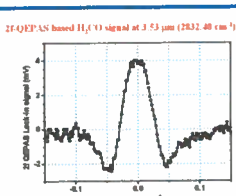
QCL based Quartz-Enhanced Photoacoustic Sensor





- $[H_2CO]$: 13.27 ppm
- QEPAS NNEA Sensitivity:

  $1.1\times10^{-8}cm^{-1}\ W/\sqrt{Hz}$;

  NEC (τ=1s): 0.28 ppmv (5 mW)

  For comparison:

  QEPAS Sensitivity for NH_3:

  $5.4\times10^{-9}cm^{-1}W/\sqrt{Hz}$

  NEC (τ=1s): 0.50 ppmv (38 mW)

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M. Horstjann et. al., Applied Physics B 79, 799, 2004

Merits of QE Laser-PAS based Trace Gas Detection

- High sensitivity (ppm to ppb gas concentration levels) and excellent dynamic range
- Immunity to ambient and flow acoustic noise, laser noise and etalon effects, which allows applications that involve harsh operating environments
- Required sample volume is very small. The volume is ultimately limited by the gap size between the TF prongs, which is < 1 mm^3 for the presently used QTF.
- No spectrally selective elements are required
- Applicable over a wide range of pressures, including atmospheric pressure
- Sensitive to phase shift introduced by vibrational to translational (V-T) relaxation processes and hence the potential of concentration measurements of spectrally interfering species
- Ultra-compact, rugged and low cost compared to LAS that requires a multipass absorption cell and infrared detector(s)
- Potential for optically multiplexed concentration measurements

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QEPAS Performance for 10 Trace Gas Species (Jan'06)

Molecule (Host)	Frequency, cm^{-1}	Pressure, Torr	NNEA, $cm^{-1}W/Hz^{½}$	Power, mW	NEC (τ=1s), ppmv
H_2O (N_2)**	7181.17	60	$2.1\cdot10^{-9}$	5.8	0.18
HCN (air: 50% hum) **	6539.11	60	$\sim2.6\cdot10^{-9}$	50	0.1
C_2H_2 (N_2)**	6529.17	75	$\sim2.5\cdot10^{-9}$	~40	0.06
NH_3 (N_2)*	6528.76	60	$5.4\cdot10^{-9}$	38	0.50
CO_2 (exhaled air)	6514.25	90	$1.0\cdot10^{-8}$	5.2	890
CO_2 (N_2) ***	4990.00	300	$1.5\cdot10^{-7}$	4.6	130
CH_2O (N_2) *	2832.48	100	$1.1\cdot10^{-8}$	4.6	0.28
CO (N_2)	2196.66	50	$5.3\cdot10^{-7}$	13	0.5
CO (propylene)	2196.66	50	$7.4\cdot10^{-8}$	6.5	0.14
N_2O (air+5%SF_6)	2195.63	50	$1.5\cdot10^{-8}$	19	0.007

* - Improved microresonator
** - Improved microresonator and double optical pass through QTF
*** - Without microresonator

NNEA – normalized noise equivalent absorption coefficient.
NEC – noise equivalent concentration for available laser power and τ=1s time constant.

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

* M. E. Webber, M. Pushkarsky and C. K. N Patel, Appl. Opt. 42, 2119-2126 (2003)

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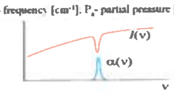
Fundamentals of Laser Absorption Spectroscopy

Beer-Lambert's Law of Linear Absorption

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

$\alpha(\nu)$ - 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 cm^3 [molecule·cm^{-3}·atm^{-1}]

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

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

Optimum Molecular Absorbing Transition
- Overtone or Combination Bands (NIR)
- **Fundamental Absorption Bands (MID-IR)**

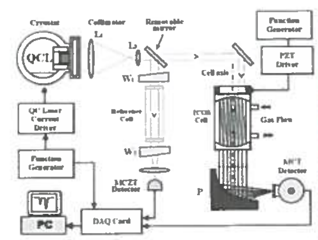
Long Optical Pathlengths
- Multipass Absorption Cell
- **Cavity Enhanced, Cavity Ringdown & Intracavity Spectroscopy**
- Open Path Monitoring (with retro-reflector)
- Evanescent Field Monitoring (fibers & waveguides)

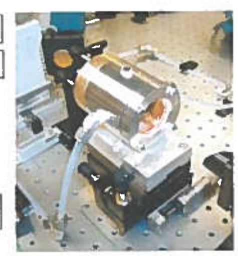
Spectroscopic Detection Schemes
- **Frequency or Wavelength Modulation**
- Balanced Detection
- Zero-air Subtraction
- Photoacoustic Spectroscopy

Important Biomedical Target Gases

Molecule	Formula	Biological/Pathology Indication
Pentane	$CH_3(CH_2)_3CH_3$	Lipid peroxidation, oxidative stress associated with inflammatory diseases, transplant rejection, breast and lung cancer
Ethane	C_2H_6	Lipid peroxidation and oxidative stress
CO_2 isotope ratio	$^{13}CO_2$ / $^{12}CO_2$	Marker for Heliobacter pylori infection, Gastrointestinal and hepatic function
Carbonyl Sulfide	COS	Liver disease and acute rejection in lung transplant recipients (10-500 ppb?)
Carbon disulfide	CS_2	Schizophrenia
Ammonia	NH_3	Hepatic encephalopathy, liver and renal diseases, fasting response
Formaldehyde	HCHO	Cancerous tumors, breast cancer (400-1500 ppb)
Nitric Oxide	NO	Inflammatory and immune responses (e.g., asthma) and vascular smooth muscle response (6-100 ppb)
Hydrogen Peroxide	H_2O_2	Airway Inflammation, Oxidative stress (1-5 ppb)
Carbon Monoxide	CO	Smoking response, CO poisoning, vascular smooth muscle response, platelet aggregation (400-3000 ppb)
Ethylene	$H_2C{=}CH_2$	Oxidative stress, cancer
Acetone	CH_3COCH_3	Fasting response, diabetes mellitus response, ketosis

Off-Axis Integrated Cavity Output Spectroscopy (ICOS) Based Gas Sensor





- Novel compact gas cell design of length 3.8 – 5.3 cm and cell volumes 80 cm^3.
- Low loss mirrors (ROC 1m) ~60-250 ppm, R ~99.975, L_{eff}=170-800 m
- Rapid eNO concentration measurements during a single breath cycle are feasible

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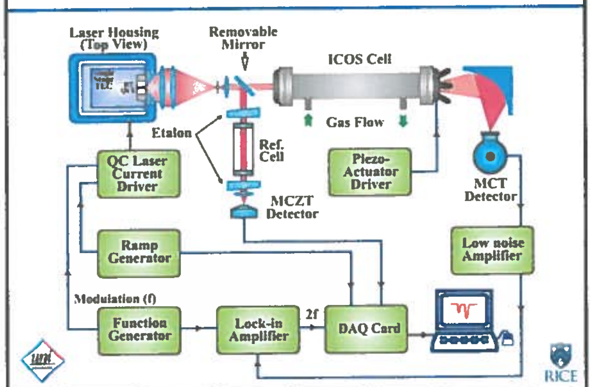
TEC – CW-DFB QCL based Nitric Oxide OA-ICOS Sensor



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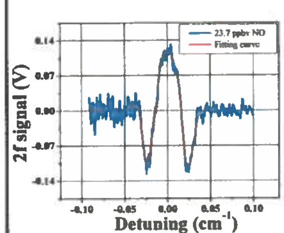
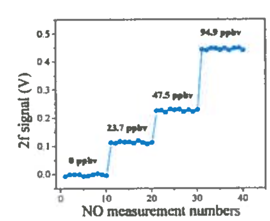
2f NO Absorption Signal at 1835.57 cm^{-1}





NO:N_2 mixture @ 100 Torr
Effective L= 700 m

Noise equivalent sensitivity: 0.7 ppbv (1σ)

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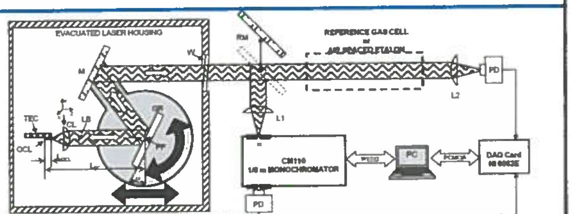
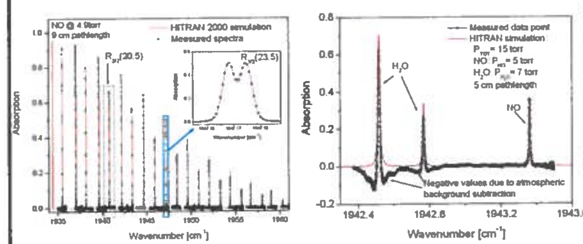
External Cavity QCL Based Spectrometer



- PZT controlled EC-length
- PZT controlled grating angle
- Optimization of cavity alignment performed by means of lens positioning using electrically controlled 3D translation stage

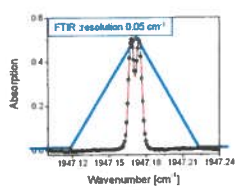
G. Wysocki et al. Applied Physics B. 81, p.769 (2005)

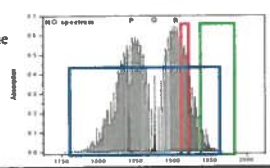
Mid-IR NO Absorption Spectra Acquired with a Tunable TEC QCL



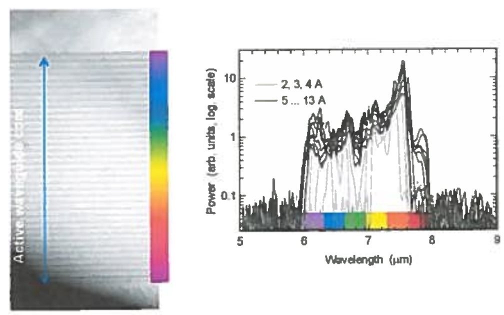
Important facts of novel EC-QCL Technology

- Laser spectroscopy provides superior resolution compared to other techniques e.g. FTIR
- Single mode operation of the laser is required
- Wavelength tunability of single mode (DFB) mid-IR semiconductor lasers is ~10cm-1
- Demonstrated wavelength tunability of the Rice EC QCL is ~ 35 cm-1 (limited by the gain chip properties and not by the designed EC configuration)
- Gain chips, which can provide tunability of >200 cm^{-1} are already reported in the literature

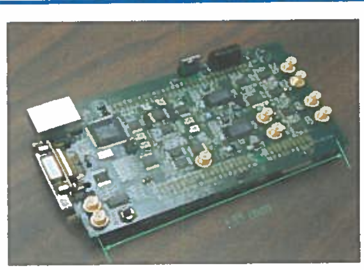




QC lasers with inhomogeneously broadened gain



Dedicated DSP-based electronics for trace gas sensing using a pulsed QC laser



Pulsed laser requires high speed pulsed processing system for minimum detection limits

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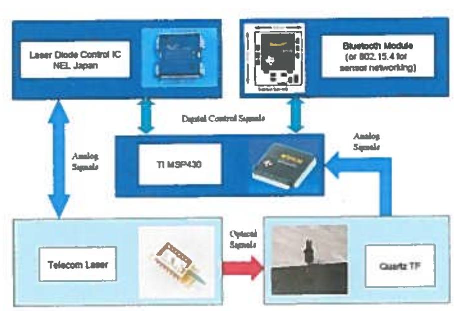
Concept of a ultra-miniature QEPAS gas sensor



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Conclusions and Future Directions

- **Laser based Trace Gas Sensors**
  - Ultra compact (~ 0.2 mm^3), robust & low cost sensors based on QE L-PAS
  - QEL-PAS is immune to ambient noise. The measured noise level coincides with the thermal noise of the QTF
  - Best to date demonstrated QEPAS sensitivity is 2.1 x 10^{-9} $cm^{-1}W/\sqrt{Hz}$ for H_2O:N_2
  - QEPAS exhibits a low 1/*f* noise level, allowing data averaging for more than 3 hours
  - Detected 14 trace gases to date: NH_3, CH_4, N_2O, CO_2, CO, NO, H_2O, COS, HCN, C_2H_4, C_2H_2, C_2H_5OH, SO_2, H_2CO and several isotopic species of C, O, N & H
- **Applications in Trace Gas Detection**
  - Environmental & Spacecraft Monitoring (NH_3, CO, CH_4, C_2H_4, N_2O, CO_2 and H_2CO)
  - Medical Diagnostics (NO, CO, COS, CO_2, NH_3, C_2H_4)
  - Industrial process control and chemical analysis (NO, NH_3, H_2O)
- **Future Directions and Collaborations**
  - QE L-PAS based applications using novel thermoelectrically cooled cw and broadly wavelength tunable quantum and interband cascade lasers
  - Investigate QTFs with lower resonant frequencies
  - Investigate amplitude modulation QEPAS potential and limitations
  - New target gases, in particular VOCs and HCs
  - Development of optically multiplexed gas sensor networks based on QE L-PAS

NASA Atmospheric & Mars Gas Sensor Platforms

Tunable laser sensors for earth's stratosphere

Aircraft laser absorption spectrometers

Tunable laser planetary spectrometer