Ultracompact photoacoustic sensor based on a quartz tuning fork

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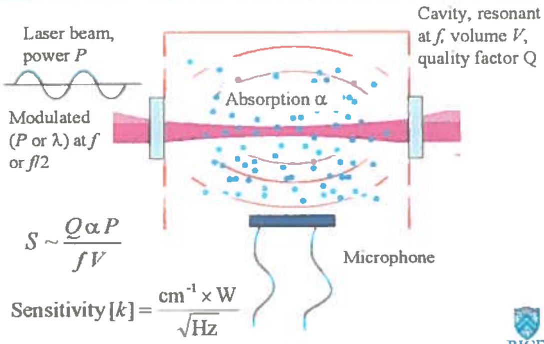
OUTLINE

JPL Review 2003
Pasadena, CA
Sept 30-31, 2003

- Principles and problems of traditional PAS
- Quartz tuning fork as a resonant microphone
- Implementation and results
- Summary and outlook

Resonant photoacoustic spectroscopy



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

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

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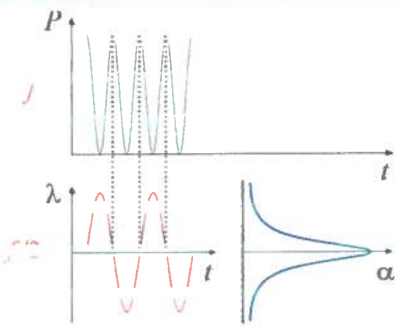
Wavelength modulation PAS



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Merits of PAS based Trace Gas Detection

- High sensitivity
- Zero background
- Low cost (compared to multipass cell + IR detector)
- Linear response to gas concentration
- Small volume cells
- Immune to laser noise
- Immune to etalon effects

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Traditional PAS Issues

- Signal proportional to Q, 1/f and 1/V – acoustic mode volume
- Energy accumulated in air (gas), hence relatively low Q

  Examples: f=8000 Hz, Q=200 ⇒ Q/f=25 ms

  f=4000 Hz, Q=18 ⇒ Q/f=4.5 ms
- Resonant cell size ~λ/2; for f=1000 Hz λ=30 cm
- Ambient noise, in particular flow noise; S_n~1/f

Accumulate energy in a MICROPHONE instead of the GAS!

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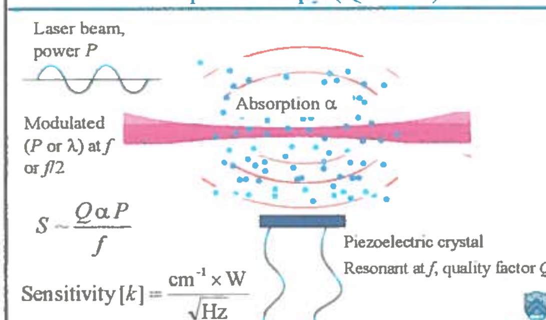
Quartz-Enhanced Photoacoustic Spectroscopy (QEPAS)



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

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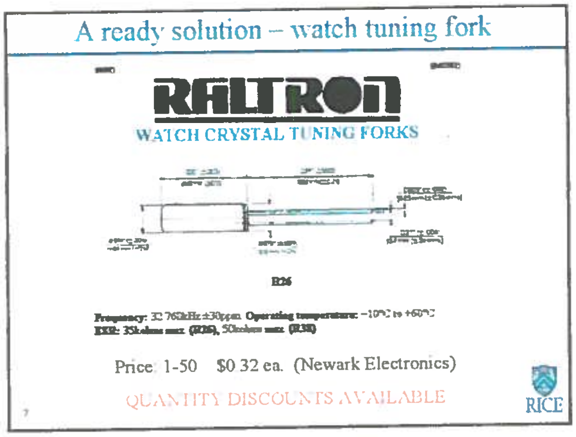
A ready solution – watch tuning fork
RALTRON
WATCH CRYSTAL TUNING FORKS
Price 1-50 $0.32 ea. (Newark Electronics)
QUANTITY DISCOUNTS AVAILABLE
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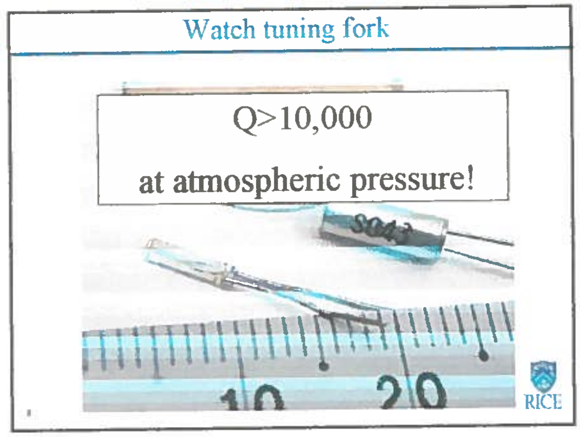
Watch tuning fork
Q>10,000
at atmospheric pressure!
S043
10
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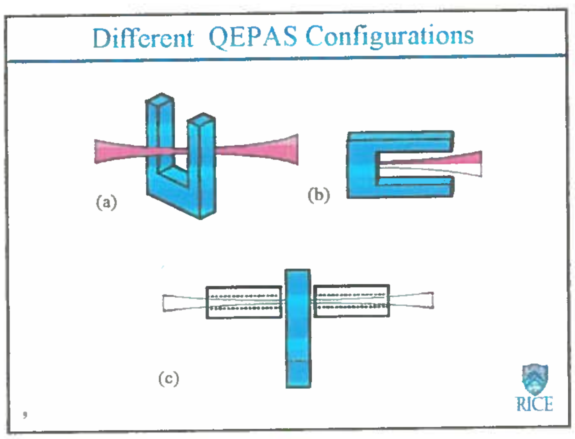
Different QEPAS Configurations
(a)
(b)
(c)
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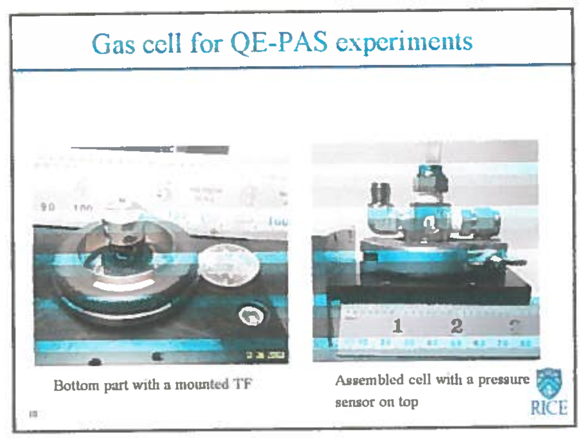
Gas cell for QE-PAS experiments
Bottom part with a mounted TF
Assembled cell with a pressure sensor on top
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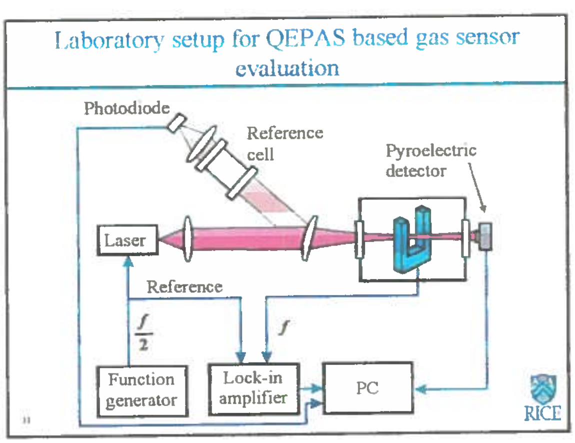
Laboratory setup for QEPAS based gas sensor evaluation
Photodiode
Reference cell
Pyroelectric detector
Laser
Reference
f/2
f
Function generator
Lock-in amplifier
PC
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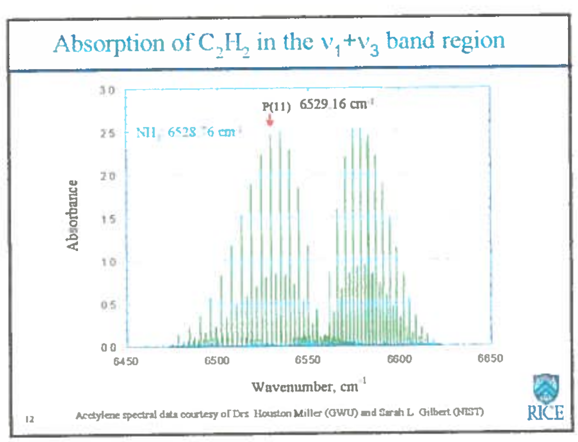
Absorption of C_2H_2 in the $\nu_1+\nu_3$ band region
P(11) 6529.16 cm⁻¹
Absorbance
Wavenumber, cm⁻¹
0.0
0.5
1.0
1.5
2.0
2.5
3.0
6450
6500
6550
6600
6650
Acetylene spectral data courtesy of Drs. Houston Miller (GWU) and Sarah L. Gilbert (NIST)
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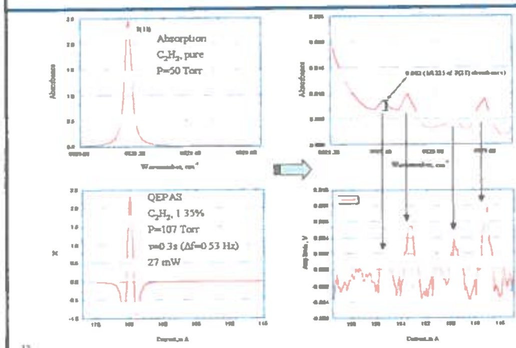
Comparison of absorption and QEPAS spectra



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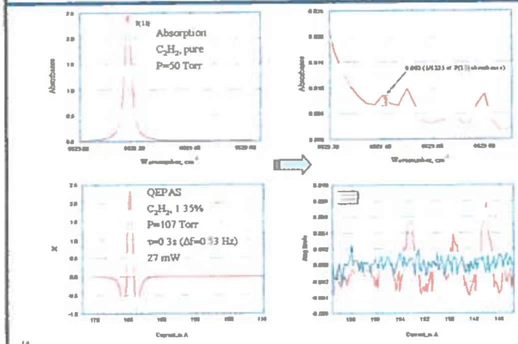
Comparison of absorption and QEPAS spectra



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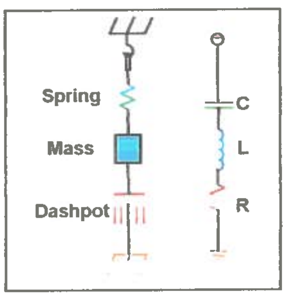
Equivalent circuit of a quartz TF



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

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

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

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

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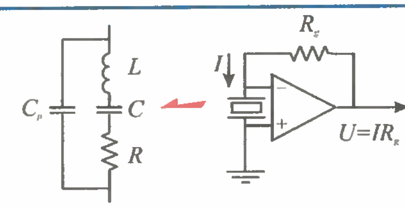
Noise analysis



$$S_1 = \sqrt{4k_BTR_g}; \quad R_g = 10\,\text{M}\Omega \Rightarrow S_1 = 4.1\cdot10^{-7}\,\frac{\text{V}}{\sqrt{\text{Hz}}}$$

$$S_2 = \sqrt{\frac{4k_BT}{R}}R_g; \quad R = 100\text{k}\Omega \Rightarrow S_2 = 4.1\cdot10^{-6}\,\frac{\text{V}}{\sqrt{\text{Hz}}} \text{ (at 760 Torr)}$$

$$S = \sqrt{S_1^2 + S_2^2} \approx S_2 \quad \text{(at resonance)}$$

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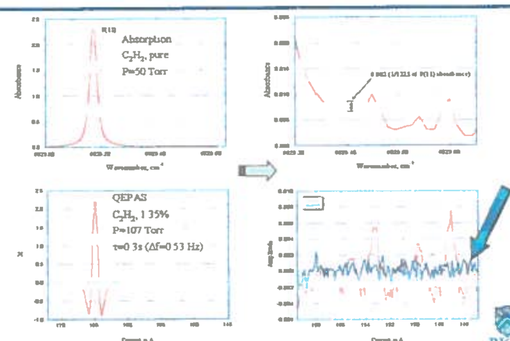
Noise in QEPAS spectra



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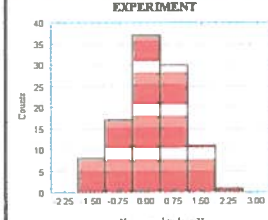
Noise: experiment vs. prediction

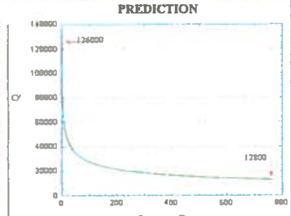
EXPERIMENT



RMS=0.94 mV, k=200, τ=0.3s (Δf=0.53 Hz)

$$S = \frac{0.94\,\text{mV}}{200\times\sqrt{0.53\text{Hz}}} = 6.46\cdot10^{-6}\,\frac{\text{V}}{\sqrt{\text{Hz}}}$$

PREDICTION



Q(760 Torr) = 12800, Q(107 Torr) = 26970

$$\frac{S(107\,\text{Torr})}{S(760\,\text{Torr})} = \sqrt{\frac{Q(107\,\text{Torr})}{Q(760\,\text{Torr})}} = 1.45$$

$$S = 4.1\cdot10^{-6}\,\frac{\text{V}}{\sqrt{\text{Hz}}}\times1.45 = 5.95\cdot10^{-6}\,\frac{\text{V}}{\sqrt{\text{Hz}}}$$

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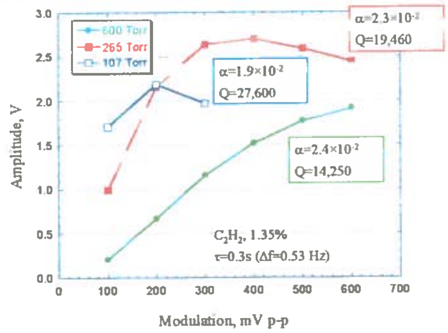
QEPAS signal vs. total pressure



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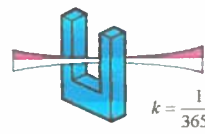
Sensitivity Estimate of QEPAS



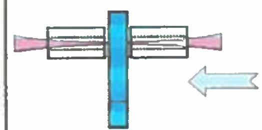
At 265 Torr:

SNR=(2.7V/200)/3.7μV=3650

Assuming SNR=1,

$$k = \frac{1}{3650} \times \frac{0.023\ \mathrm{cm}^{-1} \times 0.027\ \mathrm{W}}{\sqrt{0.53\mathrm{Hz}}} = 2.3\times10^{-7}\ \frac{\mathrm{cm}^{-1}\mathrm{W}}{\sqrt{\mathrm{Hz}}}$$

Previously reported (Opt.Lett. 2002) k=8.8×10⁻⁷ – a 3.8 times improvement!
Most probably due to the RIGHT OA in transimpedance preamplifier



Was reported to be 7 times more sensitive (1.2×10⁻⁷ cm⁻¹WHz⁻¹ᐟ²). There is hope!

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What does such gas sensitivity mean ?

- Acetylene P(11), ν1+ν3, SNR=1, k=1.2×10⁻⁷ cm⁻¹WHz⁻¹ᐟ², 40 mW, ~1min data acquisition time (Δf=0.01 Hz) ⇒ 180 ppb
- Ammonia in near-IR (6528.76 cm⁻¹) - 7 times weaker line ⇒ ~1.25 ppm
- Mid IR - ~100 times stronger absorption ⇒ ~10 ppb range for reliable (3×SNR level) detection with ~1min data acquisition time
- Sensitivity is directly proportional to the laser power

We expect to reach k<2×10⁻⁷ cm⁻¹WHz⁻¹ᐟ² due to better selection of TF geometry and acoustic microcavity optimization

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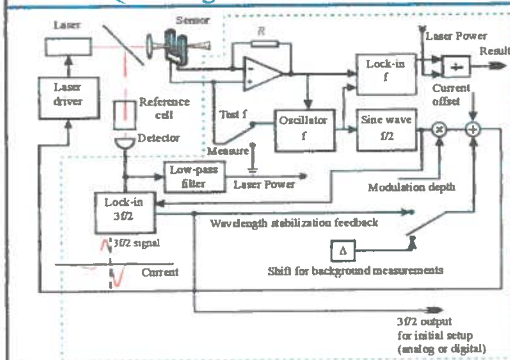
QEPAS gas sensor architecture



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QEPAS sensor electronics

Preamplifier with a TF

FUNCTIONS:

- Measures TF resonant frequency f
- Modulates laser current at f/2 (sine wave)
- Demodulates photodiode (PD) signal at 3f/2 and uses it to lock the laser wavelength to an absorption line
- Converts TF current to voltage and amplifies it
- Demodulates TF signal at f, normalizes to PD signal and measure on- and off- the absorption line to provide the number proportional to the species concentration
- Can operate autonomously or communicate with a PC via RS232 port

Electronics design by D. Serebriakov and I. Morozov, Institute of Spectroscopy, Russia

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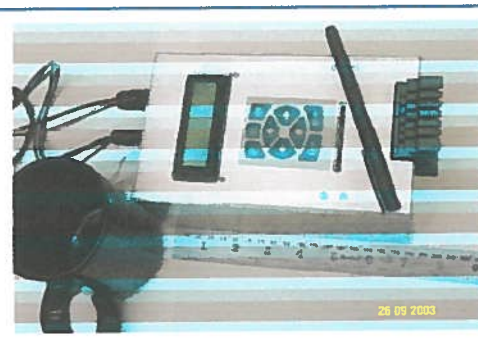
Packaged QEPAS control unit



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Summary and Outlook

- QEPAS is immune to ambient noise. Experimentally measured noise level agrees with a theoretical limit.
- Required sample volume is very small. It is ultimately limited by a gap size between the TF prongs, which is 0.15 mm^3 for the presently used kind of TF
- The best demonstrated sensitivity of QEPAS unit to date is 1.2×10^{-7} $cm^{-1}WHz^{-1/2}$, but it is expected to be improved
- Compact dedicated control unit for an autonomous QEPAS sensor is developed

NEXT STEPS:

- Test several kinds of commercially available TFs, including crystals with lower resonant frequencies (20 kHz and 10 kHz)
- Optimize acoustic microresonator design (geometry and material)
- Test QEPAS performance with amplitude-modulated sources to proof its ability to detect broadband absorbers
- Optimize light delivery (fiber, GRIN lens, light tube…)
- Combine QEPAS with mid-IR laser sources (e.g. QC lasers) for improved gas sensing

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