Photoacoustic Laser spectroscopy :
A cutting-edge detection technique for applications ranging from industry to the medical sector

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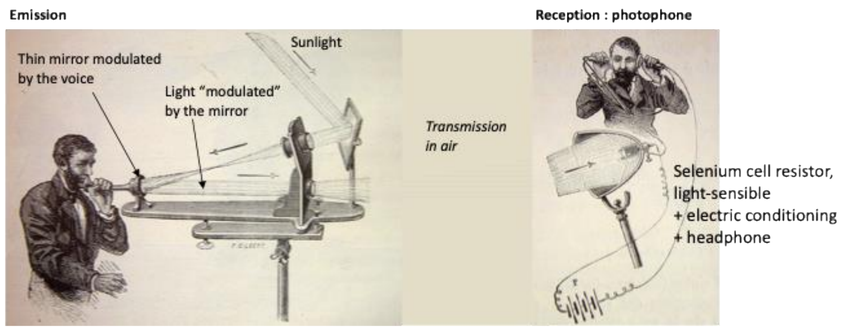
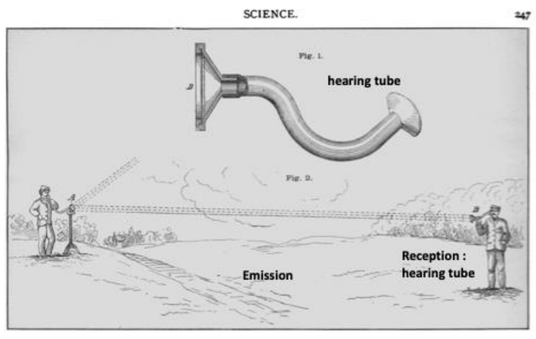
Photoacoustic spectroscopy : from history to new technologies

1880 first wireless communication

Alexander Graham Bell, invention of the photophone



Simpler version, no electronics ⍰ photoacoustics discovery



For different substances deposited (B):
1) A sound is generated near the substances
2) The sound intensity depends on the substances (Photoacoustics on solids)
3) The reception is sensible to what is happening to the light : presence of clouds, shadows…

Bell and collaborators experimented liquids and gases using the earing tube
Gases were able to produce the loudest sounds

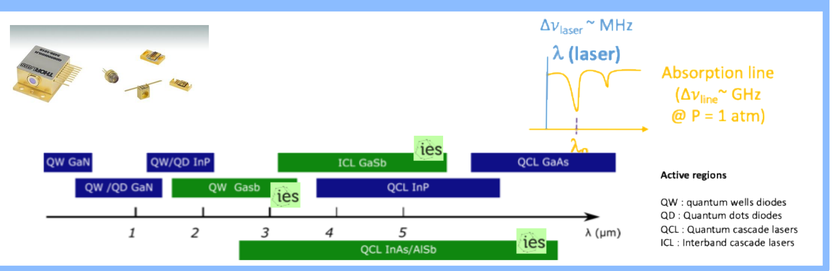
Light on dark substance ⍰ high **heating** effect
ΔT in ambient air ⍰ ΔP in ambient air **= sound**
= photo-acoutics : ***a sound wave generated after light absorption***

First applications on molecular spectroscopy

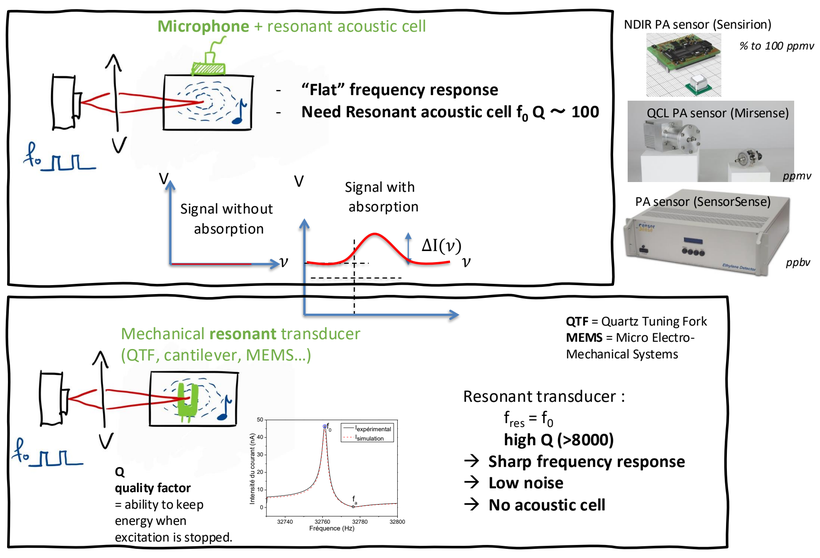
Lack of sensitivity of the detection systems

- **1880** **Bell and co** — Experiments on liquid/solids/gas absorption - Photophone configuration
- **1938** **Viengerov** — Implemented **microphones** on spectroscopic setups to monitor **gas** concentration
- **1968** **Kerr and Atwood** — used a **laser** to detect CO_2
- **1971** **Kreuzer** — worked on CH_4
- **> 1970** **The renaissance of photoacoutics !** — Lasers++, microphones++

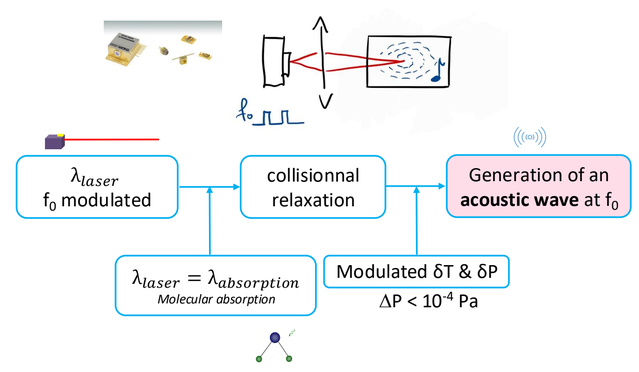
Lasers



How to detect the sound wave ? Photoacoustic detection



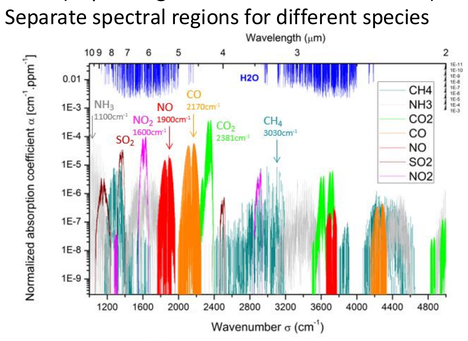
Photoacoustic effect

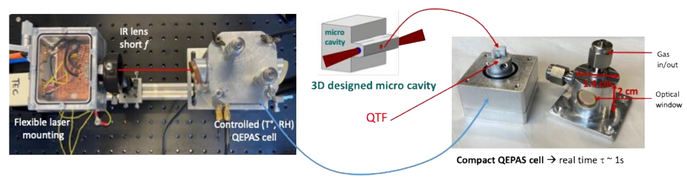


- ✓ **Selective**
- ✓ Independent on absorbed wavelength ⍰ **No need of specific photodetector**
- ✓ Proportional to the **laser power**, no need of long optical path ⍰ **Compact**

InfraRed absorption spectrum

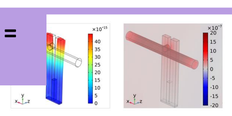
Ro-vibrational energy levels composition of vibrational + rotational motion of molecules
→ **Simple or complex** spectral features (depending on the molecules structures)
→ Separate spectral regions for different species



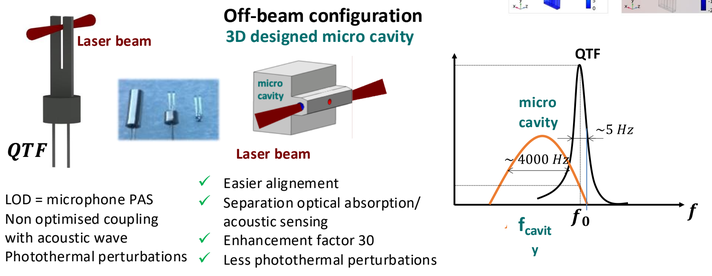


Gas sensing based on Photoacoustic Spectroscopy

Quartz Enhanced Photoacoustic Spectroscopy = QEPAS

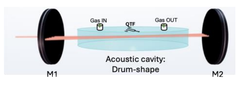


Off-beam configuration
3D designed micro cavity

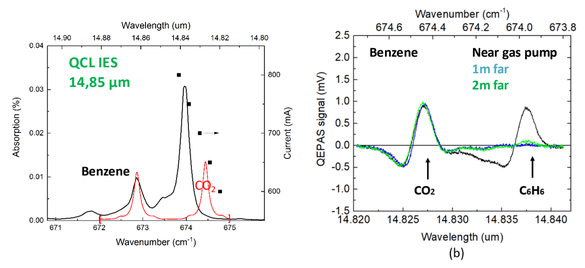


- ✓ LOD = microphone PAS
- ✓ Non optimised coupling with acoustic wave
- X Photothermal perturbations
- ✓ Easier alignement
- ✓ Separation optical absorption/ acoustic sensing
- ✓ Enhancement factor 30
- ✓ Less photothermal perturbations

Multipass configuration



Benzene QEPAS sensing near a gas station



- LOD = 30 ppbv
- Benzene in gasoline vapors can reach 60 ppmv
- ✓ **Near pump 5 < c < 25 ppmv**
- ✓ **1m far 0,3 < c < 3 ppmv**
- ✓ **2m far 1 < c < 3 ppmv**
- ✓ **Inside the car 1 < c < 9 ppmv**

⍰ Carcinomic concentrations 😟

Detected molecules :
CH_4, CO, CO_2, NH_3, NO, H_2O,
Ethylene, benzene, Isoprene, acetone

Wavelengths (µm):
1,6 - 2,3 - 2,4 – 3,3 – 4,6 – 5,2 – 5,6 – 8,2 – 11 – 15 …

Limits of detection
10 ⍰ 400 ppbv in 1 s

QEPAS Breath analysis

Ambient Air
N_2 : 78%
O_2 : 21%
Ar : 0,9 %
CO_2 : 0,04%
H_2O : 1-4%
Other : 0,01 %

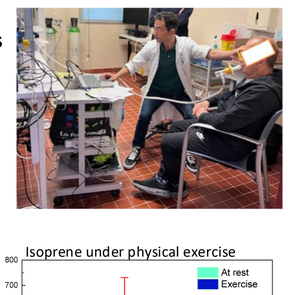
Exhaled breath
N_2 : 78% (=)
O_2 : 16% (↘)
Ar : 1 % (=)
CO_2 : 5% (↗)
H_2O : 5% (↗)
Other : variable

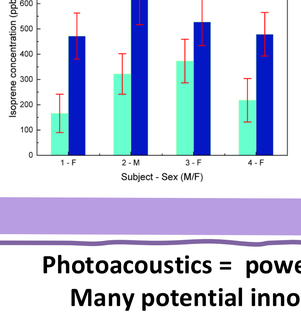
- ✓ Breath = complex gas mixture
- ✓ Many pathologies generate specific species in breath
  - ⍰ Interest in **medical diagnostic**
  - ⍰ But **one pathology** does not mean only **one molecule**

Molecules	Associated diseases	Required working range
Carbon monoxide (CO)	Inflammation cystic fibrosis Oxydative stress CVD*	1-10 ppmv
Nitric oxide (NO)	Asthma COPD cystic fibrosis Lung cancer CVD	10-50 ppbv
Acetone (C_3H_6O)	Diabete CVD [2]	0-10 ppmv > 300 ppbv
Benzene (C_6H_6)	Lung cancer Breast cancer	0-10 ppbv
Methane (CH_4)	Food intolerance Gut bacteria Oxydative stress	2-10 ppmv
Isoprene (C_5H_8)	CVD Cholesterol Cancers	> 100 ppbv

COPD = Chronic Obstructive Pulmonary Disease
CVD = Cardio Vascular Disease

Clinical evaluations





Improve

PA Spectroscopy

Apply

Innovate

MEMSPAS

MEMS
MEMSPAS MEMS Enhanced Photoacoutic Spectroscopy
Capacitive transduction
f = 15 kHz

- ✓ Separation PA excitation/capacitive measurement
- ✓ Complete analytical model
- ✓ Complete process development *
- ✓ Patented design on gap variation

Zone 2: capacitive transduction
- ✓ Low viscous damping effect with thin arms
- ✓ Optimized displacement

Zone 1: photoacoustic energy collection
- ✓ Large surface to catch the PA wave
- ✓ Small displacement
- ✓ Without any damping effect

Sensors developement

	Link to CVD
Carbon monoxide (CO) $\lambda = 4.6\ \mu m$	Increased risk of CVD
Nitric oxide (NO) $\lambda = 5.2\ \mu m$	Cardiomyopathy
Acetone (C_3H_6O) $\lambda = 8.2\ \mu m$	Heart failure
Isoprene (C_5H_8) $\lambda = 11\ \mu m$	Acute myocardial infraction

Simultaneous measurements :
4 gases/CO
+Flux/volume
+ HbCO (blood)
+ clinical respiratory exploration

Photoacoustics = powerful sensing technique, sensible, selective
Many potential innovations : integration, photonics circuits, instrumentation, optics…
Many applications fields inside and outside the laboratory, in industry, life science, health, defense…

- Abou Naoum F. Breath Isoprene Sensor Based on Quartz-Enhanced Photoacoustic Spectroscopy. *Sensors* 2025, *25*, 6732.
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- Seoudi,. Highly Sensitive Capacitive MEMS for Photoacoustic Gas Trace Detection. *Sensors* 2023, *23*, 3280.
- Ayache D. Benzene sensing by Quartz Enhanced Photoacoustic Spectroscopy at 14.85 µm," Opt. Express 30, 5531-5539 (2022)