Laser Spectroscopic Trace Gas Sensing: Novel Applications and Future Directions

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OUTLINE

- Motivation - Trace Gas Detection
- Laser-based Gas Sensing Technology
- Quantum Cascade (QCL) and Interband Cascade (ICL) lasers
- Quartz-Enhanced Photoacoustic Spectroscopy (QEPAS) and portable sensors
- Cooperative Gas Sensing and Asynchronous Sensor Networking for Detection Applications
- Summary

Nokia

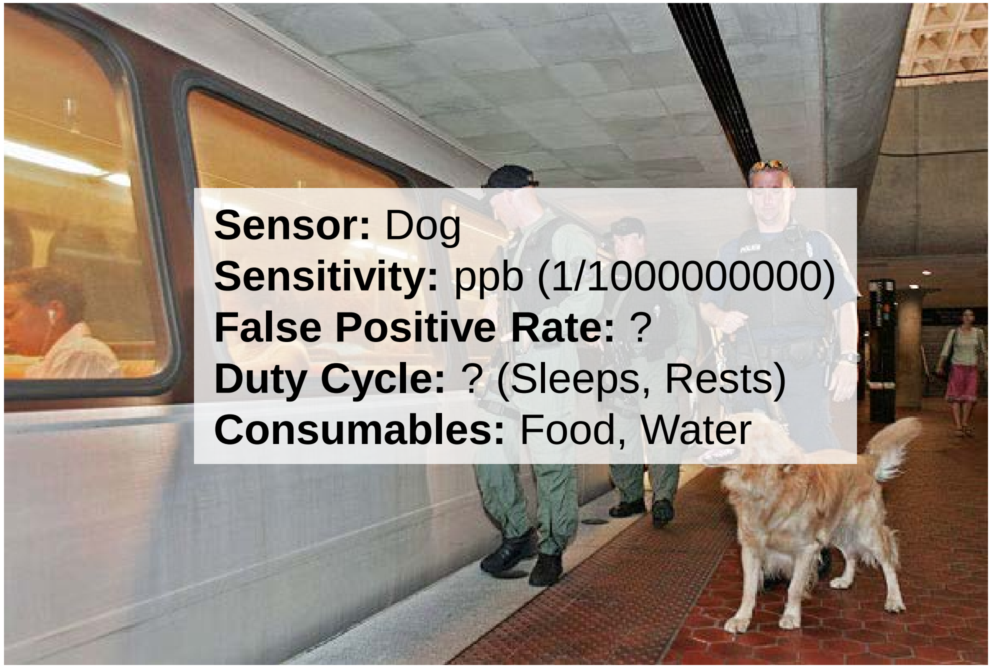
Dallas, TX
Feb. 8, 2006

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

Air Pollution: Houston, TX

Trace Gas Detection Applications

- Urban and Industrial Emission Measurements
  - Industrial Plants
  - Combustion Sources and Processes (early fire sensing)
  - Automobile Emissions
- Rural Emission Measurements
  - Agriculture
- Environmental Monitoring
  - Atmospheric Chemistry
  - Volcanic Emissions
- Chemical Analysis and Industrial Process Control
  - Chemical, Pharmaceutical, Food
  - Semiconductor Industry
- Spacecraft and Planetary Surface Monitoring
  - Crew Health Maintenance & Human Life Support Program
  - Mars Rovers
- Medical Diagnostics (e.g. breath analysis)
- Toxic Chemicals, Explosives, and Biological Agents
- Fundamental Science and Photochemistry



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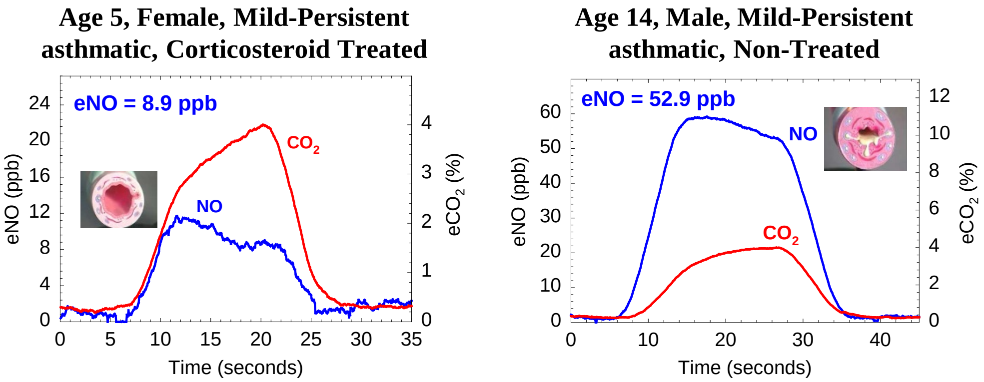
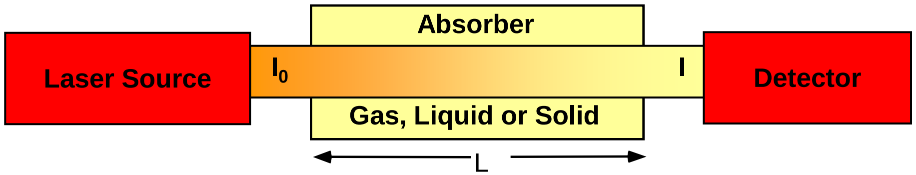


Fundamentals of Laser Absorption Spectroscopy (LAS)



Beer-Lambert's Law of Linear Absorption

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

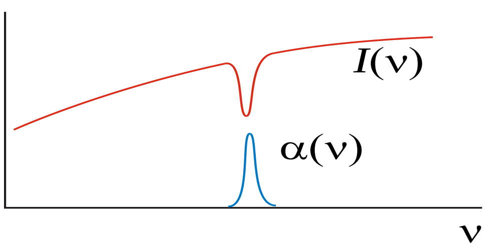
$\alpha(\nu)$ - absorption coefficient [cm^{-1} atm^{-1}]; L – path length [cm]

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

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

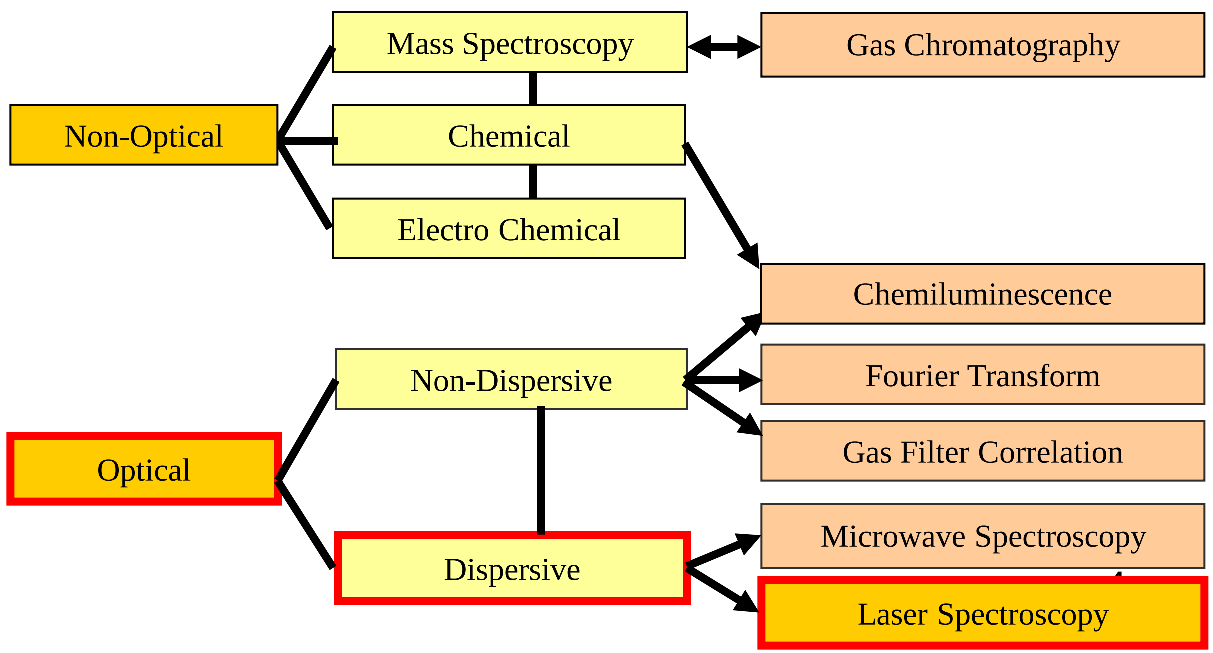
S – molecular line intensity [cm ·$molecule^{-1}$]

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



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

Methods for Trace Gas Detection



Example: Motivation for NH_3 Detection

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

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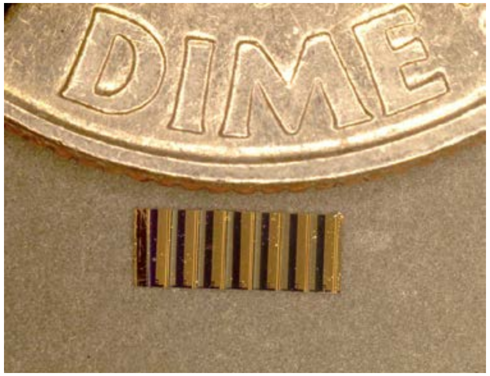
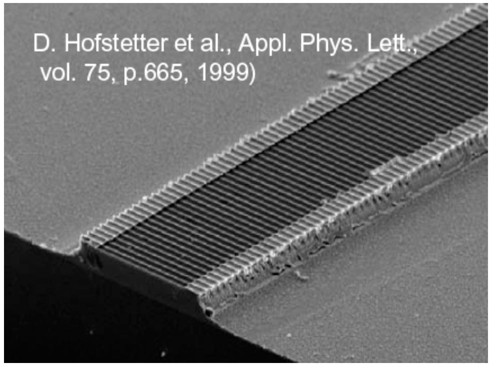
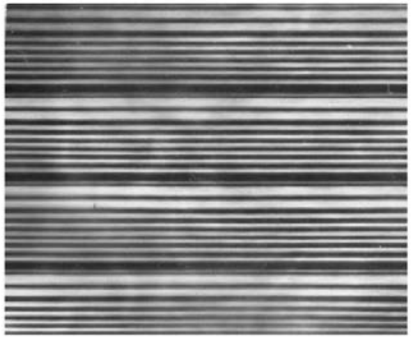
Quantum and Interband Cascade Laser: Basic Facts

- Band-structure engineered devices
  - Grown by MBE or MOCVD
- QCLs operate from 4 -160 μm
  - Quantum well nanostructures
  - Cascading (each electron creates N laser photons and the number of periods N determines laser power)
- Compact, reliable, stable, long lifetime, commercial availability
- Broad spectral tuning range in the mid-IR (4-24 μm for QCLs and 3-5 μm for ICLs)
- High output powers
  - Pulsed peak powers of 1.6 W; high temperature operation ~ 425 K
  - Average power levels: 1-600 mW
  - ~ 50 mW, TEC CW DFB (Alpes Laser, Switzerland)
  - >600 mW (CW FP) and >150 mW (CW DFB) at 298 K (Northwestern University)



4 mm



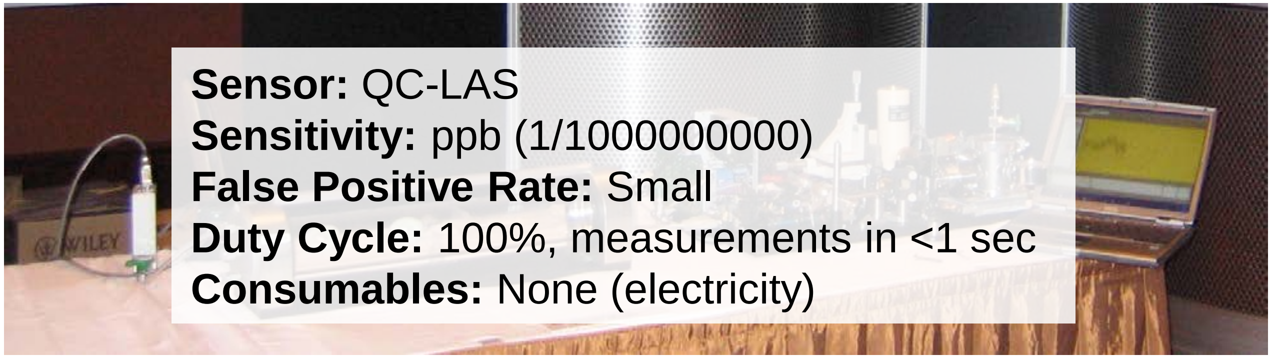


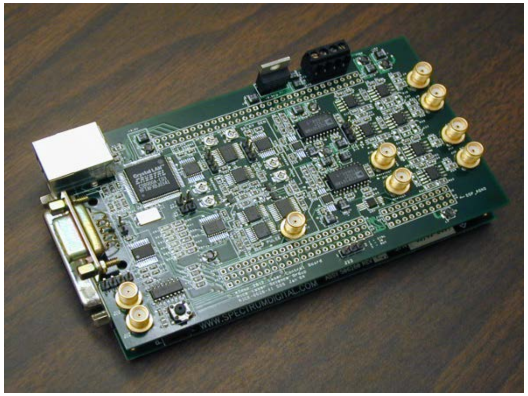
45 nm

Previously Integrated Carbon Monoxide QC-LAS Sensor

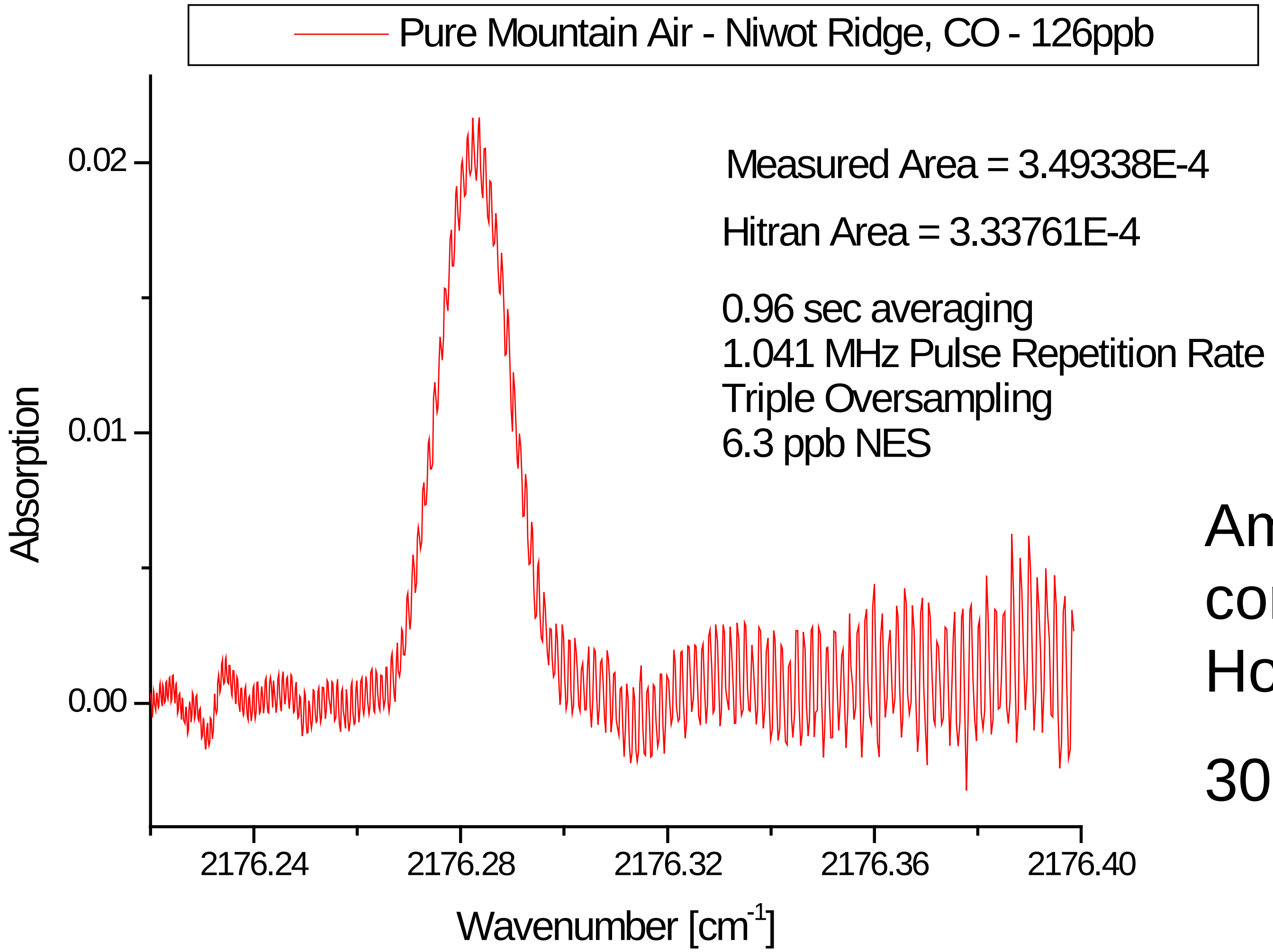
- First Rice laser based trace-gas sensor with custom DSP control and processing
- Designed for high speed acquisition, remote monitoring
- Detection limit improved
  - 6ppb in 3 seconds using commercial acquisition equipment
  - 6ppb in 1 second using custom solution

- Quantum Cascade Laser @ 4.6μm wavelength
- 100 meter multipass cell
- 4 mW pulsed optical power @ -30 ºC
- Peltier thermoelectrically cooled
- Pulsed analog front end
- Subthreshold current modulation (wavelength tuning)
- Autonomous control and processing
- High speed signal acquisition and processing





Detection Limit of QC-LAS CO Sensor



Ambient CO concentration in Houston, TX

300ppb-1ppm

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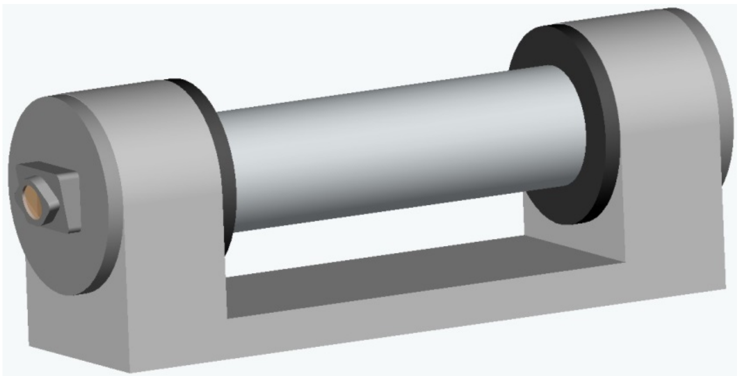
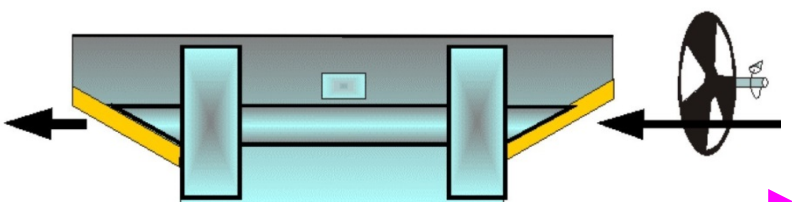
S. G. So, G. Wysocki, J. P. Frantz, F. K. Tittel, "Development of Digital Signal Processor controlled Quantum Cascade Laser based Trace Gas Sensor Technology", Accepted to IEEE Sensors Journal, Jan 2006.

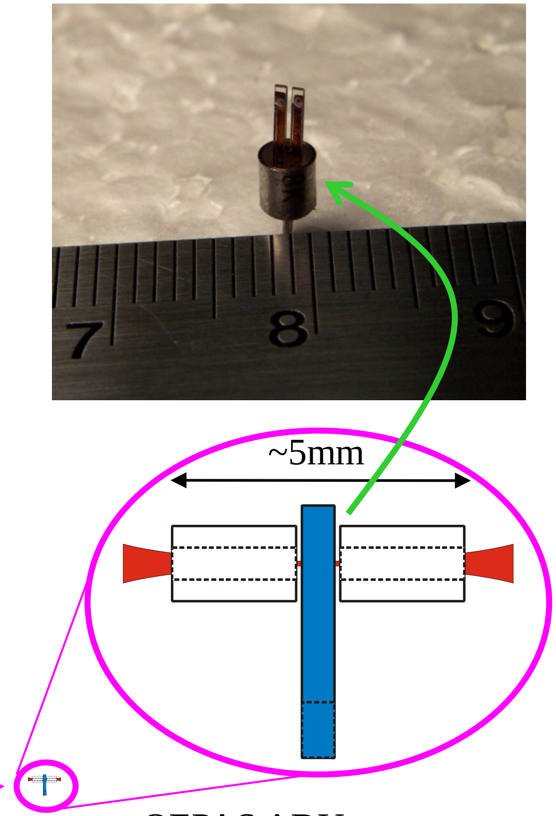
Absorption Detection Modules



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

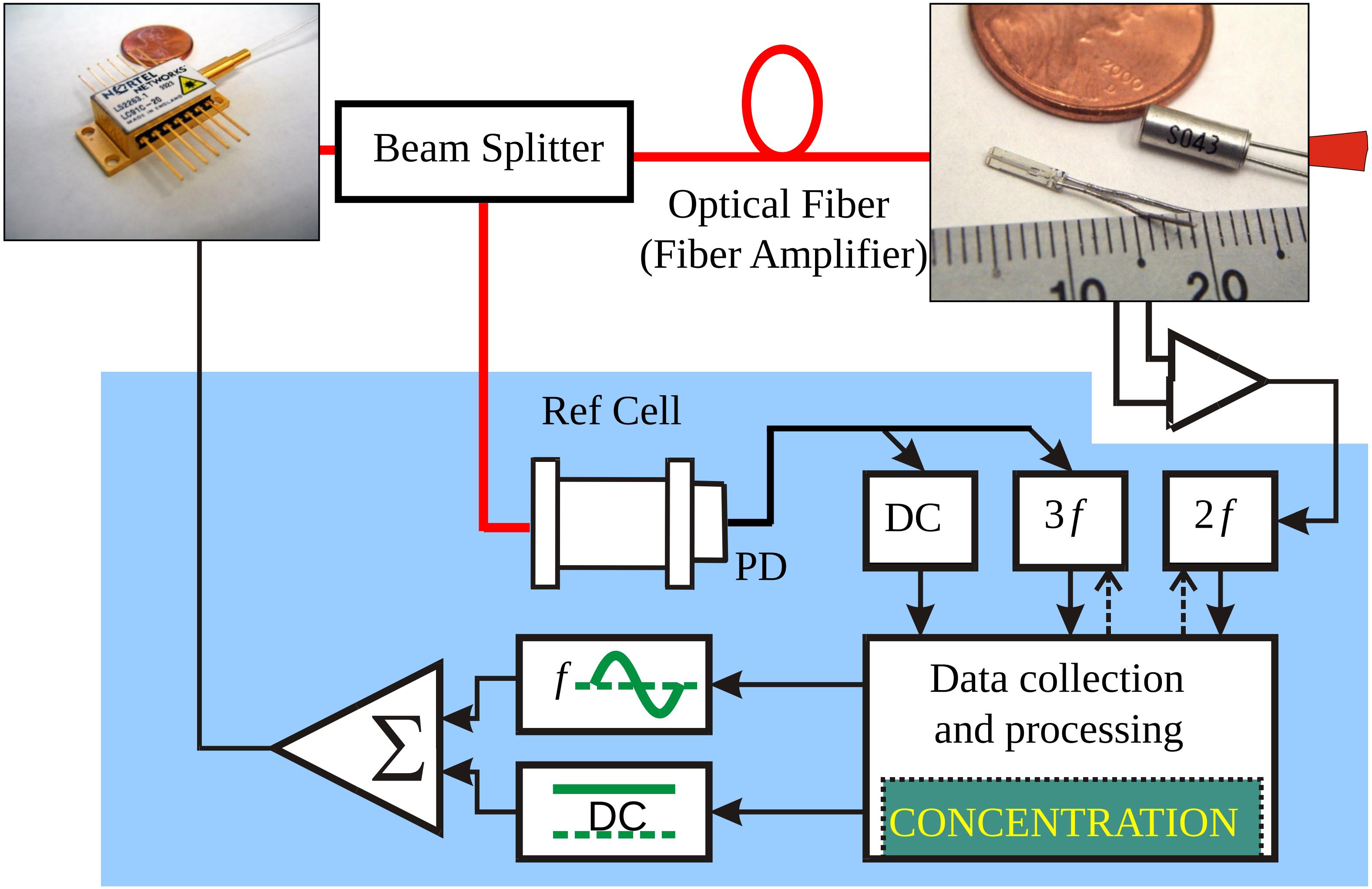


Resonant photoacoustic cell (1000 Hz):
l~60 cm, *V*~50 cm^3



QEPAS ADU:
l~0.5 cm, *V*~0.05 cm^3

QEPAS Fiber based Gas Sensor Architecture



Fiber Connection   Electrical Connection

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eBay: JDS U 1550nm 2.5Gb/s DF...

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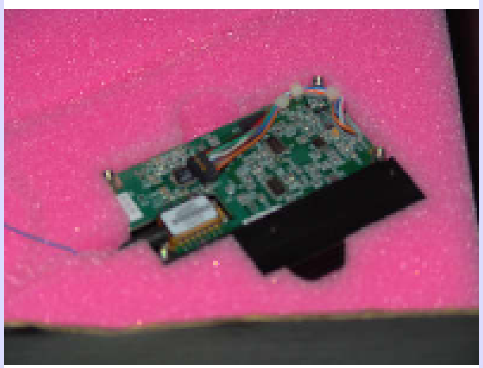
JDS U 1550nm 2.5Gb/s DFB Laser Fiber Optic TX Module

JDS UNIPHASE

Bidding has ended for this item

If you are a winner, Sign In for your status.

List an item like this or buy a similar item below.



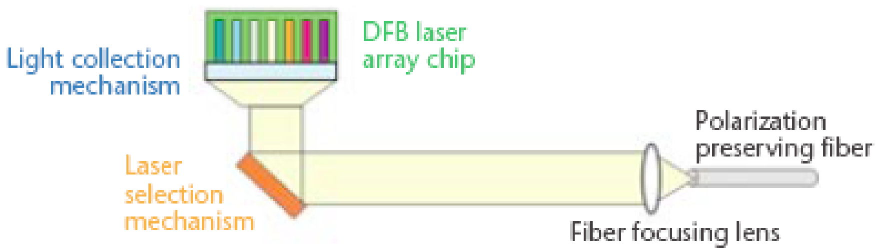
Larger Picture

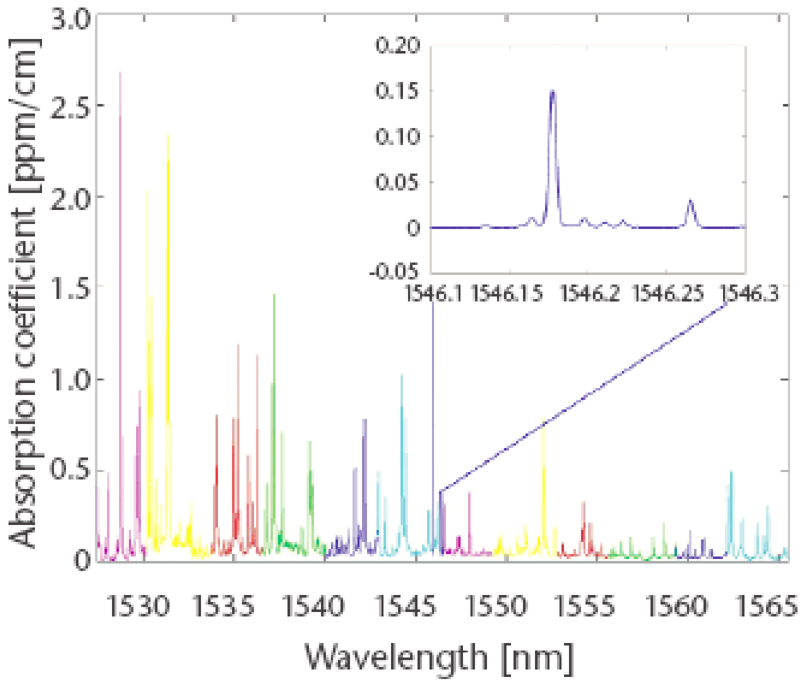
Winning bid:	**US $19.95**
Ended:	Jan-16-06 12:53:02 PST
Start time:	Jan-09-06 12:53:02 PST
History:	1 bid (US $19.95 starting bid)
Winning bidder:	
Item location:	Richardson, Texas United States
Ships to:	United States
Shipping costs:	US $10.50 -- Standard Flat Rate Shipping Service

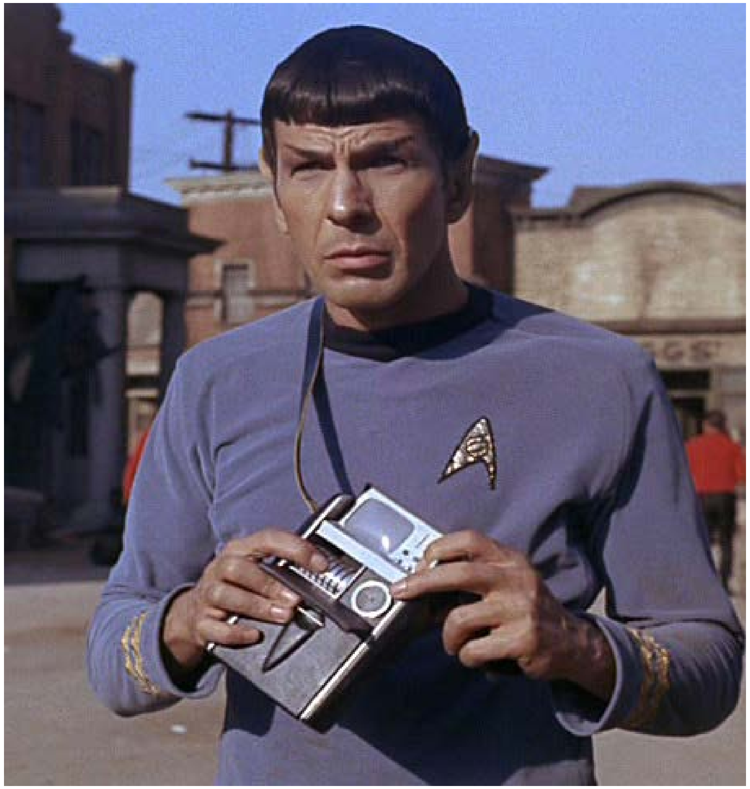
Shipping, payment details and return policy

Low cost lasers for low cost sensors!

Multispecies Detection: DFB-A Telecom Laser Arrays







Paramount Pictures

A. A. Kachanov, E. R. Crosson and B. A. Paldus, “Expanding the Horizon for Laser Absorption Spectroscopy”, Optics and Photonics News, July 2005

Important Biomedical Target Gases for Breath Analysis

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, lung cancer**
CO isotope ratio	**^{13}CO / ^{12}CO**	**Marker for Helicobacter pylori infection, Gastrointestinal and**

New Israeli mobile phone to detect breast cancer

Dec 09 1:37 PM US/Eastern

Email this story

An Israeli psychologist has reportedly developed a radical new technology which would enable an ordinary mobile phone to diagnose breast cancer and various type of heart disease.

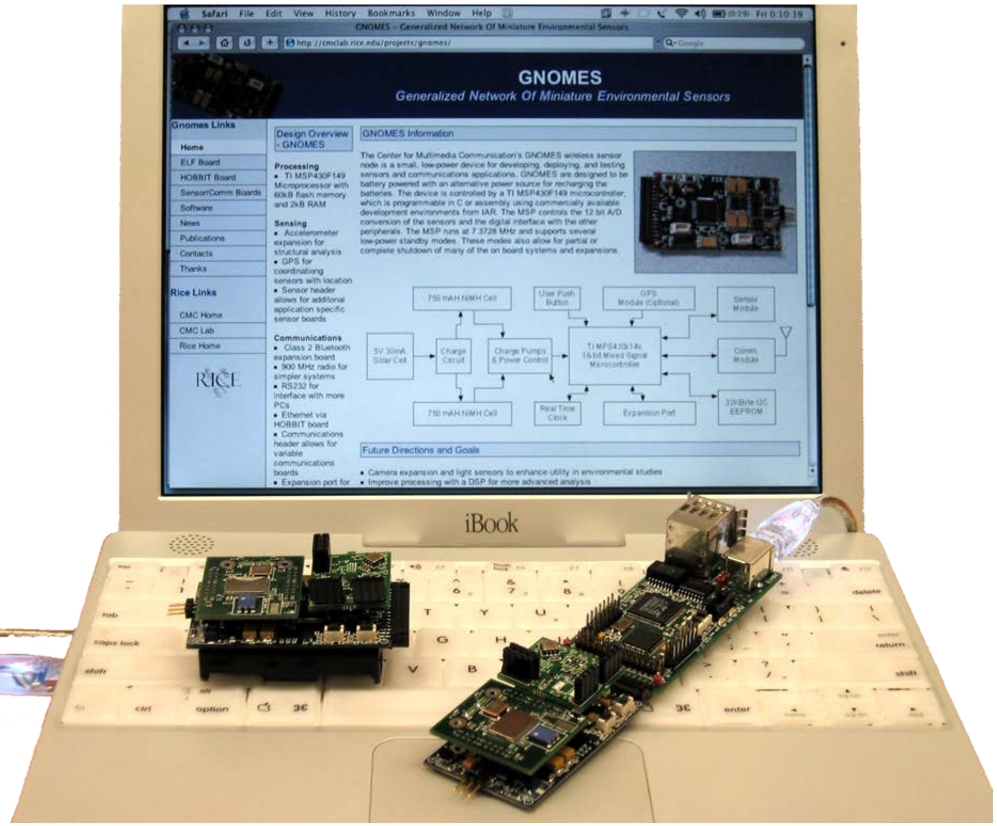
By installing new software and adding a basic infrared camera, a mobile phone could be transformed into a highly-effective diagnostic tool, offering far more accurate results than the self-checks many women do themselves, the Haaretz daily reported.

Molecule	Formula	Biological/Pathology Indication
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

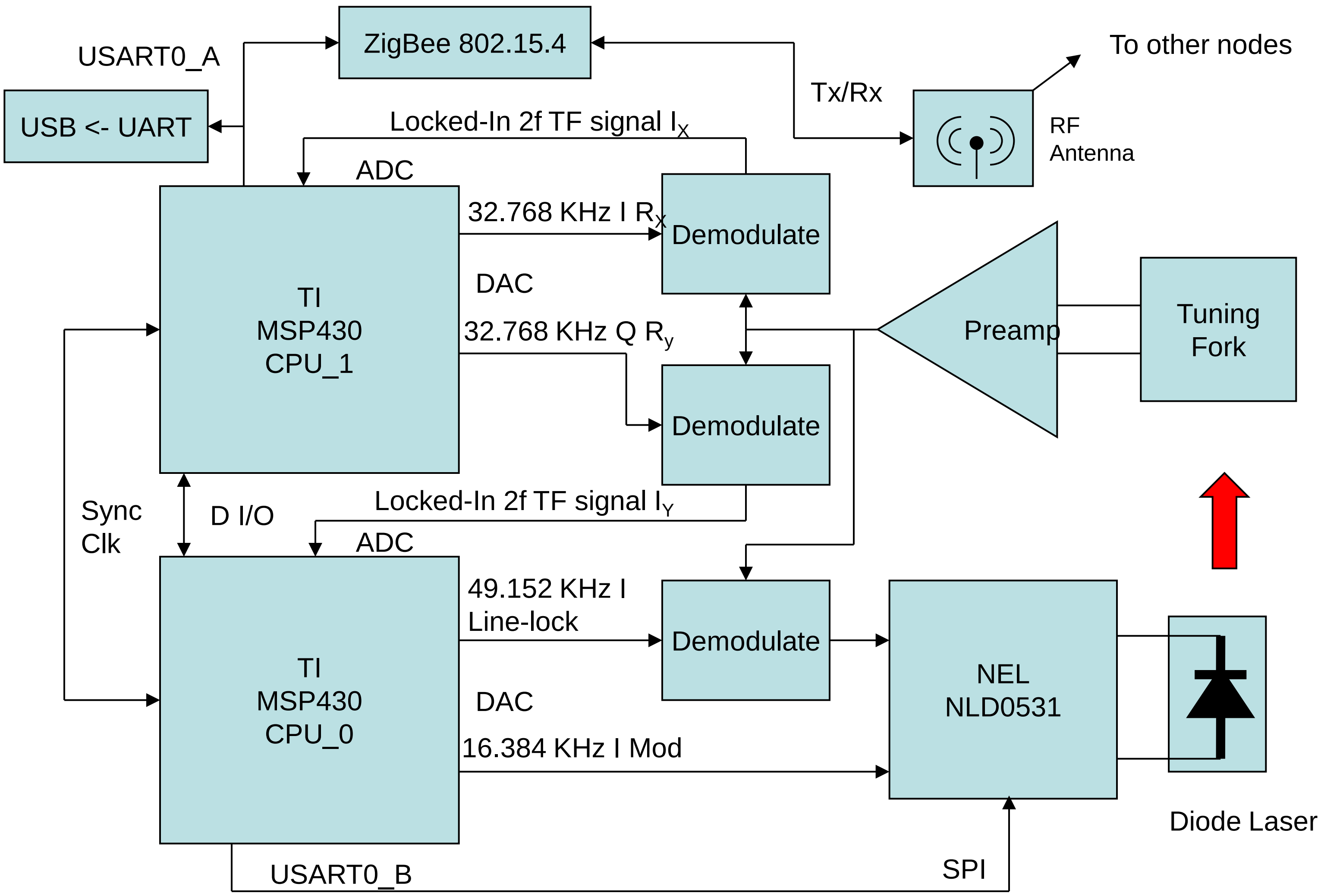
■ Studied at Rice Laser Science Group

GNOMES 3.0 Hardware Architecture

- Dual TI MSP430F169 processors
  - CPU_0
    - Sensing Application
    - Master for Processor-to-Processor Communication
  - CPU_1
    - Communication Software
    - Networking Software
    - Extra Analog Sensing / Processing
  - Individual 32kHz clocks; Shared 8MHz clock
  - 12 bit communication bus between processors
- 2MB off chip data storage per processor
- Serial Port over USB for PC connection
- 802.15.4 support
- User LEDs and Pushbuttons
- 3 expansion interface ports
  - 2 Digital (One per processor)
  - 1 Analog
- Power management done separately



QEPAS Sensor Network Node using GNOMES 3.0



S.G. So, E.J. Welsh, S. Narayanan, J.P. Frantz, D. Jones, and F.K. Tittel, “Low-Cost DSP and MSP-Based Solutions for Trace Gas Sensing Via Laser Spectroscopy “, MSP430-ATC America, Europe, 2005

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Sensor Network Requirements

- Ultra-low power consumption in nodes
  - Replacing batteries may be impossible
  - Lifetime / Uptime of network depends on application
- Ease of initial deployment
  - Environment may not be conducive to sensor network deployment
  - May need quick deployment on a large area
- Little Maintenance and Self-configuration
  - Nodes must on-line quickly once deployed
  - Network must be tolerant to node failure
- Local low-power information processing
  - Preprocessing of information to reduce communications is key
  - Advances is processor technology / integration makes this possible

Sensor Network != Ad-hoc Network

- Abundance of research in ad-hoc network technologies but sensor networks have unique constraints
- Typical ad-hoc networks can afford sophisticated routing and network topology discovery methods
- Data throughput is an index of performance in ad-hoc networks.
  - Sensor networks typically need only very low data rates

    eg. toxic gas detection systems may only communicate a few kilobits of data at once
- Due to low data rates, power consumption in sensor networks is receiver-dominated
- Nodes can be stationary in many sensor network applications

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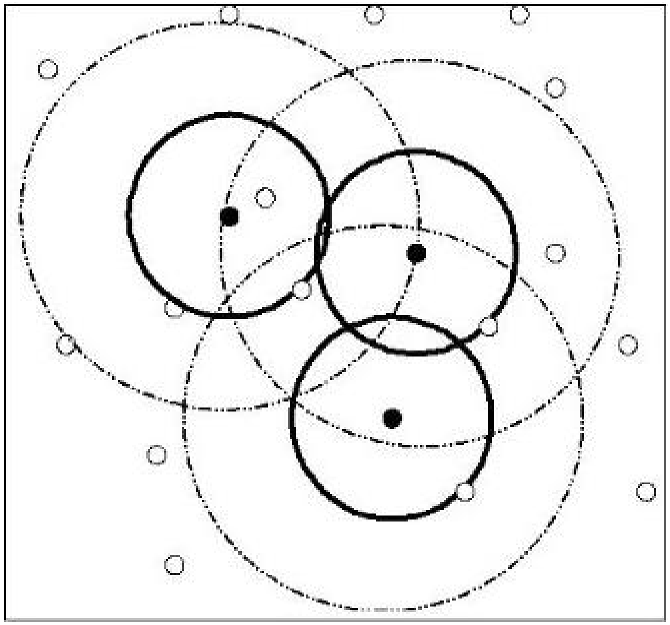
Asynchronous Sensor Network (ASN)

- Trade off transmit power, bandwidth and sophisticated routing for low power, easy deployment and simplicity
- Turn nodes off periodically to save power
- Nodes unaware of the sleep/awake cycles of other nodes; eliminates synchronization overhead
- Nodes may be distributed randomly throughout the region of observation
- Multihop network to keep radio transmission range small
- Flooding Protocol: Messages are broadcasted to the entire network; upon receipt of a message, node forwards the message if it is not the intended recipient



Snapshot of an ASN
Dark circles: Sensor Coverage Areas.
Dotted Circles: Radio transmission range
Filled dots: Awake nodes
Unfilled dots: Asleep nodes

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Needs of an ASN

- For detection applications, probability of detection improves with the density of nodes in the network
- Advantages of ASN come at the cost of an increased number of nodes
- Therefore, low cost per node is a must to make ASN an acceptable alternative to more sophisticated networks
- Need a testbed to demonstrate viability; nodes must be low power, low cost, and easily programmable

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Summary

- New optical techniques for spectroscopy allow for many novel applications (QEPAS, Laser Arrays)
- Nanotechnology - QCL and ICL technology - will push detection limits to part-per-trillion in a compact, low power, robust package in the near future (Room Temperature, High Efficiency)
- New field of medicine based on quantitative breath analysis is emerging (Nitric Oxide & Asthma FDA Approval)
- Sensor networks will monitor large areas for environmental (Kyoto Protocol) and security applications (Airport Explosives)

Research Affiliates:

Center for Multimedia Communication

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Texas Instruments

National Institutes of Health

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The Welch Foundation — Advancing Chemistry. Improving Life.