Photonics and the Evolution of Ultrasensitive Gas Analyzers: Past, Present, and Future

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aeris: “AYRis”, air (latin)

- The atmosphere (top $O_3$ layer) extent is only $1/400^{th}$ the Earth’s diameter
  - This thin, fragile shell supports all life and controls the climate.

- We can now monitor the atmosphere with sufficient resolution via photonics
  - Wide use is limited by cost

- The future of atmospheric monitoring lies in the commoditization of emerging photonics technologies.
Markets

GHG Monitoring
- N$_2$O

Air Quality
- H$_2$CO
- EtO

Energy, Natural Gas
- CH$_4$
- CO
- CO$_2$+isotopes
- C$_2$H$_6$, C$_3$H$_8$, C$_2$H$_2$, C$_2$H$_4$, C$_6$H$_6$

Critical environmental species drive many parallel markets
Tough Requirements: Greenhouse Gases, Pollutants

- **GHG’s**: WMO/NIST target **accuracy**
  - CO$_2$: 100 ppb (@ 400 ppm)
  - CH$_4$: 2 ppb (@ 1840 ppb)
  - N$_2$O: 0.1 ppb (@ 325 ppb)

- **Pollutants**: regulatory (EPA, OSHA)
  - CO: 2 ppb
  - HCHO: 2 ppb (LEED is <20 ppb abs.)
  - Ethylene Oxide: <1 ppb

- >10$^{-3}$ accuracy at **trace levels** is non-trivial!
  Traditional methods are inadequate
  - (e.g. NDIR, FTIR, Chemi-)

**Ultrasensitive gas analysis methods are required!**
The Past: Ultrasensitive Cavity Technique Origins

- **1980’s**: Cavity Ringdown methods (CAPS, CRDS) came from high R mirrors for defense
  - R=99.99% mirrors: laser-ring gyros for defense guidance (missiles, etc.)
  - Laser weapons programs: SBL and ABL at 3.7um (HF/DF) and 1.3 micron (COIL)
  - PVD, IBS, IAD methods all developed using metal-oxide and (redacted)-fluoride coatings.
- The need to kill or prevent yourself from being killed was a great motivator!
- What else were cavity methods good for?
1989-2000: CRDS Evolution via Photonics

- Late 80’s: *U.C. Berkeley* we used CRDS for pure spectroscopy using large lasers:
  - Molecular beams, ss jets, plasmas: Dye Lasers
  - 5 miles through snow on foot to the lab

- 1994: *(Sandia Labs)* we extended CRDS to the MIR for flame research using tunable OPO’s

- mid 1990’s: *Los Gatos Research (LGR)* we invented new cavity methods for use with new NIR semiconductor lasers (ICOS and OA-ICOS)
  - Others also integrated NIR lasers with CRDS

- Mid 1990’s: *LGR* we paid Sarnoff $200K for a single NIR wafer run
  - by 2000 NIR lasers commoditized for telecom
2000’s: Commercialization of Cavity-based NIR Analyzers

- Revolution from cryogenic diode lasers to COTS room temperature devices was a game changer

- $B telecom markets commoditized NIR, single frequency, tunable semiconductor lasers
  - Wavelengths 1300 nm & 1500-1600nm

- Cavity methods + telecom lasers=commercially viable ultrasensitive gas analyzers

- To date, 1000’s of cavity-based gas analyzers sold, still considered by some state-of-the-art
  - LGR (ABB), Picarro, Tiger, AP2E, LiCor

- 201X-Present, ... systems still relatively large, power hungry, mirrors remain weakest link
  is there a better way....?
Transition to the MIR: Moving Away From Cavities

Absorption (Beer’s Law) \( \approx \text{line strength} \times \text{path length} \times \text{concentration} \)

**MIR:** Cavities no longer required to achieve the same/superior sensitivity
Transition to the Middle Infrared (MIR)

- **Late-90’s to 200X**: Quantum Cascade MIR lasers (QCL’s)
  - expensive ($30K), limited supply, high power/heat

- **In 2002**, we founded *NovaWave*: Telecom lasers and NLO’s to make MIR lasers using *Difference Frequency Generation (DFG): Two Telco lasers+crystal*
  - Innovative Photonics Solutions: high power single-frequency diode lasers eliminated the need for fiber amplifiers in DFG

- DGF provided a path to high fidelity, tunable MIR-based gas analyzers, but prices still $50K+

- Acquired by Thermo-Fisher in 2010, NovaWave developed DFG-based products, e.g. *Delta-Ray* for isotope analysis
New MIR Enabling Photonics: Interband Cascade Lasers

- **200X to Present**: ICL MIR lasers successfully developed and commercialized (Nanoplus)
  - High heat load, high power of QCL’s solved
  - It took 15+ years to maturity

- Other key photonics developments:
  - MCT and InAsSb photodetectors (Vigo)
  - Chalcogenide aspheres (Lightpath)
  - Novel multipass cell designs (Aeris)

We founded Aeris in 2013
Mission: commoditize MIR-based ultrasensitive gas analyzers
The Present: Aeris MIRA: **Middle InfraRed Analyzer**

The World’s Most Sensitive, Portable Laser-based Gas Analyzer

**MIRA Pico: Ultrasensitive “Lab-in-a-Lunchbox”**

- ppb/s sensitivity and ppb level accuracy
- 10x smaller, lighter, lower power
- Currently ½ the price of comparable, 10x larger systems
- Unmatched economy of scale
- Three platforms: *Pico, Ultra, and Strato*

**MIRA Redefines the State-of-the-Art in Laser-Based Analyzers**
MIRA: Mid-IR Laser Absorption Spectroscopy

- Direct absorption spectroscopy
  - Simple, quantitative, linear
- Fingerprints are more discrete and **stronger in the Mid-IR**
  - 200x stronger for CH₄
  - 6000x for C₂H₆
  - 32,000x for N₂O
- No FM: scanned spectrum provides tracability

The robust nature of direct absorption provides unmatched scalability
Aeris Patented, High Performance Sensor Engine

- **MIRA**: Disruptive, miniature sensor
  - Compact, **Patented** multipass cell
  - 13m path length in 60cc volume
  - $<1\text{ppb}/s$ sensitivity typical.
  - 100x less susceptible to “dirty mirrors”
- Proprietary custom electronics
  - Low Power, miniature, lower cost
  - High A:D, fast digitizers, 8-layer design

**10x reduction in analyzer size, weight, and power consumption at a disruptive price point**
The MIRA Platform: *Pico, Ultra, and Strato Series*

**MIRA PICO Series: “lab in a lunchbox”**
- 1ppb/s sensitivity typical for most species
- Lunchbox sized (5.7 l vol., 2.75kg/6lbs)
- AC/DC, 15W, 6hr battery, GPS, WiFi, RS-232

**MIRA Ultra Series: Low Drift**
- Same core technology as Pico Series, except...
- Low drift via *temperature stabilized optical core*
  - 1-2ppb drift typical
- Portable and 3U Rackmount versions available
- Battery Option: 2-3 hours continuous operation

**MIRA Strato Series: Drone**
- Same as Pico, but smaller and lighter (2.8l vol., 1.9kg)
- 1.5 hour battery
Applications and Markets

- Environmental: Pollutants, Toxics, GHG
  - Formaldehyde: Indoor Air Quality, Low VOC products
  - Carbon Dioxide, Carbon Monoxide
  - Nitrous Oxide
  - Ethylene Oxide: Highly toxic carcinogen
  - Methane, ethane, ethylene, acetylene, propane...

- Oil and Gas:
  - Natural gas (Methane) leak detection
    - Fixed, Mobile, Drone: up-, mid-, and downstream

*Monitoring these species in real-time using ultrasensitive systems will be commonplace in the future as costs/prices drop*
MIRA Ultra N$_2$O/CO$_2$

- CO$_2$ is the #1 GHG, N2O is #3
  - Global GHG monitoring networks
  - Meets/exceeds WMO/NIST targets
- Solar powered capability will enable autonomous monitoring in remote locations
Oil and Gas Markets: Up, Mid, and Downstream

Fixed CH₄ Monitoring:
- 24/7/365 Wellpad monitoring: 1M wells in US alone
- Compressor stations: (1400 large in US)
- Storage facilities (414 underground in US)
- Biogenic Methane Sources:
  - Landfills (3100 active, 10,000 old in US),
  - Livestock operations, feed lots (26,000 in US)

Mobile
- Utilities: mobile mapping: 70M gas customers in US
- Pipeline inspection (500K miles in US)
- Wellpad surveys: rapid screening tool
- Drone-based leak detection: high value assets

Handheld
- Utility Leak surveys: “up to the meter”
- Wellpad/refinery/facility surveys
Autonomous (Fixed) Wellpad Monitoring: 24/7/365

- Solar Powered!
- ID leaky operations
- <1ppb/s CH₄/C₂H₆
Wellpad Monitoring
ARPA-E MONITOR (DE-AR0000545)

- Aeris methane/ethane + wind + GPS + Neural Net Analytics = \textit{leak location and size}

- Actual leak location is \textcolor{red}{red}, Calculated location \textcolor{yellow}{yellow}

- In the future, AI will be combined with this approach to autonomously monitor wellpads 24/7/365
• Wind + sensor data+analytics = \textit{leak location and size}

• In the future, such systems will be commonly used to monitor urban pipeline health for gas utilities.
The Future: What market will commoditize MIR analyzers?

1,000,000 O&G wellpads in the US alone!
(Secret: They ALL leak methane)
The Future: Commoditizing MIR Technologies

- **Ultrasensitive MIR analyzers for <$8-10K is possible!**
  - There is currently no parallel large market for components as was the case in the NIR
- The simplicity of the MIR platform reduces the BOM, build, operational and maintenance costs
  - No $$$ and fragile cavity optics, no wavemeters, no complicated fiber-coupled laser packaging, no piezo-scanned cavities, ultra-low power
- What is required of the component technologies?
  - Numbers- it’s a numbers game!
  - more players and vendor sources

*Can SAAS business models for sensor data remove the capex burden and change the game entirely?*
Summary

- Ultrasensitive gas analysis has evolved in parallel with photonics technologies over the last 30 years: Telco NIR lasers + Cavities
- MIR Photonics have evolved significantly in the last 20 years
- Aeris has leveraged MIR Photonics advances to produce a disruptive gas analyzer platform, with 10x improvements in critical metrics: size, weight, power, performance. Enables new remote, handheld and mobile applications
- The future commoditization of MIR gas analysis is a numbers game, which could be realized in the near future by the need to monitor O&G operations

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