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Trace Gas Detection with Distributed Feedback Quantum Cascade Lasers

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OUTLINE

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- Motivation and Technology Issues
- Direct Absorption Spectroscopy with QC-DFB lasers
- Selected Applications for Trace Gas Detection
- Summary and Future Outlook

Wide Range of Gas Sensor Applications

- Urban and Industrial Emission Measurements
  - Industrial Plants - Fenceline perimeter monitoring
  - Combustion Diagnostics
  - Automobile
- Rural Emission Measurements
  - Agriculture
- Environmental Monitoring
  - Atmospheric Chemistry
  - Volcanic Emissions
- Spacecraft and Planetary Surface Monitoring
  - Crew Health Maintenance & Life Support
- *Diagnostic and Industrial Process Control*
  - Petrochemical and Semiconductor Industry
- Medical Diagnostics

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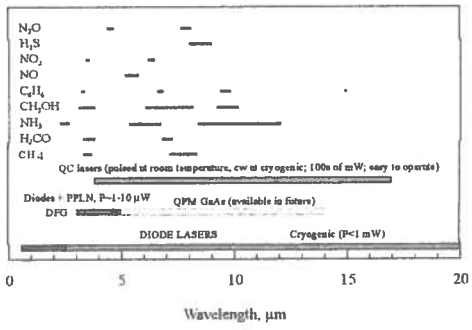
Spectral Coverage by Diode/QC Lasers



Key Characteristics of Quantum Cascade Lasers

- Laser wavelengths cover entire range from 3.5 to 24 μm determined by layer thickness of same material
- Intrinsically high power lasers (determined by number of stages)
  - CW: 0.2W @ 80 °K, ~100 mW single frequency
  - Pulsed: 1 W peak at room temperature, ~50 mW avg. @ 0 °C (up to 80 % duty cycle)
- High Spectral purity (single mode: kHz-330MHz)
- Wavelength tuning by current or temperature scanning
- High reliability: low failure rate, long lifetime, robust operation and extremely reproducible emission wavelengths

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Molecules detected with QC Laser at Rice

Molecule	Wavelength and method
$^{12}CH_4$ and $^{13}CH_4$, N_2O, H_2O and HDO	8 μm, CW and pulsed, ambient air, 100 m pathlength, Voigt fit and linear regression analysis
C_2H_5OH	8 μm, CW, 100 m pathlength, linear regression analysis
NO	5.2 μm, CW, ICOS and CRDS
NH_3	10 μm, pulsed, 1 m pathlength
CO	4.6 μm, pulsed, ambient air, 1 m *pathlength, reference channel*

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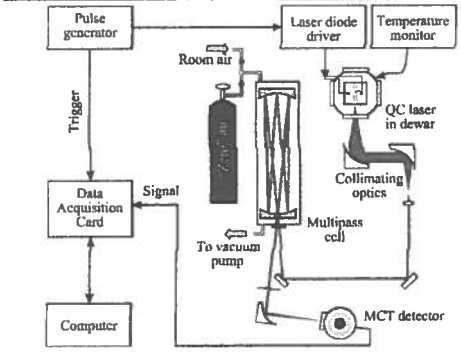
Trace Gas Detection with a Multipass Cell



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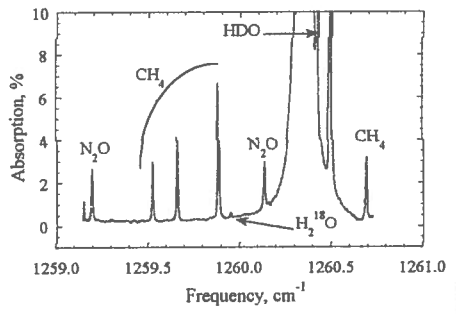
Absorption Spectrum of Room Air



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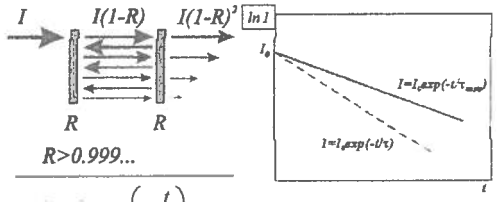
Cavity Ring-Down Spectroscopy



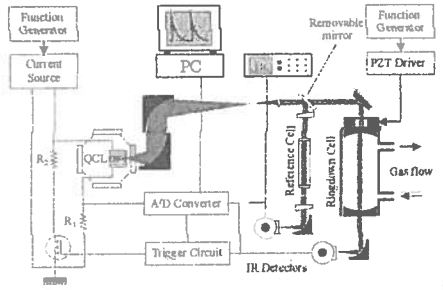
$R > 0.999...$

$$I = I_0 \exp\left(-\frac{t}{\tau}\right)$$

$$\tau = \frac{l}{c} \cdot \frac{1}{\alpha l - \ln\sqrt{R_1 R_2}}$$

$$\alpha = \frac{l}{c}\left(\frac{1}{\tau} - \frac{1}{\tau_{empty}}\right)$$

CRDS Based Gas Sensor



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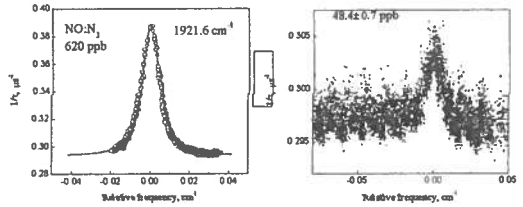
NO Absorption Spectrum in N_2 at 60 torr Total Pressure



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Pulsed Operation of a QC-DFB Laser

ADVANTAGES	DISADVANTAGES
♦ Laser can be operated at near-room temperature	♦ Broader linewidth (~300 MHz)
♦ Facilitates temperature control	♦ Reduced average power
♦ No consumables (liquid N_2)	♦ More sophisticated electronics for driving QC laser and data acquisition are required
♦ Compact	

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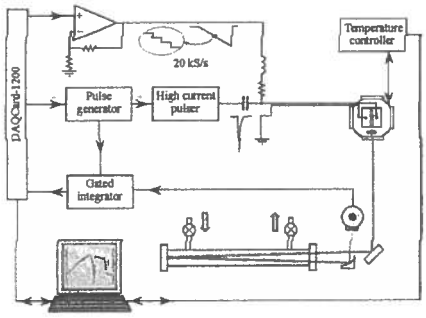
Pulsed 4.6 μm QC Laser Based Gas Sensor



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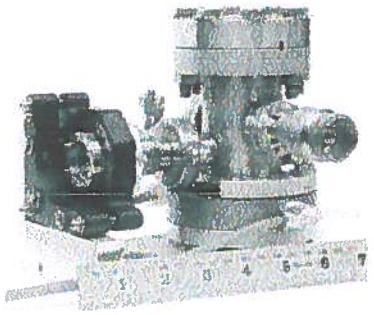
Pulsed QC-DFB Laser Housing



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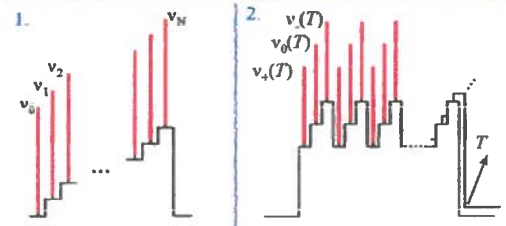
Manipulating the Pulsed QC Laser Frequency



Fast scanning of the laser frequency with a subthreshold current

Fast cycling of the laser frequency with a subthreshold current and slow scanning with temperature (wavelength modulation)

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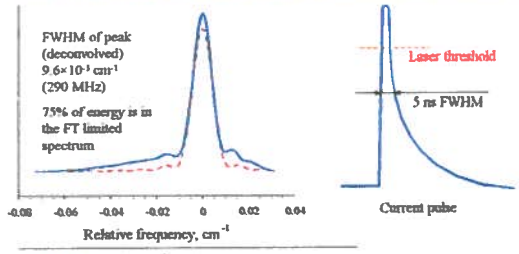
Spectral Shape of a Pulsed QC Laser Line



Measured lineshape

Simulated: FT of a 3.1 ns rectangular pulse convolved with an absorption line envelope

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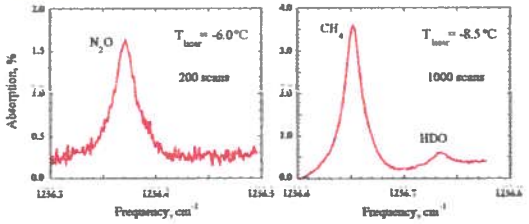
"Fast Scan" Detection of Trace Gases in Air



Pathlength: 100 m (multipass cell)

Pressure: 85 Torr

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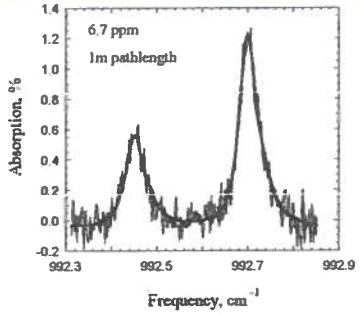
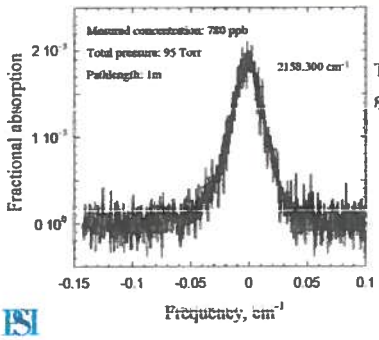
NH_3 Spectrum at 993 cm^{-1}



CO Absorption: Ambient Air Sample



Two IR detectors

Sensitivity ~10 ppb

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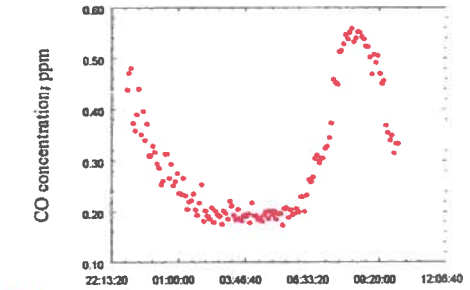
CO Concentration Measurements



Summary

- Diode and Quantum Cascade Laser Based Trace Gas Sensors
  - Compact, tunable, robust (alignment insensitive),fieldable
  - High sensitivity ($<2\cdot10^{-4}$ to 10^{-5}) and selectivity (10–300 MHz)
  - Fast data acquisition and analysis
  - Detected trace gases:NH_3, CH_4, H_2CO, NO_2, N_2O, H_2O, CO_2, CO, NO, HCl, SO_2, C_2H_5OH, isotopic species of $^{12,13}C$, $^{16,17,18}O$, $^{35,37}Cl$
- Applications in Trace Gas Detection
  - Environmental monitoring: H_2CO, CO, CH_4 (NASA, NCAR, NOAA, EPA)
  - Industrial process control and chemical analysis
  - Medical diagnostics (NO, CO, CO_2)
- Future Directions
  - Fiber lasers and amplifiers
  - Longer mid-IR wavelengths with orientation patterned GaAs and QC lasers, detection of complex molecules
  - Cavity enhanced and cavity ringdown spectroscopy

References

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- A.A. Kosterev, R.F. Curl, F.K. Tittel, C. Gmachl, F. Capasso, D.L. Sivco, J.N. Baillargeon, A.L. Hutchinson, and A.Y. Cho, "Effective utilization of quantum cascade distributed feedback lasers in absorption spectroscopy" Appl. Opt. 39, 4425 (2000)
- A.A.Kosterev, F.K.Tittel, F. Capasso, C. Gmachl, A. Tredicucci, A.L. Hutchinson, D.L. Sivco, and A.Y. Cho, "Trace gas detection in ambient air with a thermoelectrically cooled QC-DFB laser" Applied Optics LP 39, 6866-6872 (2000).